7. Development of nutrient emissions from Berlin's urban area to surface waters during the last 150 years

7.1 The development of the specific nutrient emissions

Results

The specific nutrient emissions per inhabitant

The specific nutrient emissions per inhabitant can be estimated from the excretion rate and the nutrient content in excretion. The specific phosphorus emissions per inhabitant in Berlin over the last 150 years show a slightly increasing rate in the period of 1850-1945, from 1 g P/(inh.·d) to 1.48 g P/(inh.·d) and very strong fluctuating development in the second half of the 20th century (Table 7.1, Figure 7.1). After the Second World Ward, there are different development curves in specific phosphorus emission per inhabitant in the Western and Eastern parts of Berlin. Inhabitants in Western part of Berlin have a peak of specific phosphorus emission in 1975, at the level of 4.65 g P/(inh.·d), almost three times higher than the level of 1945. 15 years later, the specific phosphorus emission of people in Eastern part of Berlin (in the GDR side) peaked at 4.62 g P/(inh.·d) (BEHRENDT, 1994, 1998). Since 1995, a slightly increasing trend in the specific phosphorus emission per inhabitant was observed (from the level 1.66 g P/(inh.·d) in 1985 to 1.93 g P/(inh.·d) in 2000). Based on previous studies (Table 7.2), the specific nitrogen emission per inhabitant is assumed to be constant for the whole Berlin over last 150 years.

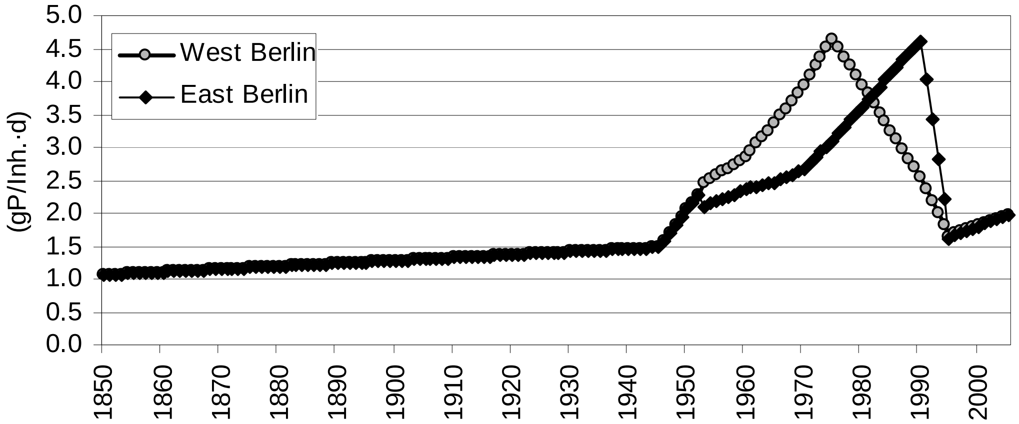

Figure 7.1: The development of the specific P emission per inhabitant over the last 150 years

Figure 7.2: Development of P – content in the popular detergents in Germany in the period of 1961-1986 according to DANOWSKI (1990)

Table 7.1: The development of the specific P emission per inhabitant in different parts of Berlin for the period 1945 to 2000 according to BEHRENDT (1998)

P emissions per Inhabitant (gP/Inh.·d)		1945	1955	1960	1965	1970	1975	1980	1985	1990	1995	2000
West Berlin	From inhabitant's excrement	1.48	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65
	From detergents	0	0.80	1.20	1.60	2.30	3.00	2.30	1.60	0.90	0.3	0.3
	Total	1.48	2.45	2.85	3.25	3.95	4.65	3.95	3.25	2.55	1.95	1.95
East Berlin	From inhabitant's excrement	1.48	1.30	1.36	1.36	1.42	1.50	1.62	1.62	1.62	1.62	1.62
	From detergents	0	0.80	1.00	1.10	1.25	1.60	2.00	2.50	3.00	0	0.3
	Total	1.48	2.10	2.36	2.46	2.67	3.10	3.62	4.12	4.62	1.66	1.92

Table 7.2: Development of specific N emission per inhabitant in Germany, 1880-1990

Location and time	N-Emission (gN/Inh.·d)	Source
Germany 1880	12	HEIDEN (1882)
Berlin 1889-92	11.5	KÖNIG (1899)
Berlin 1900	7-11.9	WEIGELT (1900)
GDR 1965	13.5	BUCKSTEEG (1966)
GDR 1985	12	FIRK & GEGENMANTEL (1986)
GDR 1982-85	10.9	SPERLING (1986)
GDR 1980	10-19	KOPPE & STOZEK (1986)
GDR 1989	11	HAMM (1991)
FRG 1980	13	TGL 27885/03

(Source: BEHRENDT, 1994)

Table 7.3: Development of specific P emission per inhabitant in Germany, 1890-1990

Location and time	Excrement (gP/Inh.·d)	Source
Berlin 1889-92	1.06	*KÖNIG (1899)*
Germany 1890	1.09	*KELLNER & MORI (1889)*
Germany1880	1.12	*HEIDEN (1882)*
GDR 1955	1.29	*HAENEL (1980)*
GDR 1965	1.34	*HAENEL (1980)*
GDR 1970	1.51	*GROSS (pers. Mitt.)*
GDR 1985	1.84	*GROSS (pers. Mitt.)*
FRG 1950	1.50	*HOPPE-SEYLER (1953)*
FRG 1958	1.66	*KLOTTER & NEUSSEL (1959)*
FRG 1964	1.65	*BUCKSTEEG (1966)*
FRG 1975	1.90	*BERNHARDT et al. (1978)*
FRG 1986	1.90	*FIRK & GEGENMANTEL (1986)*
FRG 1987	1.90	*HAMM (1991)*

(Source: BEHRENDT, 1994)

The development of the area specific nutrient deposition

The area specific emission of nitrogen is the sum of the nitrogen deposition from the atmosphere and the nitrogen compounds from litter fall and excreta from animals (4kg N/(ha·a)) (BEHRENDT, 2001, 2003). Area specific nitrogen depositions for the period of 1850-1955 were estimated from NO_x and NO_y depositions in this time (EMEP, 2005). The atmospheric nitrogen deposition data for the period of 1955-2000 was originated from BEHRENDT's estimation (1998). Area specific nitrogen deposition increased from 3.8 kg TN/(ha·a) in 1850 to the maximum level of 31 kg TN/(ha·a) in 1985 (Table 7.4, Figure 7.3). The nitrogen deposition development has a continuously increasing trend since 1850 until the peak in 1985, with the fastest increasing trend in the period of 1950-1985. Since 1986, nitrogen deposition has a continuously deceasing trend with the level of 17.1 kgTN/(ha·a) in the year 2000, equivalent to the level of the period of 1961-1965.

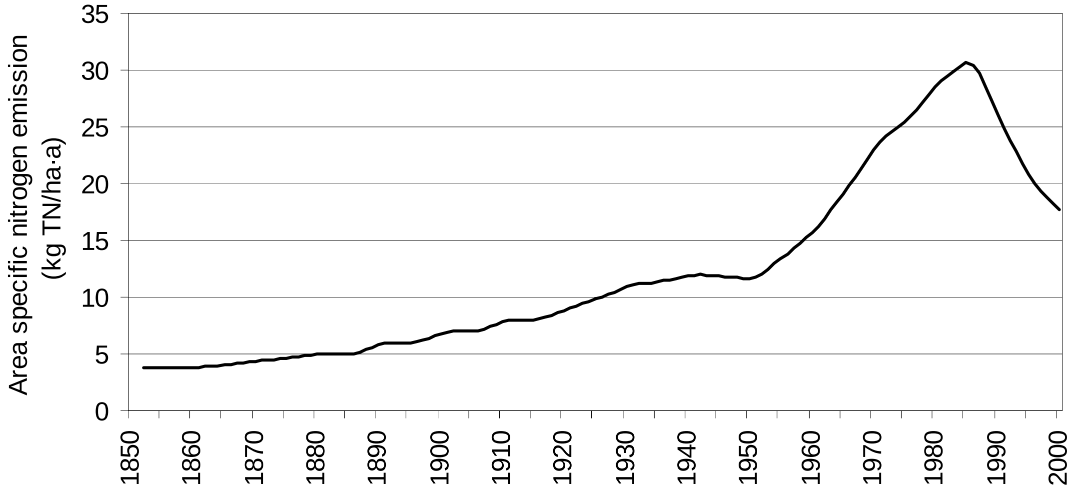

Figure 7.3: The long-term development of the area specific nitrogen emission in Berlin *(Source: BEHRENDT, 2003 and own estimations)*

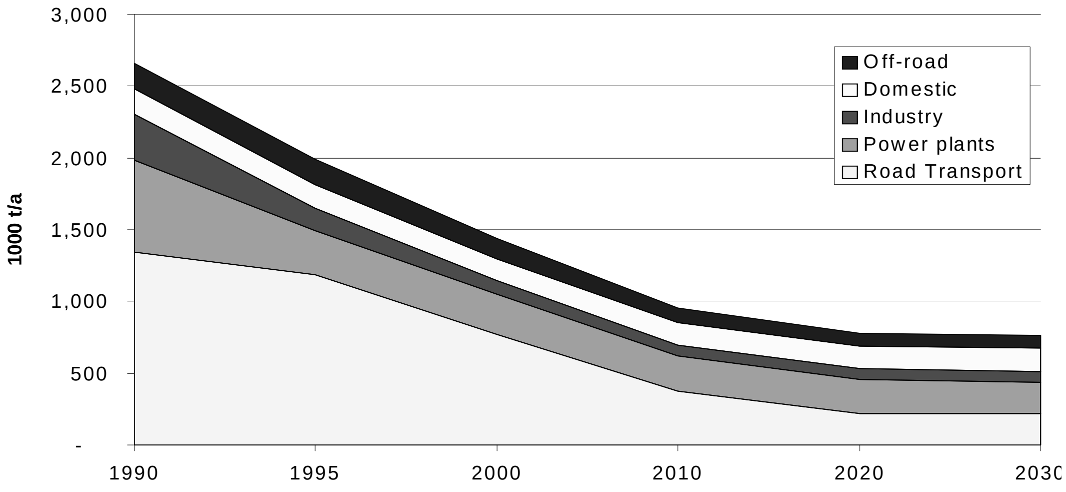

Figure 7.4: Estimated NO_x emission in Germany in the period of 1990-2030 *(Source: IIASA, 2006).*

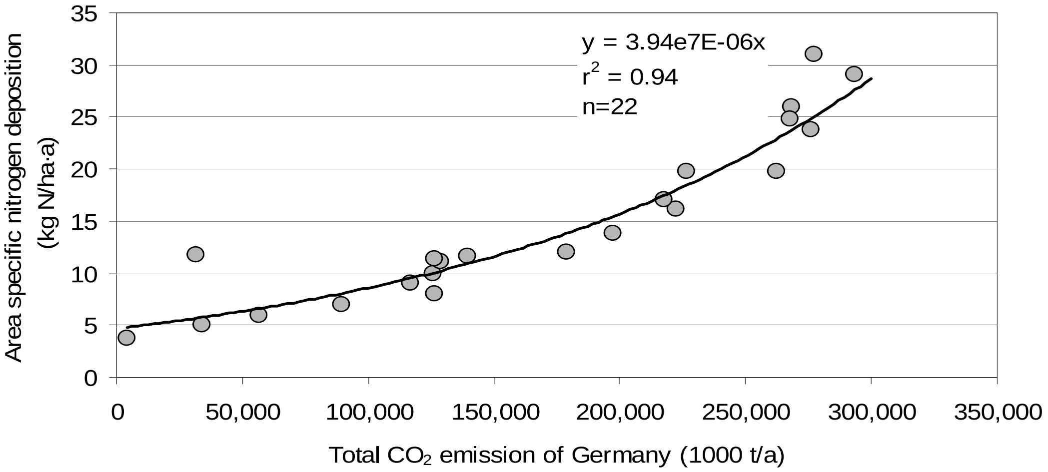

Figure 7.5: Relationship between the area specific nitrogen depositions ($NO_x + NH_y$) and the total carbon dioxide emission of Germany in the period of 1850-2000

(Data source: CIDAC, 2006)

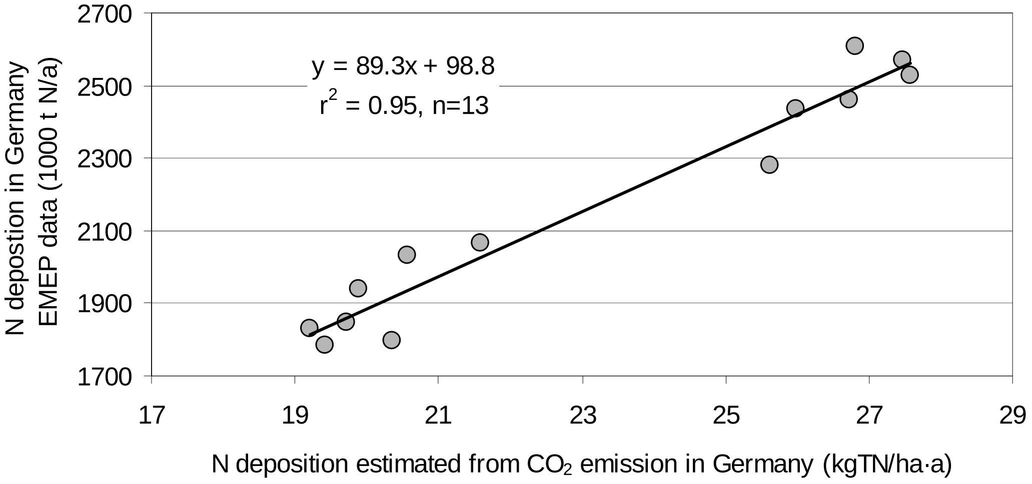

Figure 7.6: Relationship between the nitrogen depositions ($NO_x + NH_y$) in EMEP database and estimated area specific nitrogen deposition in the period of 1985-1997

(Data source: EMEP, 2005; CIDAC, 2006)

The area specific emission of phosphorous originates from the atmospheric deposition, animal faeces and traffic sources. The atmospheric phosphorus deposition is closely related to the total carbon dioxide emission and can be estimated by an empirical formula:

$$DEP_P = 5 \cdot 10^{-11} \cdot E_{CO_2}^{1.8208}, \ r^2 = 0.98 \qquad \text{(eq. 7.1)}$$

where

DEP_p = area specific phosphorus deposition from atmosphere ($kg \cdot ha^{-1} \cdot a^{-1}$) and

E_{CO_2} = total carbon dioxide emission of Germany the period of 1850-2000 (1000 t/a).

Based on the equation 7.1 and the data on CO2 emission of Germany the period of 1850-2000, the long-term development of the area specific phosphorus emission is estimated and shown in Figure 7.3 and Table 7.4.

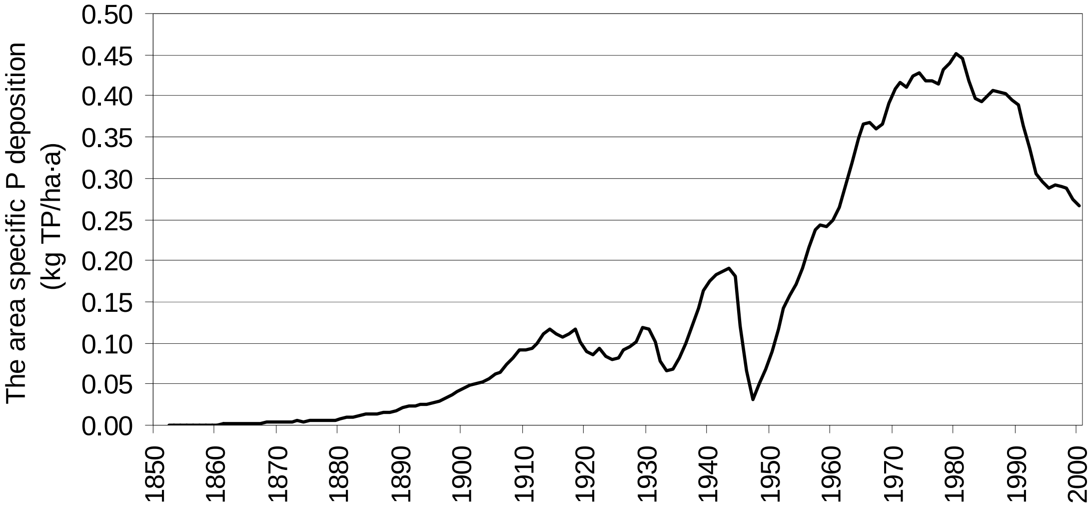

Figure 7.7: The long-term development of the area specific phosphorus deposition in Berlin *(estimated from CO_2 emissions)*

Table 7.4: The area specific nutrient emissions in Berlin in the period of 1750-2000 (including atmospheric deposition, excreta of animal, traffic compounds etc.)

Year			1750	1800	1860	1880	1885	1890	1895	1900
TN deposition [kg TN/(ha·a)]			2.98	3.14	3.83	5.15	5.42	5.67	6.17	6.69
TP deposition [kg TP/(ha·a)]			1	1	1.001	1.009	1.014	1.023	1.029	1.052
Year	1905	1910	1915	1920	1925	1930	1935	1940	1945	1950
TN deposition [kg TN/(ha·a)]	7.29	7.92	8.43	8.97	9.53	10.05	11.07	12.13	11.84	11.56
TP deposition [kg TP/(ha·a)]	1.069	1.091	1.097	1.085	1.097	1.101	1.098	1.183	1.008	1.228
Year	1955	1960	1965	1970	1975	1980	1985	1990	1995	2000
TN deposition [kg TN/(ha·a)]	13.82	16.17	19.84	23.70	25.86	29.10	29.00	24.77	19.81	17.09
TP deposition [kg TP/(ha·a)]	1.442	1.605	1.812	1.960	2.050	2.230	2.297	2.382	2.282	2.263

(Source: BEHRENDT, 2003 and own estimations)

Discussion

The specific nutrient emissions per inhabitant

Since 1850, the specific nitrogen emission per inhabitant has not been deviated a lot in the whole Germany (BEHRENDT, 1994, 2003; BILLEN, 1999), see also in the Table 7.2. Therefore, the level of 11 g N/(inh.·d) was used for Berlin area.

The specific phosphorous emission per inhabitant includes the major parts: human excrements, food residues and wash and cleaning agents (SCHMOLL, 1998). These levels depend on the living standard of the target population, the application of washing machine and also the introduction of regulation on P– free detergent in recent years. After the Second World War, there are two different living standards as well as P-related regulations in the Western and Eastern parts of Germany. Due to the separation, the sources of the specific phosphorus emission are different not only in the dietary sources, but also the non-dietary sources. Dietary sources (including emissions from human excrement and food remains), depend on the living standard. Non-dietary sources including P-content detergents and industrial emissions, depend on the content of phosphorus in washing powder, the use of washing machines as well as the related regulations and industrial emission rate (SMIL, 2000).

Before 1945, there were almost no use of P in washing and cleaning agents and automatic washing machines in Berlin. Therefore, the specific phosphorus emission came mainly from the excrement source with a slightly increasing trend in the period of 1850-1945 (Figure 7.1, Table 7.3). In general, the specific phosphorus load per inhabitant had a rapidly increasing trend when sodium phosphate was used often as a "builder" in household detergents to improve the cleaning power. The trend was decreasing when regulations or commitments of the industrial sector on substitution of polyphosphates by other agents in washing powders were enforced. The increasing trends were observed in both, West and East Berlin since 1945 as a result of increasing living standard and extensive use of P-content detergents. The decreasing trends of specific P emission per inhabitant in West Berlin since 1975 and in East Berlin since 1990 are the result of the application of non-P detergent regulations as well as the advanced technique of washing machines resulting in reduced request of detergent volume (Figure 7.2). The peak of the specific phosphorus emission per inhabitant in West Berlin coincides with a peak in the development curve of P–content in detergents in Germany in the period of 1961-1986 (DANOWSKI, 1990). The decreasing trend can be observed since the self-commitment of the detergent industry (according to the Washing and Cleaning Agents Regulation) on substitution of polyphosphates by other agents in washing powders began in 1975 in West Germany. This commitment was enacted in East Berlin just after the unification of Berlin in 1990.

The slightly increasing trend of the specific phosphorus emission per inhabitant of Berlin in the period after 1995 origins from the growing use of automatic dishwashing machines in of Berlin especially in the Eastern part. Today, one in every two households in Berlin has an automatic dishwasher, whereas no automatic dishwasher machines in East Berlin's households existed before the reunification (BEHRENDT, pers.com.). Although most liquid detergents for hand-washing dishes are phosphorus free, most automatic dishwasher detergents contain complex phosphates, the same chemicals have been removed from laundry detergents. The role of phosphorus in automatic dishwasher detergents is to build the surfactant to keep dishes from spotting. The automatic dishwater detergent powders and tablets frequently have 6 to 8 % phosphorus content by weight (BURNSDIE and MCDOWELL, 2001; HANRAHAN and WINSLOW, 2004).

The area specific nutrient deposition

The NO_x emissions in Germany are originated mostly from road transport, power plant different sources in the period of 1990-2005 (Figure 7.4). The close relationship between the area specific nitrogen deposition and the total carbon dioxide emission of Germany can be observed in the period of 1850-2000 (Figure 7.5 and 7.6).

The area specific nutrient emissions are the sum of the nutrient deposition from the atmosphere and the nutrient emissions by litter fall and animal excreta. These values were strongly impacted by the atmospheric composition at regional and global scales, contributed by emissions from fossil fuel combustion, industry, burning biomass, and agriculture. In these processes, anthropogenic emissions are important, and often dominant, contributors to the abundances of NO_x and NO_y (BARRIE et al., 1998; ANDERSON and DOWNING, 2006).

Nitrogen deposition is composed mainly of NO_x and NH_y. Anthropogenic emissions of NO_x (including NO and NO_2) were originated from traffic, fossil fuel combustion and to a minor part animal excrements from agricultural activities as well as natural emissions from the soil due to natural biogenic processes. NO_x concentrations vary from low values in "non-contaminated" areas (0.1 ppb-4 ppb NO_x) to high values (more than 100 ppb NO_x) in cities (SANHUEZA, 1982, MORALES et al., 1999; BARRIE et al., 2000). In addition, the other cause for the decline of specific nitrogen deposition is the implementation of the upgraded catalyst system (reduce nitrogen oxides to elemental nitrogen and oxygen) in cars since the middle of the 1980ies in response to tighter nitrogen oxide emission standards (KAHN, 1996; BARTNICKI, 2006).

The energy production of Germany over past 150 years heavily depended on fossil fuels (more than 60% in 1998). Fuel combustion is a major source of NO_x emission. Therefore, NO_x emissions are strongly connected to the energy production and consumption in Germany and neighboring countries. CO_2 emission can be used as an indicator for the fuel combustion in the past. In general, the largest fraction of CO_2 emissions (40%) is from burning of solid fuels (MARLAND et al., 2006). Newly compiled energy statistics allow an estimation of the complete time series of annual carbon dioxide (CO_2) emissions from fossil-fuel in Germany since 1751 (CIDAC, 2006).

90% or more of NH_3 emissions into the atmosphere were originated from agricultural activities (animal waste and mineral fertilizers) (BUIJMAN, 1987, 1988). In the second half of the 19th century, the agricultural activities, including the husbandry, have not been supported by mineral fertilizer. The industrial synthesis of ammonia from nitrogen gas was developed by Fritz Haber and Carl Bosch in 1913. The population expansion demanded a huge amount of food products and this was possible only by the additional use of mineral fertilizer. Since the 1940ies, the industrial production of mineral fertilizer has grown exponentially. Due to increasing numbers of livestock the NH_y emissions into the atmosphere by decomposing organic matter, from the volatilization process of animal and human urine and other excreta has been rapidly increased until the 1990ies. After the economic changes in the Eastern part of Germany, the total livestock numbers declined sharply (reduced 50% in the period of 1990-1993) (NITSCH & OSTERBURG, 2004).

The area specific phosphorus emission (Table 7.4) depends on the amount of phosphorus deposition from the atmosphere and phosphorus content in animal excrement and traffic emissions. Major sources of particulate P in the atmosphere are P from industrial sources (the stationary combustion sources, phosphate industry) and soil particles containing both naturally occurring and fertilizer derived (GRAHAM & DUCE, 1979; ANDERSON & DOWNING, 2006). Because of the increasing trend in coal/oil combustion and fertilizer use in and around Berlin in the period of 1850 – 1985, the atmospheric deposition of P increased continuously, especially in the time after 1945. In 1945, due to the destruction of the Second World War, the P emission amount dropped. From 1945-1980, due to the economic expansions in both sides of Germany, the P emission was increased. Since the early 1980s in West Germany, the P-emission has a decreasing trend mostly due to the installation of the particulate filter in response to tighter emission standards for combustion sources. This process was delayed 10 years in the Eastern part of Germany after reunification.

7.2. Nutrient emissions from diffuse sources

7.2.1 Nutrient emissions from different diffuse pathways

Results

Direct nutrient depositions into surface waters

Nutrient input from the atmospheric deposition to surface waters is the product of the total surface water area and the area specific nutrient deposition. Nitrogen emission from atmospheric deposition increased from 22 t TN/a in 1850 to 185 t TN/a in the year 1985. In the 19th century, this emission was around 40 t TN/(ha·a) and the specific phosphorus depositions were lower than 0.3 t TP/ha (Figure 7.8, Table 7.5).

In general, the development of direct nitrogen deposition from atmosphere can be divided into three periods:

- the period of 1850-1945: increasing TN deposition period;
- the period of 1945-1985: the exponentially increasing TN deposition period; and
- the period of 1985-2000: decreasing TN deposition period.

The direct TP emissions from the atmospheric deposition on Berlin waters have an increasing trend in the period of 1850 – 1914. Since the First World War, the TP deposition has a strong variation and reached the bottom of period 1915-1943 in 1933 – coined with the worst time of the Great Depression, then increased rapidly. Strongly decline in TP depositions were recognized in the period of 1944-1945 (Figure 7.8). TP depositions on Berlin surface water has rapidly increasing trend in the period of 1946-1980. Since 1981, this emission has a declining trend.

Table 7.5: Direct nutrient depositions into water bodies of Berlin in the period of 1850-2000

Year	1850	1875	1900	1920	1945	1975	1980	1985	1990	2000
TN (t/a)	22.7	28.1	41.8	53.8	70.5	154.7	174.0	185.0	148	102.2
TP (t/a)	0.001	0.037	0.31	0.51	0.047	2.29	2.7	2.44	2.28	1.57

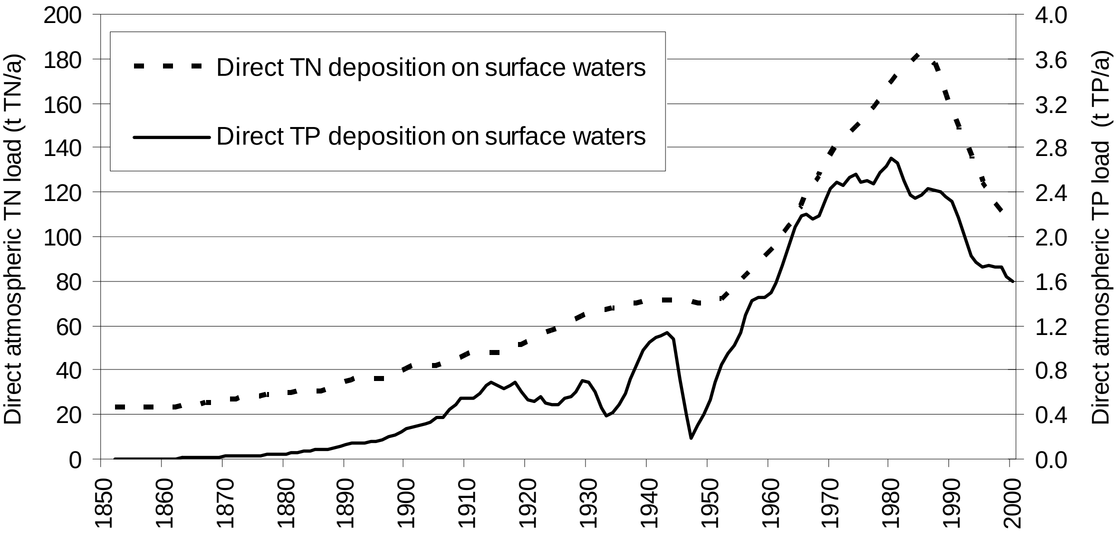

Figure 7.8: The development of direct nutrient depositions into Berlin's water bodies over the last 150 years *(Model result)*

Nutrient emissions from surface runoff

Nutrient emissions via surface runoff over the last 150 years is estimated by the equation 6.8 and shown in Figure 7.10. The development of TN emissions via surface runoff has two major trends:

- The period of 1887-1985: increasing TN emissions with an exception for few years after the Second World War; and
- The period of 1986-2000: decreasing TN emission.

The development of TP emission from surface runoff (Figure 7.10) has two major trends:

- The period of 1887-1990: increasing TP emission with an exception for few years after the Second World War; and
- The period of 1991-2000: decreasing TP emission.

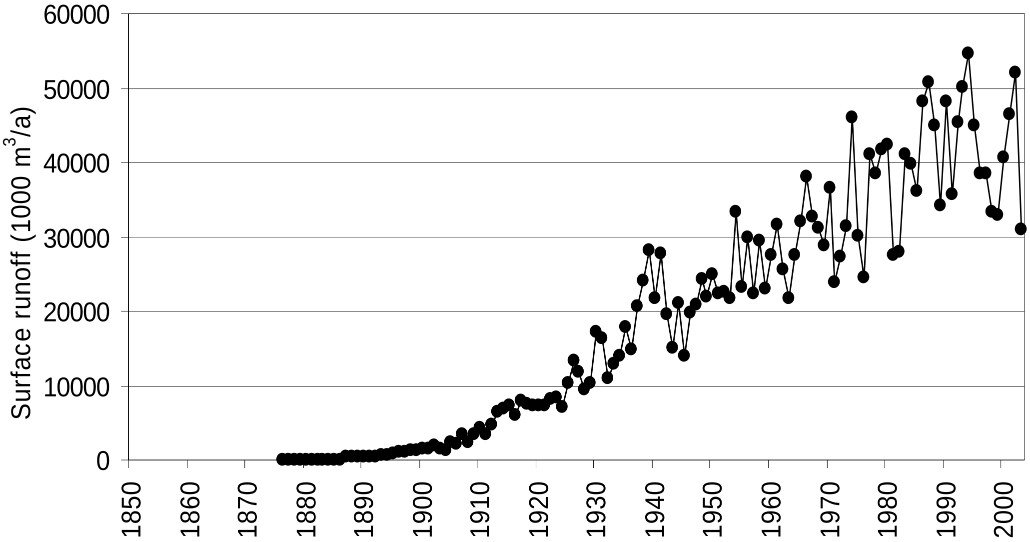

Figure 7.9: Surface runoff from separate sewer system into water bodies of Berlin over the last 150 years *(Model result)*

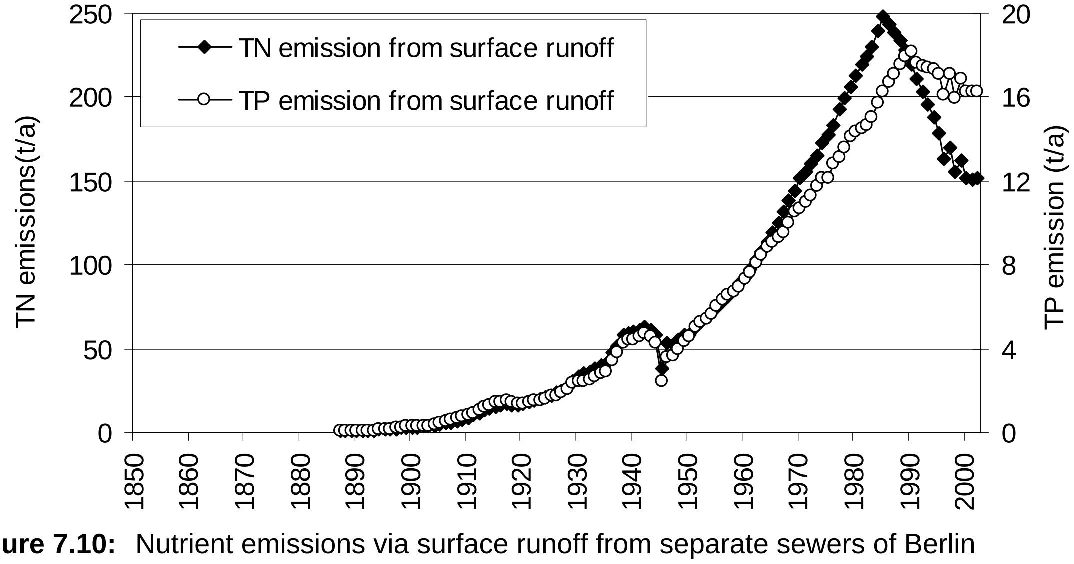

Figure 7.10: Nutrient emissions via surface runoff from separate sewers of Berlin over the last 150 years *(Model result)*

Nutrient emissions from the overflow water

Nutrient emissions from overflow water of Berlin in the period of 1875-2000 is estimated bv the equations 6.10, 6.11, 6.12, 6.13, 6.14, 6.15 and 6.16 and shown in Figures 7.11, 7.12.

The nutrient emissions via overflow water in the combined sewer system of Berlin had a rapidly increasing trend in the period of 1875-1920, a fluctuation at high stand in the period of 1921-1987, and then a decreasing trend (Figure 7.12).

In 1960, approx. 90% of overflow water in West Berlin discharged directly to surface waters. This rate decreased rapidly to 23% in 1966. In the period of 1966-1994, on average 19 % of overflow water has purred into surface waters. In the period of 1995-2000, only 8.4% of overflow water discharged into water bodies (Table 7.6).

Table 7.6: Storm overflow quantities of the pumping plants in Berlin

Year	West Berlin	West Berlin	West Berlin	East Berlin	Total Berlin	Total storm-water basin overflow
	Storm overflow	Storm-water basin overflow	Total	Storm overflow		
	(m^3/a)	(m^3/a)	(m^3/a)	(m^3/a)	(m^3/a)	(m^3/a)
1989	509,850	1,987,868	2,497,718	303,170	2,800,888	2,291,038
1990	711,200	4,185,100	4,896,300	889,200	5,785,500	5,074,300
1991	232,600	2,519,400	2,752,000	377,750	3,129,750	2,897,150
1992	389,572	3,107,200	3,496,772	617,700	4,114,472	3,724,900
1993	356,400	1,561,000	1,917,400	434,400	2,351,800	1,995,400
1994	852,800	3,289,700	4,142,500	1,060,200	5,202,700	4,349,900
1995	306,790	3,275,400	3,582,190	729,800	4,311,990	4,005,200
1996	244,630	2,104,700	2,349,330	574,130	2,923,460	2,678,830
1997	240,760	2,365,000	2,650,760	613,000	3,218,760	2,978,000
1998	62,390	1,699,900	1,732,290	954,000	2,686,290	2,653,900
1999	41,900	822,900	864,800	574,700	1,439,500	1,397,600
2000	194,270	1,789,400	1,983,670	788,690	2,772,360	2,578,090

(Data source: Gewässerkundlicher Jahresbericht des Landes Berlin, Abflußjahr 1990; BWB, 2000)

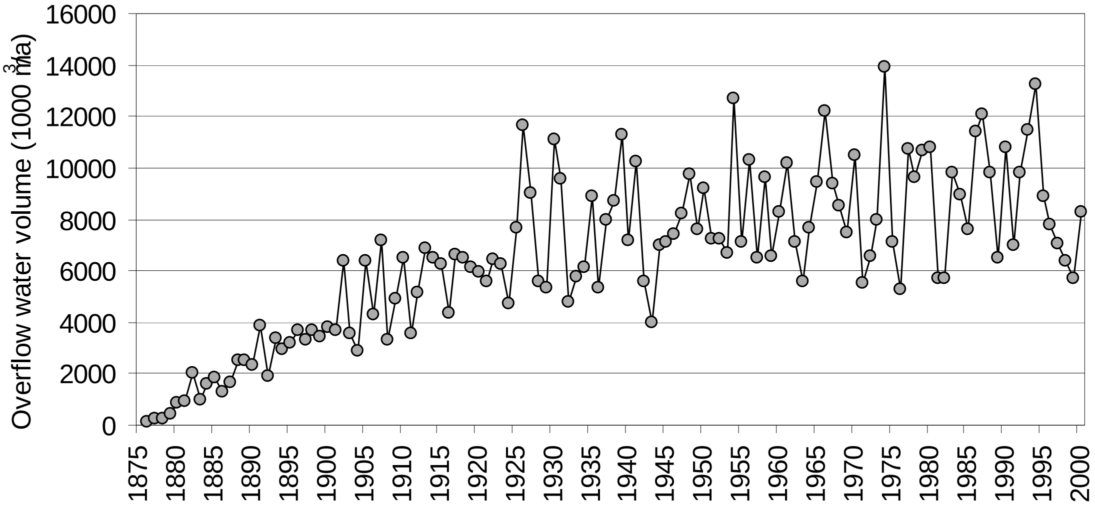

Figure 7.11: Overflow water volume direct discharged into the receiving water bodies of Berlin in the period of 1875-2000 *(Model result)*

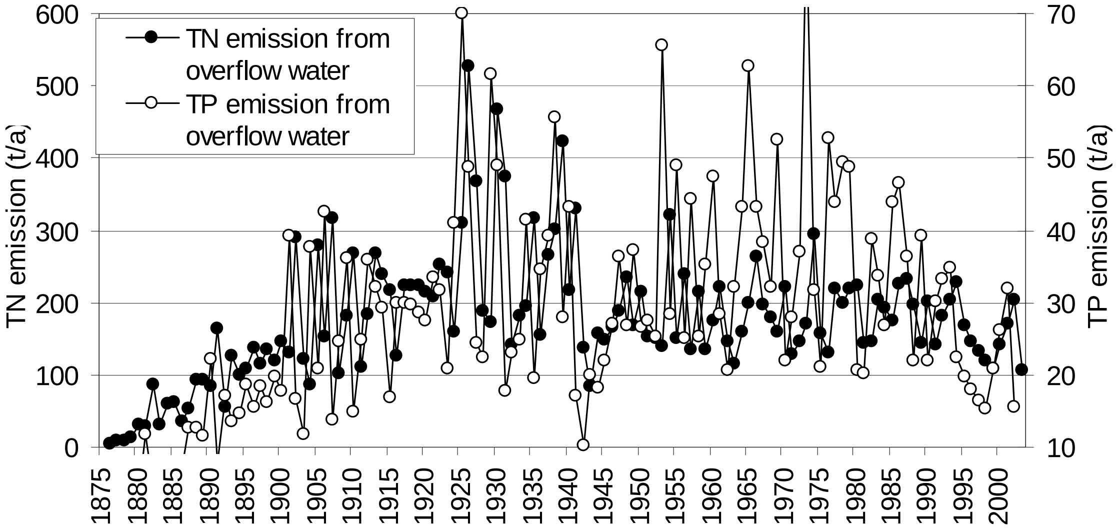

Figure 7.12: Nutrient emissions from combined sewer overflow of Berlin in the period of 1875-2000 *(Model result)*

Discussion

Direct nutrient depositions into surface waters

Nutrient input from the atmospheric deposition to surface waters depends on two major parameters: the total surface water area and the area specific nutrient deposition.

Assuming that the surface water area is constant during the last 150 years, the main cause of the development trend of direct nutrient depositions is the development of the area specific nutrient emissions (see also 7.1).

Nutrient emissions from surface runoff

Urban areas with sealed surfaces discharge part of total runoff either directly to bodies of water, or indirectly by way of waste water treatment works. The remaining runoff infiltrates and percolates at the edge of sealed surfaces, or within partially sealed surfaces, into deeper soil layers below the zone influenced by evaporation, and eventually enters groundwater (SENSTADTUM, 2001). In the separate sewer system, storm water sewers collect the precipitation that falls onto the streets, rooftops and yards and also the cooling water from factories and water from drainage ditches.

In Berlin, surface runoff can follow the combined sewage system to sewage farms or WWTPs in the inner city area, or can follow rain water sewers in the separate sewage system to the surface water bodies (Figure 2.20). Therefore, the surface runoff contributes to surface water bodies mostly come from the extension areas of Greater Berlin. Except the heavy rain days, the surface runoff mostly collected precipitation from sealed surface, including the streets, rooftops and yards. Therefore, the nutrient emissions of surface runoff mainly come from the atmospheric deposition and from leaves, animal feaces on the streets. Surface runoff from separate sewer system into water bodies of Berlin over the last 150 years is shown in Figure 7.9.

Nutrient emissions from the surface runoff depends on the area specific nutrient deposition and the impervious area serviced by the separate sewage system of Berlin. Obviously, considerable emissions of nutrient are transported by overland flow into bodies of water when the new urban areas to be developed and connected to the sewer system.

The nutrient emissions via surface runoff depends on the construction of waste water collection system as well as the development of impervious area in Greater Berlin over the last 150 years. Since 1856, there were some important changes in the water supply system. Further more the application of water closets, impacted on the way of waste water generation in household, changed the domestic waste water composition and the collection and treatment system.

Before 1875, all waste water of Berlin purred into the river Spree and other water bodies via open gutter system without any treatment. Since 1887, the separate sewer system has been installed mostly in the new urban area of Greater Berlin (SENSTADTUM, 2001; BÄRTHEL, 2003). Almost all areas in the extension pats of Greater Berlin were serviced by the separate sewer system. The impervious area in the extension parts of Greater Berlin had rapidly development trend with 21% in the total impervious area in 1850, and then 47% in 1890, 72% in 1910 and 75% in 1920 (Figures 2.10, 2.11).

The increasing period of nutrient emissions from this source is a consequence of two increasing development trends in impervious area serviced by the separate sewer system in the new urban area of Berlin and an increasing trend in area specific emission of nitrogen and phosphorus (Figures 7.3, 6.7). The period of decreasing trend in TN and TP emissions mostly originated from the decline trend of the area specific emissions of nutrient. This general trend is a result of emission mitigation efforts in Germany to reduce the Greenhouse gases but different in case of nitrogen and phosphorus. The P–deposition has a decreasing trend mostly due to the installation of the particulate filter in response to tighter emission standards for combustion sources in West Germany since the 1980s and in East Germany after reunification.

Nutrient emissions from the overflow water

The nutrient emissions from overflow water depend on the waste water collection capacity of the combined sewer system, the number of days with significant precipitation, the area of impermeable, the area specific nutrient deposition and the specific nutrient emissions per inhabitant. The nutrient emissions from overflow water have a strong fluctuation for year to year mostly due to the variation of the annual rainfall (Figure 7.11).

The combined sewer system is located mostly in the inner city area of Berlin (Figure 2.20). It contains combined sewer overflows, storm water overflows, overflow channels and storm water tanks. In storm water tanks, precipitation of heavy rains can be stored and later discharged into the closest WWTP or to the nearest receiving water bodies when its storage capacity has been exhausted (FRANZKE, 2001). The capacity of the combined sewer system is the most limited because of limited investments. In addition, this system was established in the inner-city areas with high population density (high domestic waste water) and highest sealed degree of urban area (high surface runoff from rainfall).

The increasing trend of nutrient emissions via overflow water in the period of 1875-1920 has the following reasons:

- The water supply volume has an increasing trend (Figure 2.15) with the first water supply in Stralauer Tor operating since 1856 with the starting capacity of 16.000 m^3/d and increasing to 64.000 m^3/d in 1875. In the early time, the central water supply provided its services just inside of the Old Berlin city (area serviced by the combined sewer system). Based on the development of the central water supply system, since the 1860ies more and more water closets were installed (Appendix 11.2). In the 1890ies, 100% of households in the inner city area of Berlin were equipped with water closets. This development resulted in the change of volume as well as composition of waste water from households. With water closet, the dissolved parts of N and P in excrement will be easily motivated and discharged into the gutter and sewer system.

- At the same time, the radial system for waste water collection has expanded rapidly in the last 30 years of the 19th century. In 1902, the last radical system (Radial sector XI in Northeast Berlin) has been in operation, completing the canalization process of the Old Berlin city (Figure 2.20) (Appendices 11.1, 11.3).

- The inner city area has a very high population density compared to the extension parts of Greater Berlin. Population in the Old Berlin city area has the highest density in the 1910s, up to 327 inh./ha compared to 42 inh./ha in the suburban areas (Figure 2.13),

- The area specific nutrient emissions have an increasing trend in this period (Figures 7.3, 7.7).

The period of high nutrient emissions from overflow water (1921-1987) has the main causes the area serviced by the combined sewer system reached maximum scope; high population density, especially before the Second World War (Figure 2.13) and the increasing trend in the specific nutrient emissions from inhabitants (after 1945) and the atmospheric deposition (Figures 7.1, 7.3, 7.7).

The decreasing trend of nutrient emissions via overflow water after 1987 has originated from the decline trend in specific nutrient emissions per inhabitant and per urban area (Figures 7.1, 7.3, 7.7). The progress in reducing overflow water directly discharged into surface water bodies was achieved mostly by increasing rainwater storage volume and retention volume of combined sewer storage in Berlin (BEHRENDT, 1999; BÄRTHEL, 2003).

7.2.2 Development of nutrient emission from diffuse sources

Results

Discharge. Non-point discharges into water bodies of Berlin over the last 150 years are shown in Figure 7.13. The total water volume run into water bodies from surfaces in the separate sewer system has an increasing trend over the whole study period. It increased from 1% of total diffuse sources in the period of 1876-1900 to 24% in the period of 1946-1975 and 35% in the period of 1991-2000. Water volume from direct precipitation on surface water (river and lake) and groundwater has an almost stable value over the last 150 years. The discharge from overflow in the combined sewerage system has an increasing trend in the period of 1876-1920 in total non-point discharge and then stayed on a stable level in the period of 1921-2000.

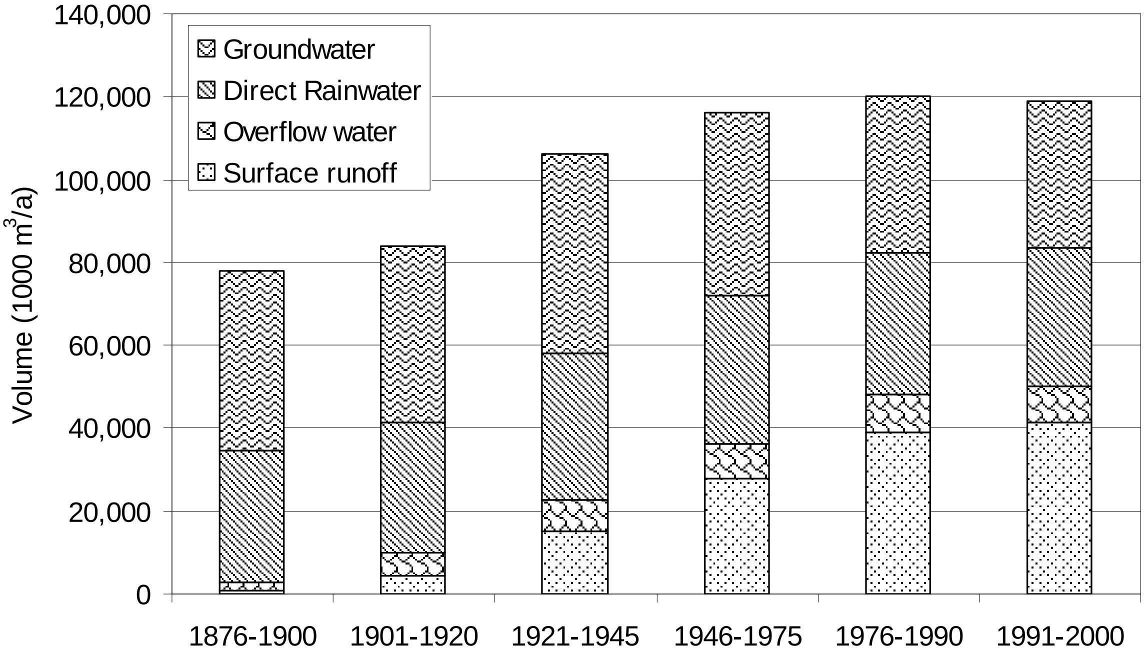

Figure 7.13: Non-point source discharges development in Berlin, 1876-2000 *(Model result)*

Nitrogen. Figure 7.14 shows TN concentrations in different non-point sources in Berlin over the last 150 years. TN concentration in overflow water is quite high compared to other non-point sources. TN concentrations in surface runoff has an increasing trend over the last 150 years.

Before 1945, the nitrogen emissions from overflow water is the biggest contributor to the total non-point nitrogen emissions. Since 1945, the surface runoff from the separate sewerage system has been replaced the overflow water as a dominant source of nitrogen emission among the diffuse sources. Nitrogen emission via direct precipitation on surface waters has its biggest contribution to the total diffuse N emission in the period of 1946-1975 (Figure 7.15).

Figure 7.14: TN concentrations in individual non-point sources in Berlin over the last 150 years *(Model result)*

Figure 7.15: TN emissions from non-point sources in Berlin over the last 150 years *(Model result)*

Phosphorus. Like TN, TP concentrations in overflow water are quite high compared to other non-point sources. TP concentrations in surface runoff have an increasing trend over the last 150 years.

Overflow water always was the dominant contributor to the total non-point phosphorus emissions. Overflow P load contributed to 44% and 58% of the total non-point phosphorus emissions in the period of 1876-1900 and 1901-1920. In the period of 1946-1975, overflow water always contributed the highest portion (65%) to the total diffuse P input. This contribution was reduced to 60% in the period of 1976-1990 and to 51% in the period of 1991-2000. The surface runoff input has an overall increasing trend. Its influence continuously increased the total diffuse P emission from 0.6% in the period of 1876-1990 to 37% in the period of 1991-2000 (Figure 7.17).

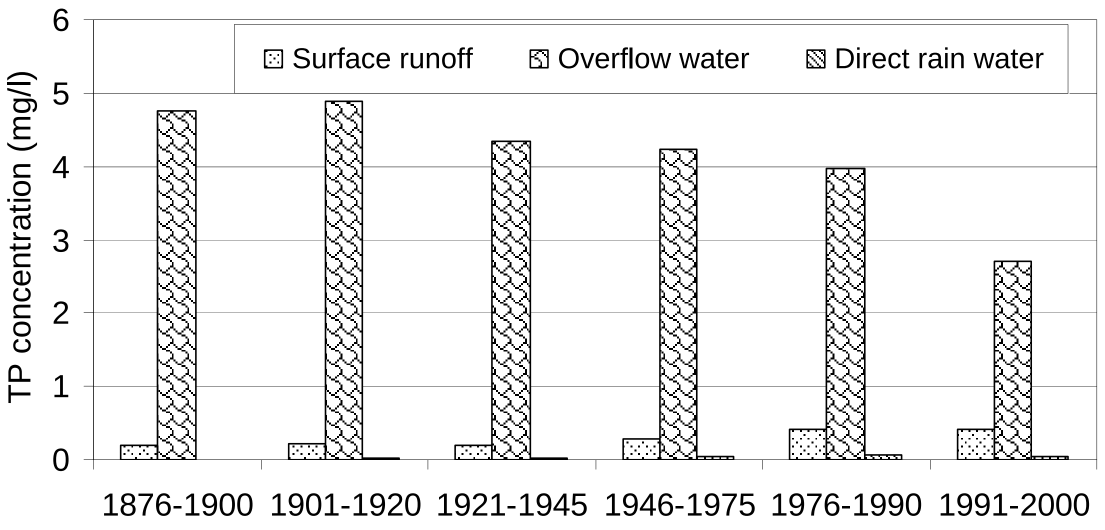

Figure 7.16: TP concentrations in different non-point sources in Berlin over the last 150 years *(Model result)*

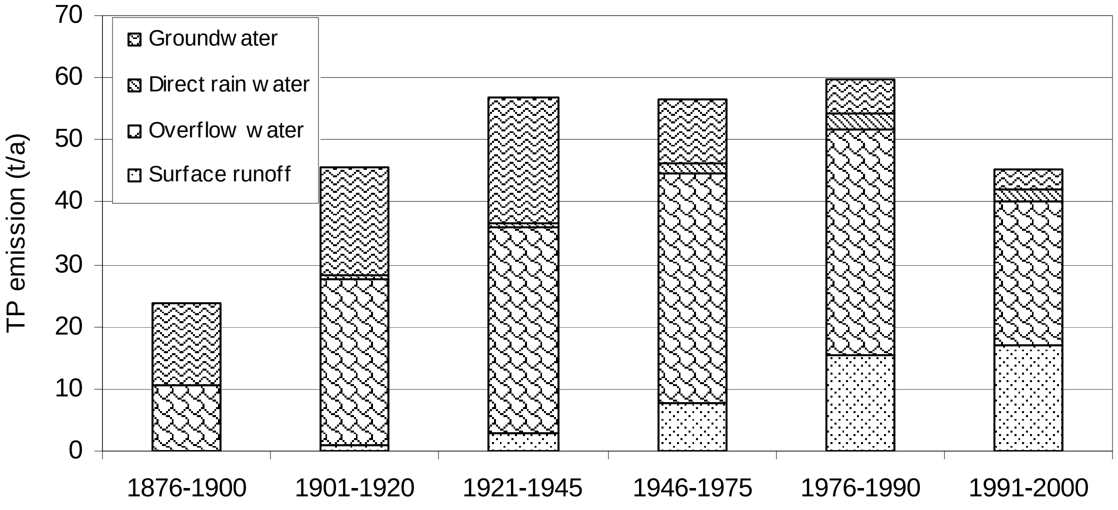

Figure 7.17: TP emission via different non-point sources in Berlin over the last 150 years *(Model result)*

Discussion

Despite of very limited volume compared to the other diffuse pathways (Figure 7.12), overflow water is always an important contributor to the total nutrient emissions from diffuse sources, because nutrient concentrations in this pathway are quite high in comparison to other non-point sources (Figures 7.14, 7.16). High nutrient concentrations in overflow water originated from domestic and industrial/commercial waste water portion in the heavy rain days (SENSTADTUM, 2001). The contribution of overflow water input to total diffuse sources reduced recently as a result of 1. the decreasing trend of overflow water (Table 7.6) (SENSTADTUM, 2001); 2. the reducing trend in population density in the inner city area

(Figure 2.13) (STATISTICHE JAHRBUCH BERLIN, 1873-1991); 3. the reducing trend in the specific nutrient emissions per inhabitant and area (Figures 7.1, 7.3, 7.7) (BEHRENDT, 2003; EMEP, 2005; CIDAC, 2006).

Surface runoff from the separate sewerage system played a more and more important role among diffuse emission sources (BWB, 2005). In the period of 1991-2000, it was the dominant contribution to the total non-point emissions of TN and the second largest contributor among diffuse P emissions. The main causes are the increasing trend in the area to be serviced by separate sewer system and also the impervious area inside this system (Figures 2.22, 2.23) (SENSTADTUM, 2001; BÄRTHEL, 2003). In addition, the area specific nutrient emissions have almost all increasing trend in the period of 1945-1987 (Figures 7.3, 7.7) (BEHRENDT, 2003).

7.3 Nutrient emissions from point sources

7.3.1 Nutrient emissions from sewage farms

Results

The contribution of nutrients from point sources depends on the type of point sources, the waste water treatment volume and technologies. According to the equation 6.1, the total nutrient inputs to sewage farm are the sum of nutrient emissions from domestic sector drainage via the combined and separate sewer systems, nutrient emissions from commercial and industrial areas, the nutrient depositions in the paved urban area connected to the combined sewer system.

According to the method provided by PÖTHIG et al. (2001), the nutrient removal capacities of sewage farms were estimated based on the nutrient surplus and the absorption, denitrification capacities and P-saturation of the sewage farm soils (Table 7.7).

Table 7.7: Estimated nutrient removal capacities of sewage farms, 1876-1985

	Removal capacity	
Year	TN (%)	TP (%)
1876	95	99
1880	67	98
1890	64	98
1900	72	98
1910	69	98
1920	65	98
1930	69	97
1940	71	91
1950	69	33
1960	69	20
1970	68	20
1980	68	20
1985	68	20

(Own estimation)

Based on the equations 6.2, 6.3 and Table 7.7, nutrient emissions from sewage farms of Berlin in the period of 1876-1885 were estimated (Figures 7.18 and 7.19).

The development of nitrogen emissions from Berlin’s sewage farms (shown in Figure 7.18) can be divided into four major periods:

- 1876-1914: period of rapidly increasing TN emissions,
- 1915-1917: period of decreasing TN emissions,

- 1918-1942: period of increasing TN emissions,
- 1943-1985: period of deceasing TN emissions.

The development of phosphorus emissions from sewage farms (Figure 7.19) can be divided into four main periods:

- 1876-1935: Period of slightly increasing TP emissions,
- 1936-1967: Period of heavily TP emissions,
- 1968-1973: Period of high TP emissions and fluctuation,
- 1974-1985: Period of decreasing TP emissions.

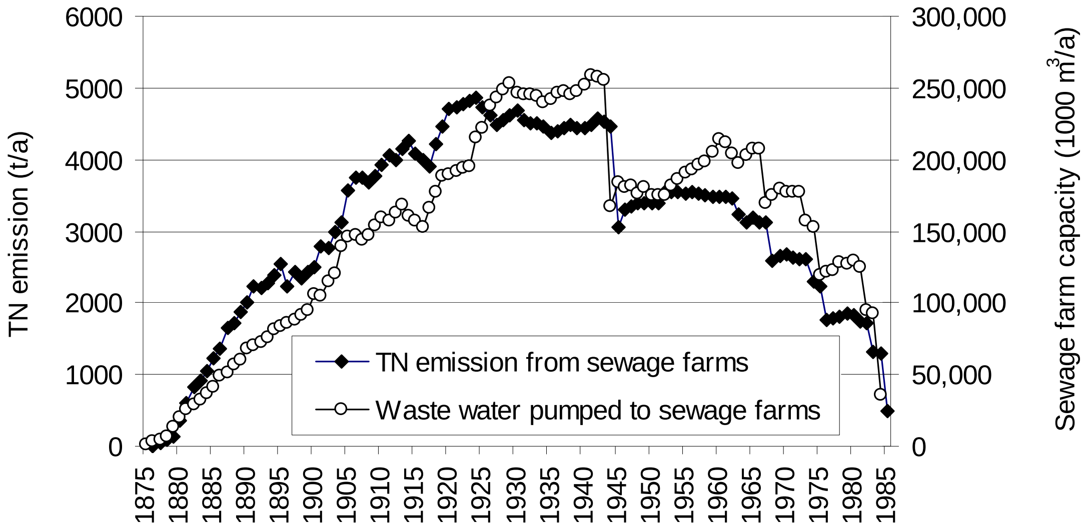

Figure 7.18: Nitrogen emission from sewage farms and purified waste water volume for the period of 1876-1985 *(Model result)*

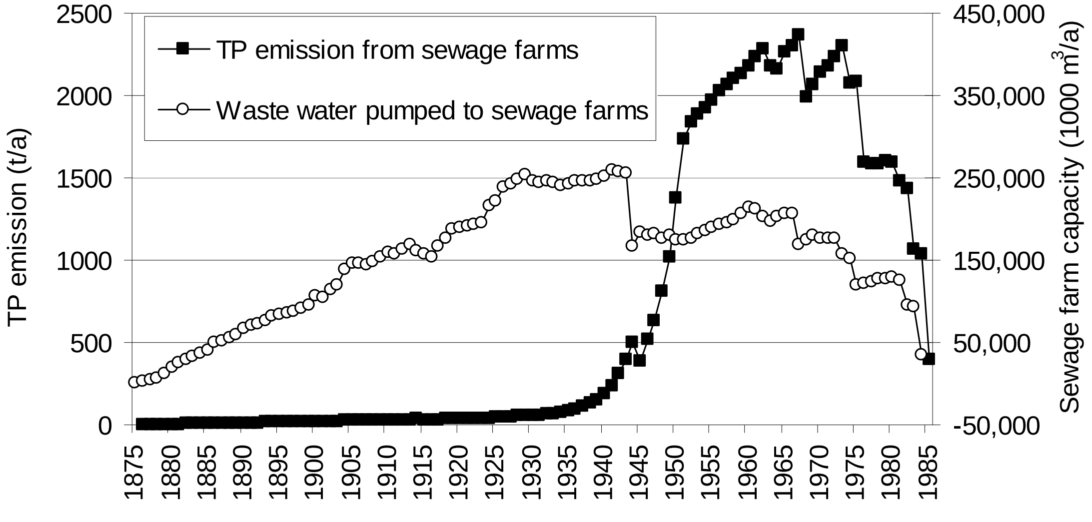

Figure 7.19: Phosphorus emissions from sewage farms and purified waste water volume, period of 1876-1985 *(Model result)*

Discussion

The nutrient removal capacities of sewage farms depend on the absorption and denitrification capacity of the soils. This capacity can be reduced when the nutrient surplus to the soil is increased over a long time period that saturation of soil can occurs (BEHREDNT, per.com.). Therefore, nutrient removal capacities are time and load dependent parameters.

Nitrogen

From 1876 to 1927, sewage farms acted as an initial and single method of waste water treatment for Berlin metropolis (HEYMANN, 1916; NASCH, 1916). From 1927 to 1973 sewage farms were the main waste water treatment facilities with a limited support from WWTPs in Waßmannsdorf and Stahnsdorf. In the second half of the 20th century in Berlin with the construction of new waste water treatment plants and their upgrading afterward, sewage farms have been shrunken in term of area and treatment capacity. Finally, almost all Berlin sewage farms were closed in the middle of the 1980ies (SENSTADTUM, 1992).

In the period of 1876-1914, the development trend of sewage farm area has the same growth rate as the canalization process in the Old Berlin city and some neighboring towns after the Hobrecht Plan as well as the development of the separate sewer system in the outer districts of Greater Berlin (HEYMANN, 1916; NASCH, 1916; BRIX, 1934).

In the second part of the 19th century and the first decade of the 20th century, waste water volume pumped to sewage farms originated mostly from the combined sewage system in the inner city area. After that the contribution of waste water volume from the separate sewage system in total waste water to be treated in sewage farms increased. This is because of the increasing sewered area in the outer districts and the increase in population density in this region (Figures 2.22, 2.23) (RUTHS, 1928; BRIX, 1934).

The main causes of the rapidly increase of the nutrient emissions from sewage farms in the period of 1876-1914 are:

- the increasing capacity of the central water supply system (GERICKE, 1956),
- the increasing application of water closets (Appendix 11.2) (WIRCHOW, 1873; STASTISHES JAHRBUCH DER STADT BERLIN, 1891; BÄRTHEL, 2003),
- the increasing connection of households to the sewerage systems (mostly in the inner city area) (Appendix 11.1; BÄRTHEL, 2003),
- The increasing trend in population density, especially in the inner city area (STASTISHES JAHRBUCH DER STADT BERLIN, 1873-1920, SENSTADTUM, 2004.

The reasons of the decreasing trend of TN emissions in the period 1915-1917 are mostly due to the reduction of population and the consequence of the First World War (Figures 2.12, 2.13).

N-emissions from sewage farms in the period of 1918-1942 had an increasing trend, caused as follows:

- The increase of total waste water volume to be treated in sewage farms as a result of the integration of waste water collection and treatment in Greater Berlin after 1920 (Figure 7.18) (STASTISHES JAHRBUCH DER STADT BERLIN, 1915-1943),

- The increase of population density in the inner city area (serviced by the combined sewers) (Figure 2.22) (STASTISHES JAHRBUCH DER STADT BERLIN, 18915-1943, SENSTADTUM, 2004).

- The expanse of the separate sewer system in the outer districts of Greater Berlin (Figure 2.23) (BERLIN IN ZAHLEN, 1925-1940),

- The increase in the nutrient deposition from the atmosphere (see also 7.1).

In the period of 1920-1964, the total area of the sewage farms of Berlin was almost constant. After long-time of overloading operation, the sewage farms could not handle an increasing volume of waste water from the city, causing a severe pollution situation in surface water bodies of Berlin. In order to reduce the serious pollution situation in water bodies of Berlin, new WWTPs were be constructed. In 1963, the WWTP Ruheleben started operating in West Berlin. This was the beginning of reducing capacity progress of the sewage farm system of Berlin and finally resulted in a stepwise closure of the sewage farms in the period of 1968-1985.

The period of deceasing TN emissions 1943-1985 can be divided into 2 parts:

- 1943-1962: period of decreasing TN emissions due to the population reduction (Figure 2.13) (STASTISHES JAHRBUCH DER STADT BERLIN, 1944-1963),
- 1963-1985: period of decreasing TN emissions as a result of reducing capacity and closure of sewage farms (SENSTADTUM, 1992, 2004).

The first decreasing trend in TN emissions since 1943 was mostly due to the reduced population in Berlin as a consequence of the Second World War, especially after 1945 (Figures 2.12, 2.13). Since 1963, with the new WWTP in Ruheleben, the increasing part of waste water from the city was purified by the more efficient technologies in WWTPs. As a result the waste water volume pumped to sewage farm was reduced. In 1968, with the opening of WWTP Falkenberg, the sewage farm Malchow with an area of 932 ha was closed, and one year later the sewage farms Falkenberg with an area of 900 ha and Hellersdorf with an area of 716 ha were also closed. In the middle of the 1970ies, two new

WWTPs were established in Marienfelde and Münchehofe, resulting in a decreasing waste water volume pumped to sewage farms and finally the closure of sewage farms Münchehofe (104 ha, capacity of 14.5 million m^3/a), Tassdorf (168 ha, capacity of 7 million m^3/a), and Osdorf (1195 ha, capacity of 20 million m^3/a). The upgrade of WWTP Ruhleben in 1983 and especially new WWTP construction in Schönerlinde in 1985 led to the closure of sewage farms: Mühlenbeck, Hobrechtsfelde, Buch, Schönerlinder and Blankenfelde. Since then, almost all waste water from Berlin was treated in the waste water treatment system in order to meet the more and more strictly treatment criteria on effluent water (SENSTADTUM, 1992, 2004).

Phosphorus

The period of slightly increasing P emissions, 1876-1935

In the 19th century, purified waste water from sewage farms had very low P-load because, at beginning, the P retention capacity of sewage farms due to P retention in soils was still maintained at a rate of 90-95% P in waste water to be retained (PÖTHIG et al., 2001) (Table 7.7).

The period of rapidly increasing P-emissions, 1936-1962

After long time of overloaded operation, the P-retention capacity in soils of sewage farms was continuously reduced. In addition, the population and impervious urban area connected to sewerage system of the city had increased rapidly (Figure 2.10) (BÄRTHEL, 2003; MOHAJERI, 2005).

P emission from sewage farms reduced in 1945 mostly due to the consequence of the Second World War, the decreasing of population in the city and the destruction of the sewer system (Figure 2.12).

The main causes of the increasing P-load in period 1946-1962 were: increasing in population and urban area connected to sewerage system (Figures 2.10, 2.13). The most important reason was the rapidly increasing in the specific phosphorus emission per inhabitants (due to the improved living-standard, the extensively application of phosphorus in detergents and cleaning powders). In addition, the atmospheric P deposition had an increasing trend in the same time (BEHRENDT, 1994, 1998). Meanwhile the P– elimination capacity of sewage farms had a continuously decreasing trend (Table 7.7).

The period of high P-emissions and fluctuation, 1963-1973

In this period, the specific phosphorus emission per inhabitant increased to the peak value for inhabitants of the Western part of Berlin. Just after around 3 decades, the specific phosphorus emission per inhabitant has increased 3 times (from 1.48 g P/(inh.·d) in 1945 to

4.65 g P/(inh.·d) in 1975). This indicator for inhabitants in the Eastern part of the city also rapidly rose more than 2 times compared to the level after the Second World War (BEHRENDT, 1994, 1998).

The reduce in P-emissions from sewage farms in the period of 1963-1964 was originated from the decline in waste water volume treated in sewage farm system, mainly because of the establishment of WWTP Ruhleben together with the upgrading in WWTPs Waßmannsdorf and Stahnsdorf in pervious years (Figure 7.19) (SENSTADTUM, 1992, 2001; BWB, 2005).

The P-emissions from sewage farms rose again in the period of 1965-1967, due to the increasing trend in the specific phosphorus emission per inhabitant in both sides of Berlin (Figure 7.1). A single year drop in P-emissions was recognized in 1968 as a result of the establishment of the WWTP Falkenberg and the closure of sewage farm Malchow in the same year (SENSTADTUM, 1992; BWB, 2005).

From 1969 to 1973, there were no more new WWTP or technologically upgrade in Berlin waste water treatment system (SENSTADTUM, 2001; BWB, 2005). Meanwhile, the P-content in inflow water to the treatment facilities has rose continuously as consequence of the increasing specific phosphorus emission per inhabitant and the specific phosphorus emission per urban area (see also 7.1).

The period of decreasing P-emission, 1974-1985

The closure of sewage farms Münchehofe, Tassdorf and Osdorf in 1976 resulted in a decreasing waste water volume pumped to the rest sewage farms. This was a consequence of new WWTPs in Marienfelde in 1974 and in Münchehofe in 1976. The upgrade of WWTP Ruhleben in 1983 and new WWTP in Schönerlinde in 1985 finally finished the historical role of sewage farms in waste water treatment of Berlin after more than one century of operation (SENSTADTUM, 1992; BWB, 2005).

Another reason for the decreasing trend in P-emissions from sewage farms in this period was the decreasing in the specific nutrient emissions per inhabitant (BEHRENDT, 1994, 1998). This trend was recognized in West Berlin since 1975 and East Berlin since 1990 as a result of the "The Detergents and Cleaners Act" in 1975 and its amendment in 1985 as well as its enforcement in the whole Berlin after reunification (BMU, 2001).

In general, the treatment capacity of sewage farms has an increasing inefficiency nitrogen and phosphorus elimination, especially after many years of overload operation (Table 7.7). Due to the low effectiveness and other environmental concerns (like heavy metal contamination of soils), almost all sewage farms in Berlin were closed in the late of 1980s.

7.3.2 Nutrient emissions from waste water treatment plants

Results

According to Berlin Water Company (BWB) and other literatures on the technologies applied in Berlin WWTPs, the nutrient removal capacities of Berlin WWTPs can be estimated as follows:

Table 7.8: Technological developments of WWTPs of Berlin

Period		Technological development	Removal capacities	
			TN (%)	TP (%)
Waßmannsdorf	1927-1931	Preliminary treatment facilities	20	20
	1932-1935	Expansion of the preliminary treatment facility to a biological sewage treatment plant and sludge drying facilities	25	20
	1935-1990	Biological sewage purification	20	20
	1995	Upgraded to simultaneous removal of phosphates and nitrates	50	95-97
	1997	A new mechanical treatment stage, further biological treatment stage	80	95-97
Stahnsdorf	1931-1945	Mechanical 50%, Biological 50%	25	20
	1946-1988	Biological treatment	30	20
	1989	Introduction of a combined chemical and biological phosphate elimination	50	91-95
	1992	Introduced of partial nitrification	58-67	91-95
	1998	Biological phosphate elimination in combination with nitrification and denitrification	80	95-97
Ruhleben	1963	Biological treatment	30	20
	1983	Second treatment stage	45	70
	1985	Biological phosphate removal in combination with nitrification and denitrification	70	90
	1993	Biological phosphate elimination in combination with nitrification and denitrification	76-84	97
	1999	Upgrade	85	97
Falkenberg	1968	Biological treatment	30	20
	1985	Introduction of chemical phosphate removal method	30	90
	1993	Upgrade	50	91-94
	1999	Upgrade	60	93-94
	2003 (Feb.)	Closed		
Mariefelde	1974	Biological treatment	30	30
	1986	Third treatment stage	30	90
	1993	Phosphate elimination upgrade	33	95
	1995	Upgrade	50	91-94
	1998 (Sep.)	Closed		
Münchehofe	1976	Biological treatment	30	30
	1985	Introduction of a chemical phosphate elimination	45	90
	1986	Application of a combined chemical and biological phosphate elimination		
	1992	Introduction of the sludge dewatering facilities		
	1995	Introduction of the nitrification with partial denitrification	66-76	92
	2000	Change of the aeration basins, finally, start-up of the upstream denitrification	72-76	92
	2003	Upgrade	83	96
Schönerlinde	1985	The first stage treatment	30	50
	1986	Introduction of a chemical phosphate elimination	30	90
	1988	Start-up of the second treatment stage	50	90
	1993	Introduction of a partial biological phosphate elimination with nitrification	60	93
	1999/2000	Biological phosphate elimination in combination with nitrification and denitrification	65-84	93-97
Adlershof	1985	The first stage treatment	30	20
	1993	Phosphate elimination upgrade	45	90
	1995	Upgrade	66	93
	1996 (Jan)	Closed		
Wansdorf	1999	Mechanical and biological sewage purification. Biological phosphate elimination in combination with nitrification and denitrification	85	97

Based on the equations 6.5, 6.6 and Table 7.8, the nutrient emissions from WWTPs of Berlin were estimated (Figures 7.20, 7.21).

The development of nitrogen emissions from WWTPs is shown in Figure 7.20 and can be divided into major periods:

- *1927-1962: period of low nitrogen emissions*
  In this period TN emissions from WWTPs increased from 200 t TN/a in 1927 to 1500 t TN/a in 1962.
- *1963-1986: period of the continuously increasing in N-emissions.*
  TN-emissions from WWTPs increased from around 2100 t TN/a in 1963 to the maximal level of around 7700 t TN/a in 1986.
- *1987-1990: period of high N-emisisons*
  N-emissions increased from 7700 t TN/a in 1987 to 7800 t TN/a in 1990. This is the period of the highest N-emissions from WWTPs.
- *1991-2000: period of decreasing in N-emissions*
  TN emissions reduced from 6800 t TN/a in 1990 to 4000 t TN/a in 2000.

In recent decades, phosphorus emissions have different development trends compared to the nitrogen emissions from WWTPs (Figure 7.21). In general, the phosphorus emissions from Berlin's WWTPs can be divided as follow:

- *1927-1962: period of low TP-emissions.*
  TP emissions increased from around 30 t TP/a in 1927 to around 40 t TP/a in 1962.
- *1963-1976: period of continuous increasing TP emissions.*
  TP emissions increased strongly from 640 t TP/a in 1963 to the maximum level of 2250 t TP/a in 1976.
- *1977-1984: period of slightly decreasing trend with high TP-emissions.*
  The TP-emission from Berlin's WWTPs in this period stand on a very high TP emissions with a level around 2000-2200 t TP/a.
- *1985-2005: period of decreasing TP emissions*
  In this period, TP-emission rapidly dropped from the level of 2045 t TP/a in 1984 to 100 t TN/a in 2000 and around 96 t TP/a in 2005.

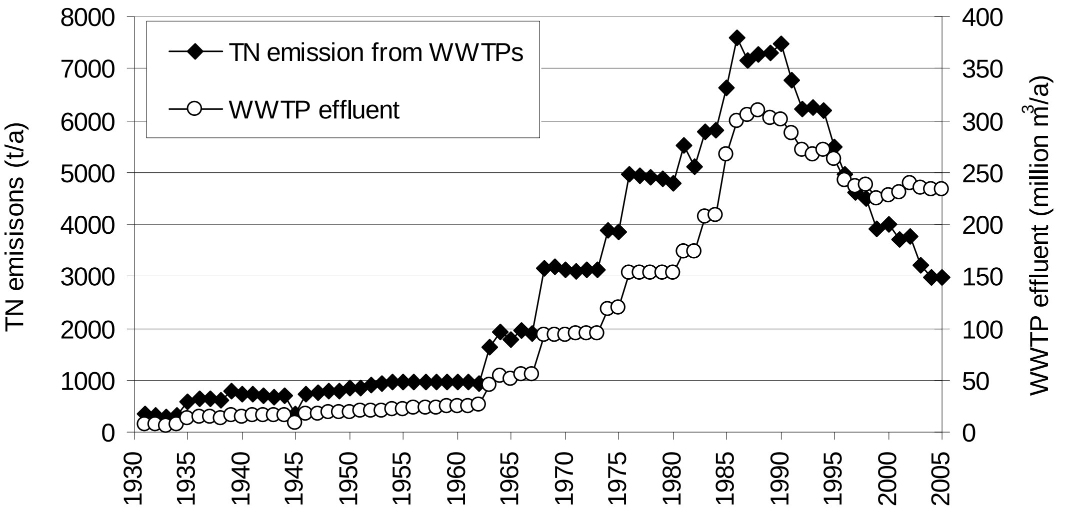

Figure 7.20: TN emissions from WWTPs in Berlin over the last 150 years *(Model result)*

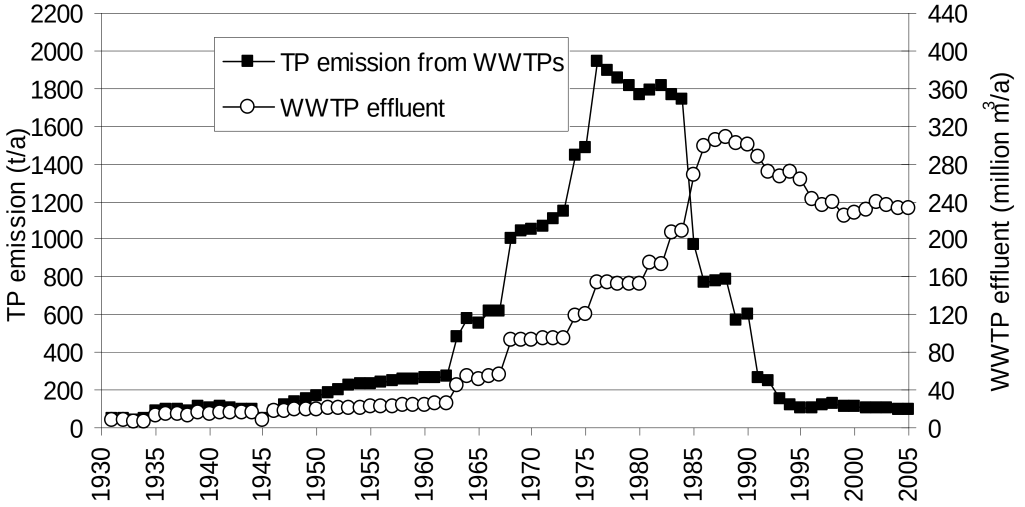

Figure 7.21: TP emissions from WWTPs in Berlin over the last 150 years *(Model result)*

Discussion

The nutrient removal capacity of the WWTPs determined the nutrient concentrations in the effluent. This capacity depended on the technological stages of the WWTPs: mechanical, biological, chemical, bio-chemical, nitrification, denitrification, phosphorus elimination… In order to mitigate the pollution (eutrophication in lakes) as well as to meet the new effluent standard required by the Federal and State's regulations, Berlin's WWTPs have been upgraded many times in the recent years (SENSTADTUM, 2001; BWB, 2005).

The total nutrient inputs to WWTP included nutrient emissions from domestic and industrial sector drainage via the combined and separate sewers as well as the nutrient deposition in the paved urban area connected to the combined sewage system. In the fist half of the 20th century, Berlin had only two WWTPs located in Waßmannsdorf and Stanhsdorf. But in the first 35 years of operation, their treatment capacity as well as nutrient removal efficiencies were very limited (MOHAJERI, 2005). WWTP Waßmannsdorf commenced its operation in 1927 due to the overloading of the sewage farms. However, its treatment facility was preliminary only, after this mechanical process, waste water was pumped to sewage farms (Waßmannsdorf, Boddinsfelde, Groß-Ziethen, Deutsch-Wusterhausen). In 1935, a part of the preliminary treatment facilities in Waßmannsdorf was upgraded to a full biological process with a capacity of 5.54 million m^3/a. Since 1931 WWTP Stahnsdorf went to operation with 50% capacity of biological treatment and the rest of mechanical treatment (BWB, 2005; BÄRTHEL, 2003). Therefore, WWTPs have been directly discharged their effluents to surface water bodies only since 1931.

The low nutrient emissions from WWTPs in the period of 1931-1962 have main causes in low waste water volume to be purified in WWTPs. In this period the dominant waste water treatment duty was given to sewage farms (Figures 7.18, 7.20). The WWTP Ruhleben was in operation in West Berlin in 1963, remarked a new development stage of Berlin waste water disposal system. The increasing trend in waste water volume and its contaminant contents of from both Western and Eastern part of Berlin was also started to be recognized. To deal with this situation, since 1968 the WWTP Falkenberg has been in operation in East Berlin. However, the domestic and industrial waste water was increasing faster than the treatment capacity of the Berlin's WWTPs and the nearly exhausted sewage farms. In order to improve the waste water treatment capacity, 2 new WWTPs were installed in Berlin afterward (Marienfelde in 1974, Müchehofe in 1976) (SENSTADTUM, 2001; BWB, 2005). With the contribution of new WWTPs, the P-emission has slightly decreased in the period of 1977-1984. Despite of a decreasing trend in specific phosphorus emission per inhabitant in West Berlin since 1976, the total TP-emission from WWTPs was still on a very high level. The decline trend of TP-emission from WWTPs started from the decline in specific P-emission per inhabitant and new WWTPs in operation.

The period of strongly decreasing TP-emission has the main causes in the technological improvements the existing WWTPs and in the new WWTP in Schönerlinde since 1985. The WWTP Ruhleben and WWTP Falkenberg were upgraded in 1985. Since 1987, the chemical phosphate removal method has been applied in WWTP Münchehofe and WWTP Ruhleben (KLOSE, 1985; PETER, 1990, LEYMANN, 1991; HENZE, SENSTADTUM, 2001; BWB, 2005). In addition to the technological improvements, the nutrient emission mitigation policies have strongly impacted some nutrient emission sources. The decline trend was recognized in the nutrient deposition from the atmosphere since 1986. Because the "The Detergent and Cleaners Acts" has enforced after the reunification of Berlin in 1990, the specific phosphorus emissions per inhabitant in East Berlin has reduced immediately.

Differences in TN and TP emissions have the main causes in the technological orientations. At fist, treatment effectiveness of WWTPs focused only on TP elimination and then TN (SENSTADTUM, 2001; BWB, 2005). In addition, the specific P emission per inhabitant was also reduced as a result of new regulations on P-content washing powders enforced in West Berlin since 1974 and East Berlin after reunification (BEHRENDT, 1994, 1998).

7.4 Total nutrient emissions from urban area of Berlin

Results

The total discharges to surface water bodies from Berlin city and their contributions are given in the Figure 7.22 with an increasing trend in the discharge volume of the point source (sewage farms and WWTPs). The total discharge from point sources increased from 40% in the period of 1876-1900 to around 67% in the period of 1901-1975, got the peak of 73% in period of 1976-1990 and decreased to 68% of total discharge to surface water system in the period of 1991-2000. Among the diffuse source discharges, surface runoff from the separate sewer system had continuously increasing trend.

In the last century, the TN emissions had not so much deviated like TP emissions. It increased from 1770 t TN/a in the period of 1876-1990 to around 4276 t TN/a in the next 20 years and stayed at the level of 5700 t TN/a in the period of 1991-2000. As shown in the Figure 7.23, the highest total TN-emissions occurred with more than 8100 t TN/a in the period of 1976-1990.

Among the different pathways, the point sources played a dominant role in their contribution to the TN emissions with an average level of 90 % over the last 150 years. Among point sources, sewage farms played the dominant role in the period of 1876-1976 and were replaced by WWTPs afterward. Nitrogen emission via surface runoff in the separate sewer system had an increasing trend in contribution to TN emission. Nitrogen emission via groundwater and overflow water, direct deposition had very limited importance in TN emissions (Figure 7.23).

An overview on the phosphorus emissions via different pathways and their contributions to the surface water bodies of Berlin over the last 150 years is given in the Figure 7.24. In general, P-emissions into surface waters in Berlin had a very dramatical development over different periods. P emissions slightly increased from 34 t TP/a in 1876-1900 to 75 t TP/a in the period of 1901-1920 and then to 250 t TP/a in 1921-1925 period. After the Second World War, P emissions had very strongly increased to 2480 t TP/a in the period of 1946-1975 and got the peak at around 2790 t TP/a in the period of 1976-1990 – more than 10 times higher than the level of 1921-1945. The decreasing trend in TP emissions was recognized since 1975 and reached the level of 190 t TP/a in the period of 1991-2000. Effluents from sewage farms and WWTPs had the most importance for the P-emissions into surface waters in Berlin in the period of 1921-2000. In the period of 1991-2000, point sources reduced their contribution to 76% of TP emissions compared to around 97% in the period of 1946-1990. P emission via surface runoff in the separate sewer system had an increasing trend in contribution to total P emissions. Although its discharge is very limited, overflow water played an important role in contribution of TP emissions, especially in the period of 1876-1920 and 1991-2000, it contributed around 33% and 12% respectively to the TP emissions. P emissions via direct deposition and groundwater havd very limited importance in TP-emissions (Figure 7.24).

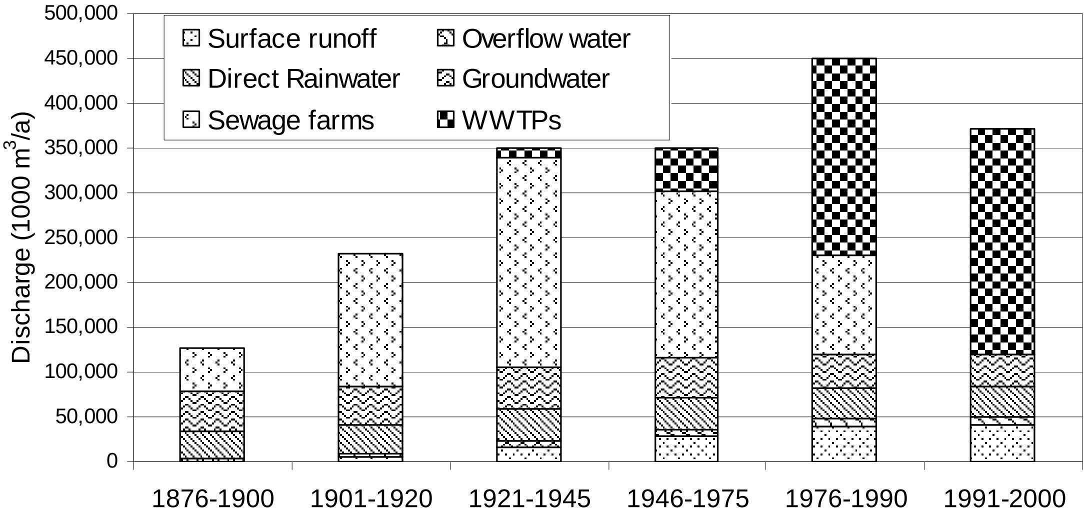

Figure 7.22: Total discharges to Berlin's surface water bodies via different sources over the last 150 years *(Model result)*

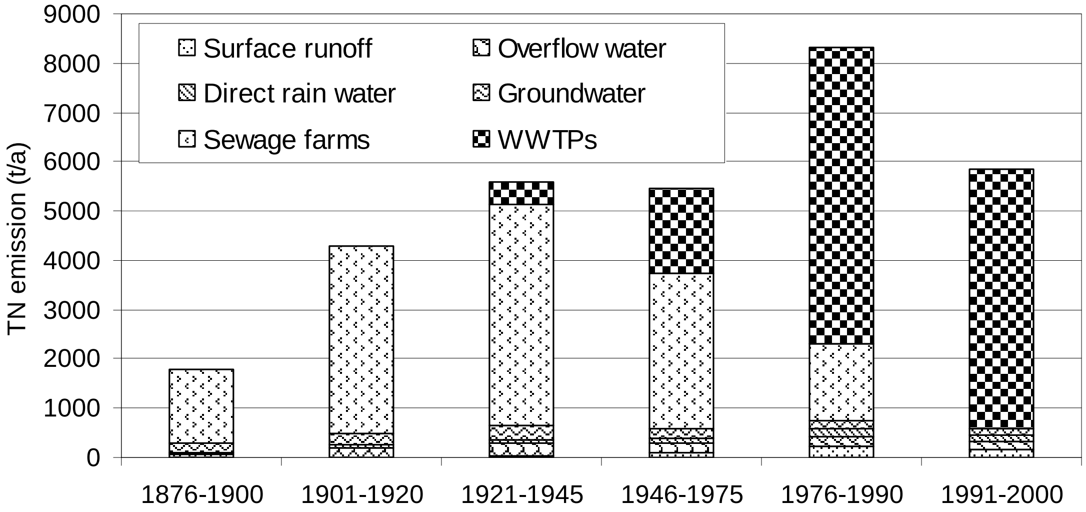

Figure 7.23: Nitrogen emissions to Berlin's surface water bodies via different pathways and their contributions over the last 150 years *(Model result)*

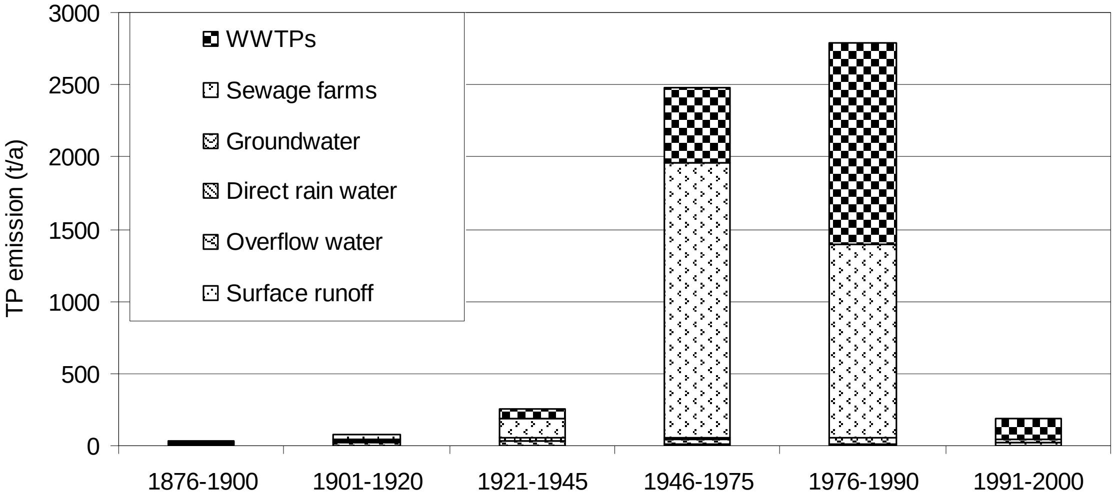

Figure 7.24: Phosphorus emissions to Berlin's surface water bodies via different pathways and their contributions over the last 150 years *(Model result)*

Discussion

The transitional points in the course of nutrient emissions into surface water bodies of Berlin are the consequences of the construction and operation of sewage farms, new WWTPs and their improvements, the closure of the sewage farms, changes in the drainage system and the legal and management system with the goal to prevent pollution at emission sources (SENSTADTUM, 1992, 2001, 2004; BÄRTHEL, 2003; MOHAJERI, 2005; LANZ, 2005; HERBKE, 2006; BWB, 2005).

Over the last 150 years, the nitrogen emissions and phosphorus emissions had different development trends. This difference has several causes:

- Differences in the specific emission per inhabitant: specific TN emission has not been deviated during the last 150 years, while the specific P emission per inhabitant has dramatically changed in the term of temporal and spatial scale, especially after the Second World War (Figure 7.1) (BEHRENDT, 1994, 1998).
- Sewage farms have quite different removal capacities for nitrogen and phosphorus due to the retention capacity, accumulation property of soil formations in sewage farms after long-time of over emission operation (Table 7.7) (BROOKS, 1905; HEYMANN, 1916; NASCH, 1916; RUTHS, 1928; BÄRTHEL, 2003; MOHAJERI, 2005).
- Nitrogen and phosphorus have also different priority in the technological improvement of waste water treatment plants. Most technological improvement in the 1980s focused on the phosphorus elimination. Nitrogen elimination has just been applied since 1990 (SENSTADTUM, 2001, 2004; BWB, 2005).

Among the driving factors, population and population density of Berlin over the last 150 years has very clear impact on the N emission via different pathways.

The difference in the way of waste water collection and treatment in the inner city area (the combined sewage system) and the outer districts (the separate sewage system) also contributed to the differentiation of nutrient-emissions to surface water quality (Figure 2.20).

The differentiation in the political conditions of Berlin in the past has also resulted in some deviations in the way of nutrient emissions in East and West Berlin, especially in the specific phosphorus emission per inhabitant (BEHRENDT, 1994, 1998).