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Nutrient removal in the river basin of the Ruhr – a German case study

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Abstract In the catchment area of the Ruhr, restructuring and upgrading measures in the domain of wastewater and stormwater treatment have been under way since 1990 to successively implement the currently applicable legal requirements for nutrient removal. With 2.1 million inhabitants and a design capacity of 3.7 million population equivalents (PE), it is expected that approximately DM 2 billion still have to be invested from 2000 onward. With this it will be possible to further cut the nutrient load in the Ruhr River, that has been declining consistently since the 1970s: by about 25% for N_{total} and about 10% for P_{total}. The anticipated decrease in ammonia-nitrogen in winter is particularly important for drinking water production from the river water (bank filtration). Whether and to what an extent the expected decline in phosphorus concentrations will curb eutrophication in the Ruhr with its several impounded stretches remains to be seen. Further nutrient load reductions cannot be achieved by sewage treatment-related measures. Load balances underline the adverse impact of diffuse or non-point sources, in particular, for nitrogen. Some potential to further improve the situation is seen in minimizing the nutrient releases from agricultural practices.

Keywords Nutrient load balance; nutrient removal; Ruhr River; surface water quality; trend analysis; wastewater quality

Introduction

The 217-km-long Ruhr is typical of the rivers found in lower-mountain areas of Germany. The average flow, at its mouth on the Rhine, is approx. 80 m^3/s (Figure 1). The runoff is subject to strong fluctuations and ranges – uninfluenced by reservoirs – from about 3.5 m^3/s to 2,000 m^3/s. Some 2.2 million people live in the catchment area of the Ruhr basin which covers 4,488 km^2. Via artificial ground-water recharge, the 27 waterworks located on the Ruhr produce around 350 million m^3 (= 11 m^3/s) per annum of potable water for 5 million people. No less than 560 million m^3 are annually withdrawn from the Ruhr, which includes water utilisation for industrial and, in particular, cooling water purposes. Approximately half of this quantity is exported into neighbouring river catchments.

Availability of sufficient water in good quality has been and still is the major concern of water management since the early stages of industrialisation more than 100 years ago. In 1899, the Ruhrverband (Ruhr River Association, at that time Ruhrtalsperrenverein or Association of Ruhr Reservoirs) assumed responsibility for this task which, since 1913, has been based on a special act. Operating 8 reservoirs with an overall storage volume of 474 million m^3, the association is in a position to supply all water abstracting parties with the required raw water from the Ruhr, at any time and also during critical dry spells. The reservoirs help, for one thing, to guarantee a minimum runoff of 15 m^3/s in the lower reaches of the Ruhr and, for another, to reduce the impact of peak floods during heavy rainfall events (Imhoff and Albrecht, 1993; Nisipeanu and Grünbebaum, 1998; Bode, 2000; Klopp, 2000).

Today, it is the Ruhrverband's major task to ensure the best possible water quality for a variety of uses encompassing, for example, drinking water production, fisheries, and

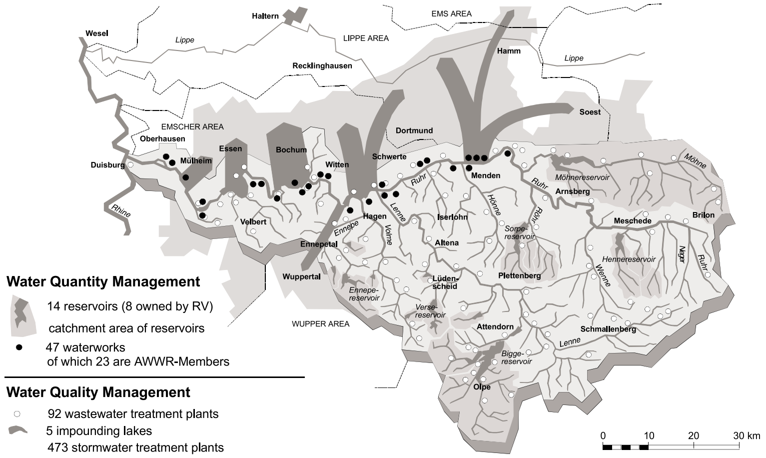

Figure 1 The catchment area of the Ruhr River with its waste water treatment plants

leisure-time sports, by building and operating both communal wastewater and stormwater treatment plants. Ninety-two waste-water treatment plants (WWTPs) with a total capacity of 3.68 million PE are presently on stream, with a level of sewer connection as high as 96%. The number of stormwater treatment plants currently amounts to almost 500.

At low water runoff, the proportion of treated municipal wastewater in the lower stretches of the Ruhr may account for 20% to 30%. Under these conditions, the water quality in the river is by a large proportion determined by the pollutants released with the effluents from the sewage treatment plants. Consequently, the purification performance of the WWTPs is of outstanding importance.

But the water quality in the Ruhr River is, of course, not only a function of specific pollutants, but above all of saprobity and trophicity. The latter is particularly relevant for the middle and lower stretches of the Ruhr characterised by 5 impoundments that have arithmetic dry weather retention times from 1 to 5 days. For that reason, the concentration of nutrients, especially of phosphorus, caused by secondary pollution is an important quality-determining factor.

German emission requirements

Up to the late 1970s, there did not exist any uniform quality standards for effluents from municipal WWTPs. In 1979, minimum requirements for the organic parameters COD and BOD_5 were introduced nationwide and tightened twice by 1989. The sewage treatment plants built during this decade were found to be outdated already in 1990, when minimum requirements were formulated for the nutrients. Also these rules were tightened twice within a few years. The current values have now been in force since 1996. Requirements increase with the size of plant: the tolerable span for COD extends from 75 to 150 mg/L, that for BOD_5 from 15 to 40 mg/L. Nitrification is required for design capacities greater than 5,000 PE, starting with 10 mg/L NH_4-N. Whereas denitrification is required for capacities greater than 10,000 PE, with a value to be met for total inorganic fixed nitrogen of 18 mg/L. Limitation of phosphorus is required for design capacities greater than 10,000 PE, starting with 2 mg/L, and coming down to 1 mg/L for capacities above 100,000 PE. As nitrification is a temperature-dependent phenomenon, the rules for NH_4-N and total fixed nitrogen apply from May 1 through October 31 or in case of wastewater temperatures above 12°C.

Compliance with these requirements is monitored by taking 2-h composite samples or so-called qualified random samples (which means at least 5 samples within a period not exceeding 2 hours, at intervals of no less than 2 minutes) and using homogenised samples for analysis. Any requirement is regarded as being met if the specific value is not exceeded in 4 cases during the last 5 tests carried out under governmental water pollution control, and if no result exceeds this value by more than 100%. The requirements defined in the Waste Water Directive are to be understood as minimum values, which means, depending on the specific use of the waterbody and the associated quality targets, the authorities might impose more rigorous standards, and have, in fact, done so in some parts of the Ruhr catchment area.

In 1991 the EU-Directive (Anon, 1991) on the treatment of municipal wastewater put the German standards at issue. According to an expert's report (Pöpel and Lehn, 1996), the requirements of the EU-Directive are not more stringent than the German rules from 1992, so that neither any numerical values, nor procedures of sampling and monitoring for compliance had to be changed.

Building programme

Due to the intensive use of the Ruhr water for drinking water purposes it has been an urgent need, right from the beginning of 20th century, to promote wastewater treatment by building new and extending old facilities and to bring them to as advanced a status as possible.

Investments into water quality made between 1948 and 1999 totalled DM 4.69 billion (building price index of 1995). The costs for building measures, primarily in sewage treatment, but since the 1990s to a growing extent in stormwater treatment, added up to this expenditure. By 1988, the annual investments averaged, with some fluctuations, DM 70 million. The following years brought an upsurge to an average amount of DM 200 million due to the above mentioned changes in the legal scenario concerning, in particular, the demand for nutrient elimination. Present-day investments are still in this range.

WWTP effluents

The large number of implemented building measures becomes manifest in the effluent quality of the sewage treatment plants. Table 1 compares the mean values found in sewage effluents from 1972 to 1999.

Figure 2 illustrates the development in effluent pollution since 1988. With 40%, the maximum decrease in concentration was achieved for NH_4-N. Also P-emissions were further cut over the last years, though targeted P-elimination had already been practised before the legal requirements were formulated, by simultaneous precipitation in selected WWTPs to tackle the eutrophication problem in the reservoirs and impoundments of the Ruhr.

Table 2 gives the mean effluent values that are presently achieved by the new or extended WWTPs of size class > 10,000 PE in the Ruhr catchment area. The average operating results outperform the requirements set by the Wastewater Directive not only with regard to organics but also to nitrogen and phosphorus. It is noteworthy to state that in winter the ammonia-nitrogen concentrations were only slightly higher than in summer.

Table 1 Flow related mean for different effluent concentrations from all treatment plants of Ruhrverband

Parameter		1972	1999
BOD_5	mg/L	53	6.6
COD	mg/L	110	34
NH_4-N	mg/L	20	6.3
N_{inorg}	mg/L	22	14
P_{tot}	mg/L	14	0.71

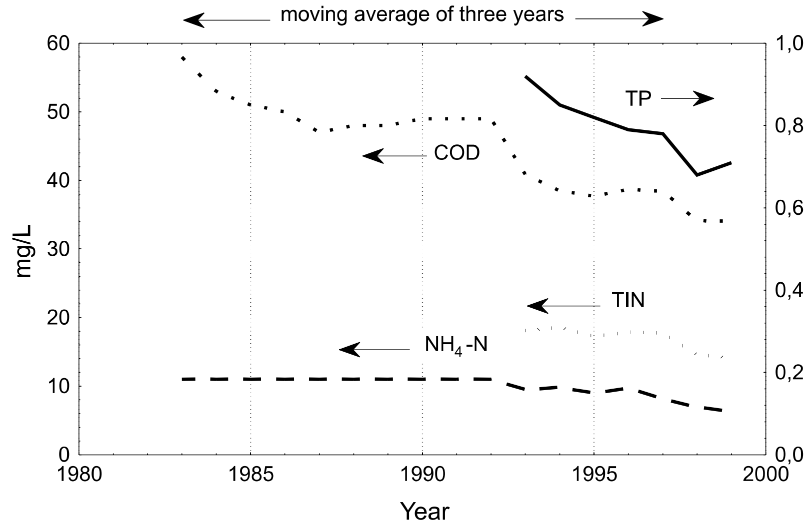

Figure 2 Development of the yearly average concentrations in sewage effluents of Ruhrverband

Table 2 Mean yearly effluent characteristics of modern WWTPs in the Ruhr catchment area

Parameter	Concentration in mg/L
BOD_5	3.4
COD	27
NH_4-N	2.3
N_{inorg}	8.9
P_{tot}	0.40

This results, among other things, from the flexible operational management concept developed to minimise especially the ammonia-nitrogen by increasing, in winter, the nitrification tank volume at the expense of the denitrification tank volume.

Ruhr water quality

Water monitoring (Bode and Nusch, 1999) is the essential instrument with which to control the success and efficiency of water management measures with regard to emissions. Whereby the chemical/analytical and the biological assessment of the water quality complement each other. Since the 1920s, the water quality in the Ruhr has been routinely monitored by taking and evaluating daily random samples in Essen-Rellinghausen, at 42 km from the river mouth, where 93% of the overall catchment area are overseen. Additional tests are carried out at 35 sampling stations, located alongside the longitudinal profile of the river, several times a year and especially during dry weather.

The time factor in the development of pollutant loads in the lower Ruhr is represented as annual mean in the sampling results from Essen-Rellinghausen. Both the nitrification process in the river and high runoffs, that increase the dilution rates, reduce the ammonium content. But the nitrification process slows down with falling river temperatures and may even come to a standstill. A declining trend is recognisable for the annual average of ammonia-nitrogen (Figure 3): in the 1970s, the mean annual values still were in the range of 1 mg/L, which could then be lowered to around 0.5 mg/L in the 1990s, thanks to improved stormwater treatment. Reductions achieved during dry-weather flow in winter are likewise significant, even in spite of strong temperature-dependent fluctuations.

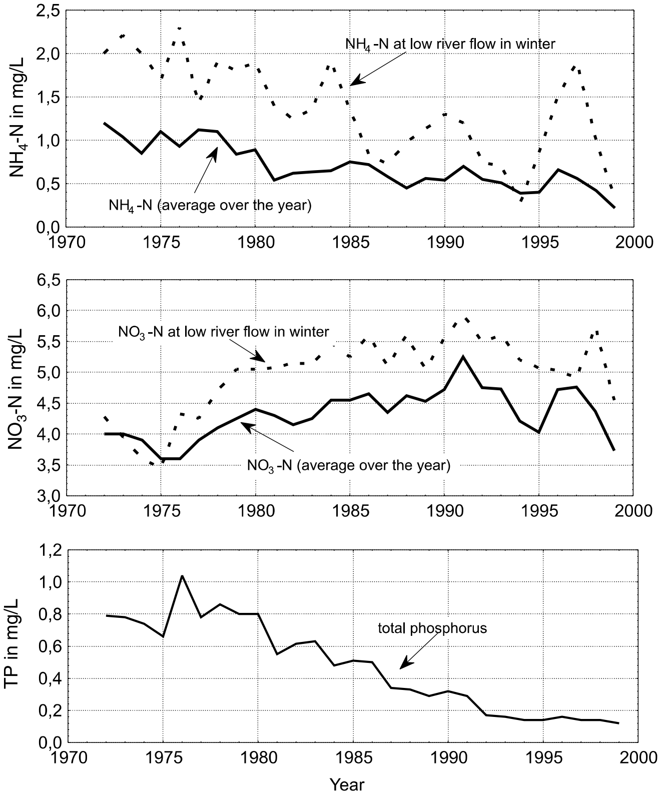

Figure 3 Development of the yearly average concentrations in Ruhr water at Essen

From the mid-1970s through the early 1990s, there has been a distinct upward trend in nitrate-nitrogen concentrations in the Ruhr. Not only the elevated releases from the WWTPs managed by Ruhrverband, but also the overabundant use of nitrogen fertilizers in agriculture have contributed to this development. The concentration of nitrate-nitrogen is hardly influenced by the flow rates in the Ruhr. The fact that the annual average at flows below 30 m^3/s and low temperatures is almost always higher than the annual average from all values, is attributable to both reduced nitrate uptake by vegetation and reduced denitrification in the river sediment. Since the early 1990s, the development has apparently changed direction due to denitrification in the WWTPs.

The figures for total phosphorus show a decline in concentration from 0.8 mg/L, in the 1970s, to 0.15 mg/L, today. It is, in particular, the development of ammonia-nitrogen and phosphorus concentrations in the lower stretches of the Ruhr that provides evidence of the decrease in pollutant emissions from municipal WWTPs.

The results from the investigations carried out along the longitudinal profile of the Ruhr, mainly during dry weather flow, illustrate the pathways of concentrations in the stream (Figure 4). While in 1972, the phosphorus load can be seen to gradually increase from the spring to the mouth of the river with the growing proportion of treated sewage effluents, there is no such tendency today due to the precipitation of phosphorus in the sewage treatment plants. Another distinct decline during dry weather flow in summer can be observed for the load of ammonia-nitrogen along the entire stream.

With its “Allgemeine Güteanforderungen” (General Quality Requirements) for running waters (creeks and rivers), the State of North-Rhine Westphalia aims at achieving the saprobity class II on the water quality scale. Involved are also a number of chemical

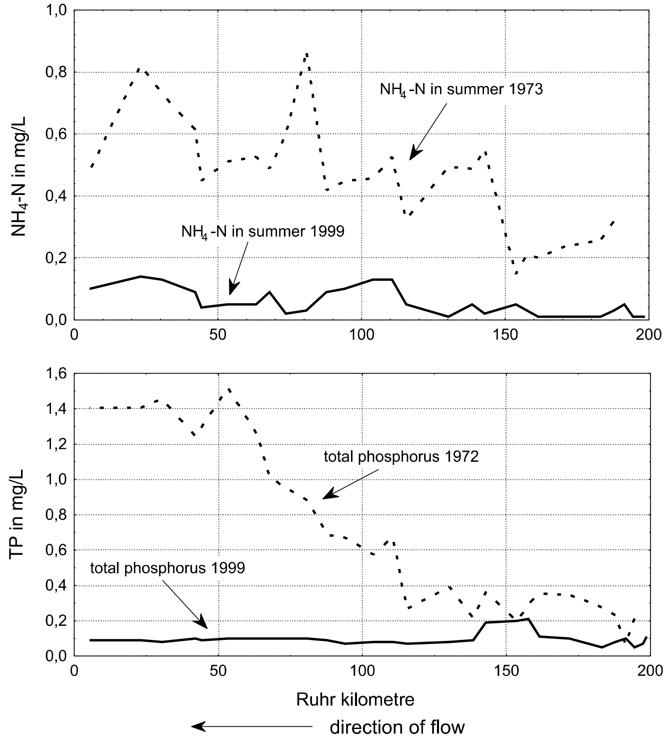

Figure 4 Longitudinal Ruhr water quality profiles

parameters defined as 90-percentile requirements. As can be taken from Table 3, the targets for nutrients in the Ruhr near Essen are met with a marked safety margin, but not so those for the cumulative organics parameters, due to secondary pollution by algal blooming in summer occurring, in particular, in the Ruhr impoundments.

Nutrient balance

Besides the effluents from sewage treatment plants there are some other but mainly non-point sources that essentially contribute to the pollution of surface waters by nutrients. These diffuse inputs are difficult to identify and quantify by measuring methods. So data from literature were used to complement the investigation results available at Ruhrverband, for example with regard to nutrient releases from agricultural and forest areas (Werner, 1991; Ruhrverband, 1998).

Figure 5 shows to what an extent the different input pathways contribute to the overall annual pollution of the Ruhr and its tributaries up to the sampling station of Essen-

Table 3 Comparison of the General Quality Requirements for “Running Waters” issued by the State of North-Rhine Westphalia with the actual status of the Ruhr near Essen in 1999

Parameter	Concentration in mg/L	
	General Quality Requirements	Actual Status 90th-percentile
BOD_5	£5	4.9
COD	£20	20
NH_4-N	£1.0	0.59
NO_3-N	£8.0	4.2
$P_{to.}$	£0.3	0.15

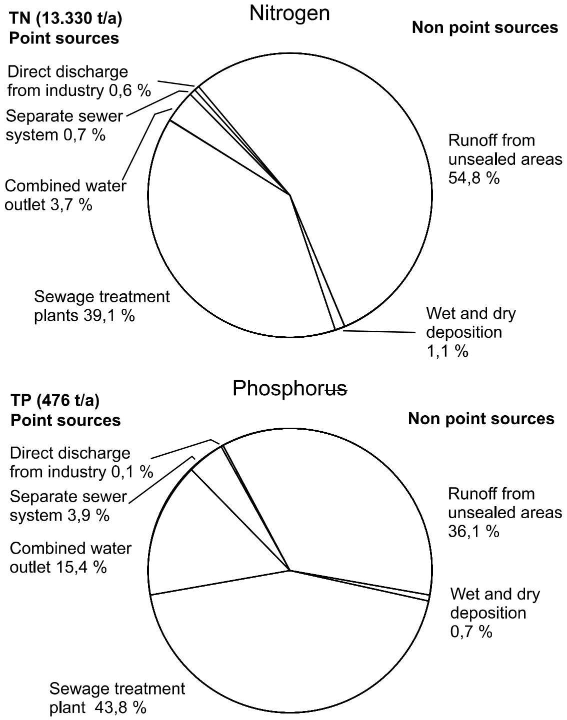

Figure 5 Nutrient balance for the Ruhr at Essen

Rellinghausen (in the year 1997). For nitrogen, the input from non-point sources (resulting from the application of fertilisers in agricultural and forest areas, including drainage – and ground water as well as atmospheric dry and wet depositions) accounts for 56% of the total load. This compares with only 39% representing the releases from WWTP effluents. Discharges from combined and separate sewers as well as from industries play a minor role. For phosphorus, things look different, as releases from point sources clearly dominate with 63%. Here, WWTP effluents account for 44% and combined water discharges for 15%. Total emissions from diffuse sources are at 37%.

The load balances clearly indicate that 56% of the nitrogen and 37% of the phosphorus inputs cannot be influenced by measures of waste water treatment. However, as regards non-point nitrogen input, which is caused to a large extent by agricultural land use, a great potential for further reductions is seen in effective efforts to combat overabundant application of fertilisers.

A comparison of all pollutant emissions with the annual sum total of pollutant loads recorded in the Ruhr near Essen-Rellinghausen – under consideration of the relevant water export – gives an insight into the purification performance and retention behaviour of the aquatic system, which comes to 20% for nitrogen and 40% for phosphorus.

Future development

Building programme

The State Government of North-Rhine Westphalia has set the goal: the implementation of the EU-Directive on Nutrient Removal must be completed by the end of 2005. Then all WWTPs >10,000 PE will be equipped with a biological nitrogen removal stage. This means, all effluent targets set by the wastewater directive, which in 1999 were achieved at 52% only, will then be fully met. The number of WWTPs operated by Ruhrverband will decrease to about 80 (Bode, 2000). Construction measures in the field of stormwater treatment – it is planned to increase the number of plants to approx. 750 – are expected to be completed by 2009. Capital investments for the expansion measures, from 1999 onward, are estimated at approx. DM 2.17 billion. However, it should be noted that the above data are based on the assumption that no additional requirements, for example relating to effluent filtration, will be imposed by legislation.

Ruhr water quality

The effects and benefits that the building measures planned in the sewage and stormwater treatment sector will have on the remaining "pollution" of the Ruhr are extremely difficult to predict, above all because it is not known in how far the reduced releases will influence the self-purification performance of the river (nutrient removal by denitrification and sedimentation). It is expected that compared with now by the year 2006 the reduction of emissions from sewage and stormwater treatment plants will be in the range of about 25% for nitrogen and of 10% for phosphorus. Assuming that both percentages will be the same for the reduction of the concentrations in the river, and taking the measuring results from 1999 as a basis, the average concentrations given in Table 4 might be typical of the year 2006. The figures indicate that the improvement would be rather marginal for phosporus, yet noticeable for total nitrogen.

Effects on water quality

The above described decrease in effluent loads will further enlarge the "safety margin" vis-à-vis the demands of the "Allgemeine Güteanforderungen" (general quality requirements) of the State of North-Rhine Westphalia. This is of particular relevance for ammonia-nitrogen for which in the past – depending on the hydrological and meteorological conditions – cases of non-compliance still were observed. A 25% reduction in total nitrogen by municipal sewage treatment translates to a significantly larger reduction in ammonia-nitrogen, the efficiency of nitrification being significantly higher than that of denitrification. It is expected that on account of the reduced WWTP emissions, winter-time concentrations of ammonia-nitrogen in the Ruhr will not exceed 1 mg/L. This has been requested by the waterworks for a long time which have to make up for too high ammonium concentrations in the raw water by an elevated use of disinfectants which might impair the odour and taste of the potable water.

Nitrogen elimination is expected to have only a minor effect on the nitrate-nitrogen content in the Ruhr. In spite of higher nitrate releases from WWTP effluents there are lower annual average concentrations in the Ruhr expected, as due to the decreasing total nitrogen load less reduced nitrogen can be nitrified in the waterbody. It should also be noted that the nitrate-nitrogen content – not having any limiting effect on eutrophication – is of no relevance for the water quality in the Ruhr. So the North Sea, for which an impact on eutrophication by nitrate is assumed, might be the only winner benefiting from the decline in nitrogen releases in the Ruhr catchment area.

The general assumption is that a decrease in the phosphorus load in slow-flowing and impounded waterbodies will curb eutrophication caused by algal blooming. Reductions by

Table 4 Estimated improvement of average nutrient loads in the Ruhr near Essen

Parameter	Concentration in mg/L 1999	2006	Reduction in %
Nitrogen_{tot}	4.6	3.5	25
Phosphorus_{tot}	0.12	0.11	10

the power of ten, measured for the loads of dissolved phosphorus in the Ruhr near Essen over the last two decades, did not produce any significant effects. As can be taken from the chlorophyll contents, strong algal blooming does still occur (Figure 6). Hence, it is not expected that the future decrease in emissions of about 10% will fundamentally change this scenario.

Estimate for the Federal Republic of Germany

Since the water management conditions prevailing in the Ruhr catchment area cannot be simply transposed to those in the overall Federal Republic (for example with regard to plant size), any projection of costs is a rough estimate. The total capital expenditure for the required building measures in the field of water quality management to promote nutrient removal, stormwater treatment, wastewater discharge and sludge disposal is to be put for Ruhrverband at approx. DM 4 billion from 1990 to 2006. Referred to a treatment capacity of 3.5 million PE (WWTPs > 5,000 PE), this equals approx. DM 1,100/PE. With this as a basis, the investments for the entire Federal Republic of Germany can be estimated at approx. DM 150 billion. However, a comparison on a European scale is not possible on account of the varying purification requirements and performances (Bode, 1999).

Since the 1990s, the required P-elimination is being practised in almost every part of Germany. So compared to the 1980s, the emissions from municipal WWTPs decreased by 80% to 11,350 t/a, now accounting for no more than 30% of the overall inputs (Anon, 2000).

In the mid-1980s, total nitrogen emissions from WWTPs amounted to 303,300 t/a. From the assumption that no specific nitrogen removal by denitrification was carried out at that time, but will be so in future with a nitrogen removal rate of 65%, it can be expected that releases from WWTPs will be reduced to 106,200 t/a. The sewage treatment plants will then account for just under 15% of the overall emissions compared to 28% in the 1980s, provided the inputs from the other sources remain at the level of the 1990s (Anon, 2000). Releases from non-point or diffuse sources play a much greater role for nitrogen than for phosphorus.

Outlook

The billion-DM investment programme for nutrient removal (upgrading of WWTPs including stormwater treatment) has made good progress not only in the river basin of the Ruhr, but throughout the Federal Republic. On completion of all construction measures, the pollution loads in the aquatic systems will be definitely curbed. Since modern sewage treatment plants, using state-of-the art technology, already accomplish far better results than those required by legislation, further pollutant reductions by water management-related measures appear to be practically impossible. Their potential influence on the loading of the waterbody would be rather insignificant, as inputs from non-point sources clearly dominate. These diffuse inputs are, for instance, responsible for the fact that no fundamental success in eutrophication abatement by P-elimination has so far been achieved. From this follows that the measures on the water management side must be complemented and supported by a distinct reduction of nutrient releases from non-point sources, whereby the application of fertilisers for agricultural purposes should be given particular attention.

On implementation of all measures relating to nutrient removal in the municipal WWTPs, the limit values set for immissions into German flowing waterbodies will, in general, be met with a high “safety margin”. In conjunction with the EU-Framework Directive, some German quarters obviously advocate more rigorous emission requirements for a range of chemical parameters that include nutrients. This is seen with some concern, because the lower Ruhr would then no longer remain in class II, an idea difficult to convey to the German citizen in view of the billions of DM invested into nutrient removal. So it is much to be hoped that the actual progress achieved in water protection and conservation will not be brought into discredit in the eye of the public just on account of more tightened evaluation yardsticks.

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