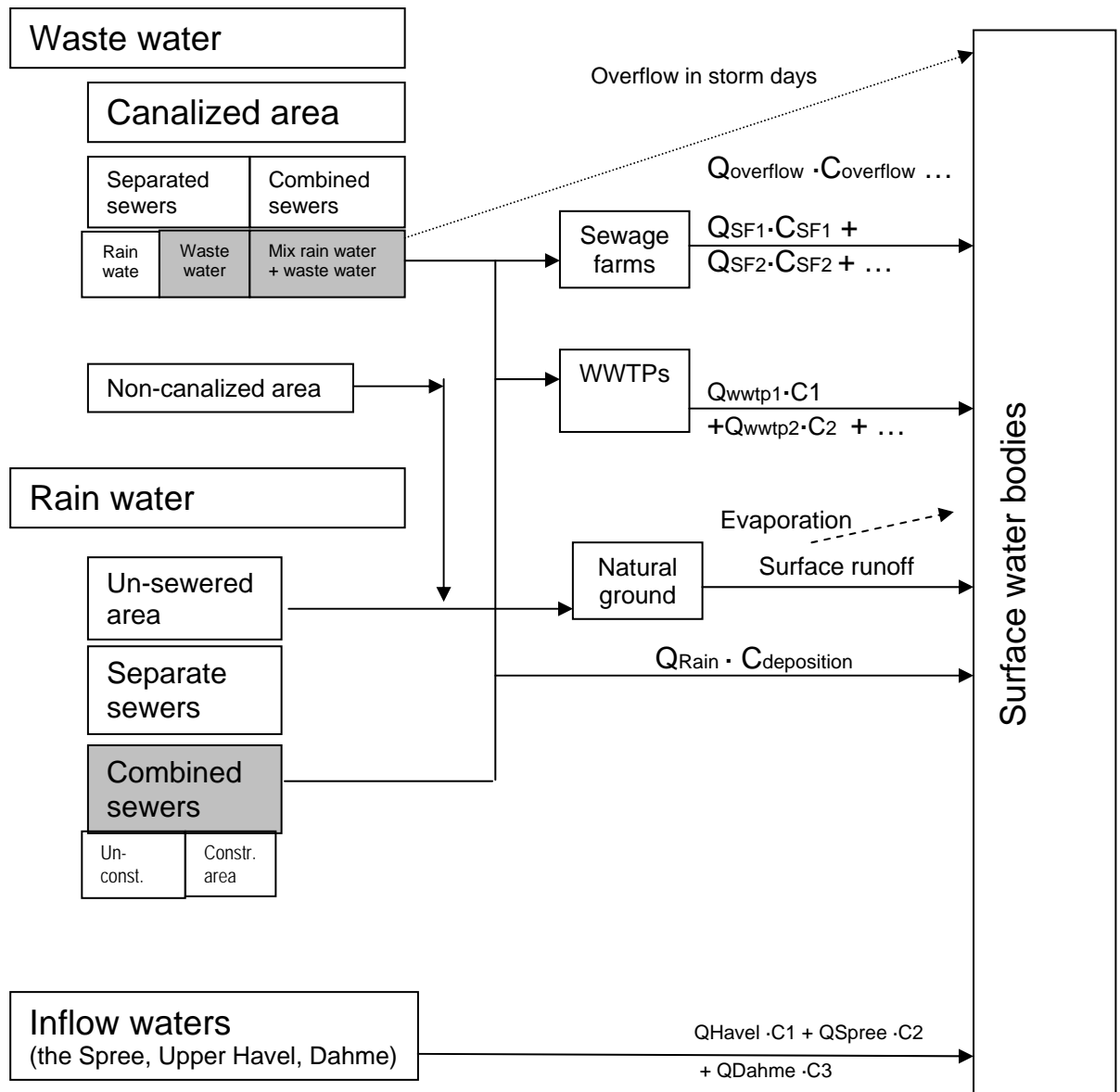


## 6. Model design

### 6.1 Modelling approach



**Figure 6.1:** Overall approaches for nutrient loading calculation for Berlin

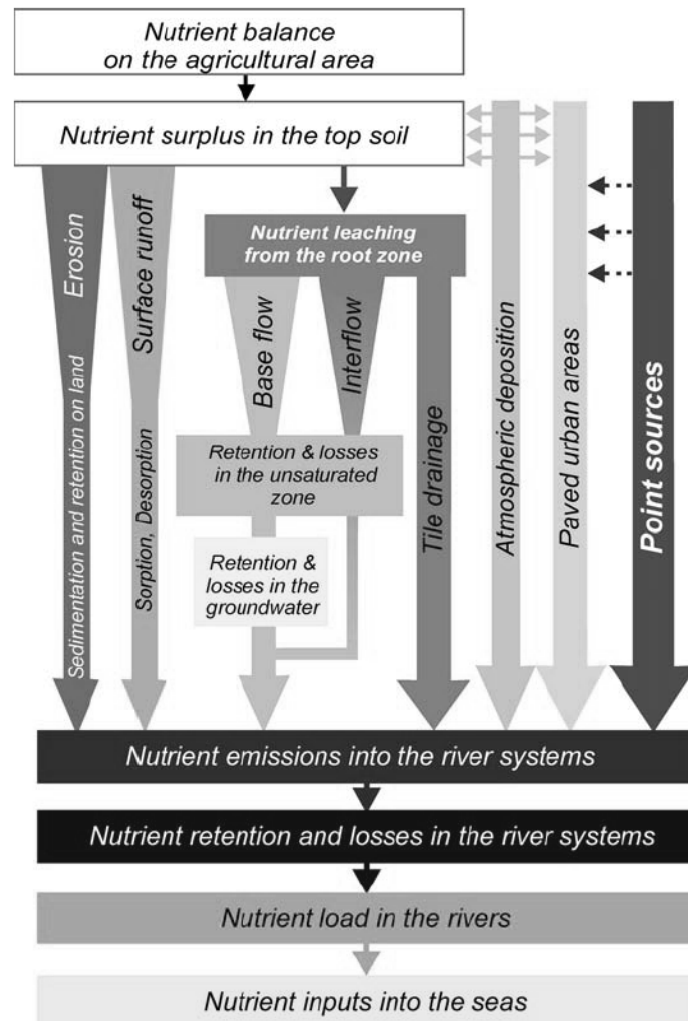
The MONERIS approach and source-apportionment methods were applied for estimating the nutrient emissions into Berlin waters over the last 150 years.

The calculation and analysis are based on an extensive database on monitoring discharge, nutrient concentrations in surface waters, sewage farms and waste water treatment plants (WWTPs) as well as specific nutrient emissions per inhabitant and area specific nutrient emissions. The long-term change of nutrient loads is evaluated through an integration method, including monitoring and statistical data, calculations and the model results to identify the current trends and analysing the emission and retention processes. Because the time series are not complete in the most cases, the gaps have to be filled and time series must be harmonized by statistical functions and specific parameterisation.

## 6.2 Estimation of nutrient emissions and loads by modelling

The nutrient emission model MONERIS (MOdelling Nutrient Emission in River Systems) (BEHRENDT et al. 2000, 2002) is a static model and was developed to estimate nutrient inputs into river basins by point sources and various diffuse pathways (Figure 6.2). MONERIS bases on monthly and annual data, therefore it is appropriate for the long-term estimation of nutrient load. MONERIS gets calibrated for a particular hydrologic period and operates with annual average conditions. MONERIS model takes seven pathways into account.

For the city of Berlin, the model application focuses on: point sources, atmospheric deposition, overflow water, surface runoff and paved urban areas with the assumption that nutrient inputs from erosion processes and agricultural activities play a minor role in comparison to other emission sources. Nutrient inputs from point source pathway in this study will be estimated by new modules for estimating nutrient loads from the sewage farms and WWTPs.



**Figure 6.2:** Pathways and processes in MONERIS

(BEHRENDT et al., 2000)

## 6.2.1 Nutrient emissions from point sources

### 6.2.1.1 Nutrient emissions from sewage farms

The total nutrient input load to sewage farms is the sum of its nutrient emissions from 1. the domestic sector drained via combined and separate sewage systems; 2. nutrient emissions from commercial and industrial areas; 3. the nutrient deposition on paved urban area connected to the combined sewage system:

$$L_{SF_{in}} = a \cdot \left( EIN_{N,P} \cdot P_{SEW} + C_{COM_{N,P}} \cdot Q_{COM_{N,P}} + ES_{IMP_{N,P}} \cdot A_{IMP_C} \cdot a_{IMP} \right) \quad (\text{eq. 6.1})$$

where

- $a$  = unit conversion factor,
- $L_{SF_{in}}$  = nutrient input load into sewage farms [t/a],
- $EIN_{N,P}$  = inhabitant specific nutrient output [g/(inh-d)],
- $P_{SEW}$  = population connected to the sewer system,
- $C_{COM_{N,P}}$  = nutrient concentration in commercial waste water [mg/l],
- $Q_{COM_{N,P}}$  = runoff from commercial areas connected to the sewer system [m<sup>3</sup>/d],
- $ES_{IMP_{N,P}}$  = specific nutrient emissions from impermeable urban area [t/(ha-a)],
- $A_{IMP_C}$  = impervious urban area connected to the combined sewer system [ha], and
- $a_{IMP}$  = the share of precipitation realized as surface runoff from paved urban area.

In addition, nutrient emissions from leaf-fall and animal excrements were considered in different periods.

The nutrient concentrations in waste water directed into sewage farms can be calculated by the total incoming loads divided by the total input discharge: from domestic sector, industrial sources and rainfall:

$$C_{IN} = \frac{L_{SF_{in}}}{q_{inh.} \cdot P_{SEW} + Q_{COM} + ES_{IMP_{N,P}} \cdot A_{IMP_C} \cdot a_{IMP} \cdot P_Y} \quad (\text{eq. 6.2})$$

where

- $C_{IN}$  = nutrient concentration in waste water discharged into sewage farms (mg/l),
- $q_{inh.}$  = daily waste water output per inhabitant [l/(inh-d)], and
- $P_Y$  = annual precipitation [mm/a].

The nutrient emissions from the outflow of sewage farms can be calculated by multiplying the amount of outflowing water, the nutrient concentration in inflowing waste water and the nutrient removal capacity of the sewage farm:

$$E_{SF} = Q_{SF} \cdot C_{IN} \cdot R_{SF} \quad (\text{eq. 6.3})$$

where

- $E_{SF}$  = nutrient emissions from sewage farms [t/a],
- $Q_{SF}$  = total input waste water to sewage farms [m<sup>3</sup>/a],
- $C_{IN}$  = nutrient concentration in inflow waste water [mg/l], and
- $R_{SF}$  = nutrient removal capacity of sewage farm [%].

### 6.2.1.2 Nutrient emissions from WWTPs effluent

When the observed data on nutrient concentrations and discharges area available, the nutrient emission from WWTP can be estimated by OSPAR method (Guideline 6) as follows:

$$E_{WWTP_{out}} = \frac{\sum_{i=1}^n Q_{WWTP_{in\ i}} \cdot C_{WWTP_{out\ i}}}{\sum_{i=1}^n Q_{WWTP_{in\ i}}} \cdot Q_t \quad (\text{eq. 6.4})$$

where

- $E_{WWTP_{out}}$  = annual nitrogen and phosphorus emissions from WWTP [t/a],
- $Q_{WWTP_{in\ i}}$  = wastewater volume of the period i [ $\text{m}^3/\text{a}$ ],
- $C_{WWTP_{out\ i}}$  = nutrient concentration of sample i [mg/l],
- $Q_t$  = total waste water volume of the year [ $\text{m}^3/\text{a}$ ], and
- $n$  = number of sampling periods.

When the data on nutrient concentrations in effluent water is not available, the nutrient emissions from WWTP can be calculated from the product of the amount of influent water to WWTP, the nutrient concentration in influent water and the removal capacity of WWTP:

$$E_{WWTP_{out}} = L_{WWTP} \cdot C_{WWTP_{out}} \quad (\text{eq. 6.5})$$

where

- $E_{WWTP_{out}}$  = nutrient emissions from WWTP,
- $Q_{WWTP}$  = influent discharge of WWTP, and
- $C_{WWTP_{out}}$  = nutrient concentration in effluent of WWTP.

$$C_{WWTP_{out}} = C_{WWTP_{in}} \cdot R_{WWTP} \quad (\text{eq. 6.6})$$

where

- $C_{WWTP_{in}}$  = nutrient concentration in waste water, and
- $R_{WWTP}$  = nutrient removal capacity of WWTP.

Since the construction of the first WWTP of Berlin, the effluent of WWTPs has increased continuously. Since 1973, using WWTP has been the major waste water treatment method for Berlin. After 1985, WWTPs became the only treatment method for waste water in Berlin.

Nutrient concentration in WWTP inflow was calculated with the same method like nutrient concentration in sewage farm inflow.

The total influent of WWTPs can be calculated from the total waste water volume of Greater Berlin minus the waste water quantity pumped into the sewage farm:

$$Q_{WWTP_{in}} = Q_{WW_{URB}} - Q_{SF_{in}} \quad (\text{eq. 6.7})$$

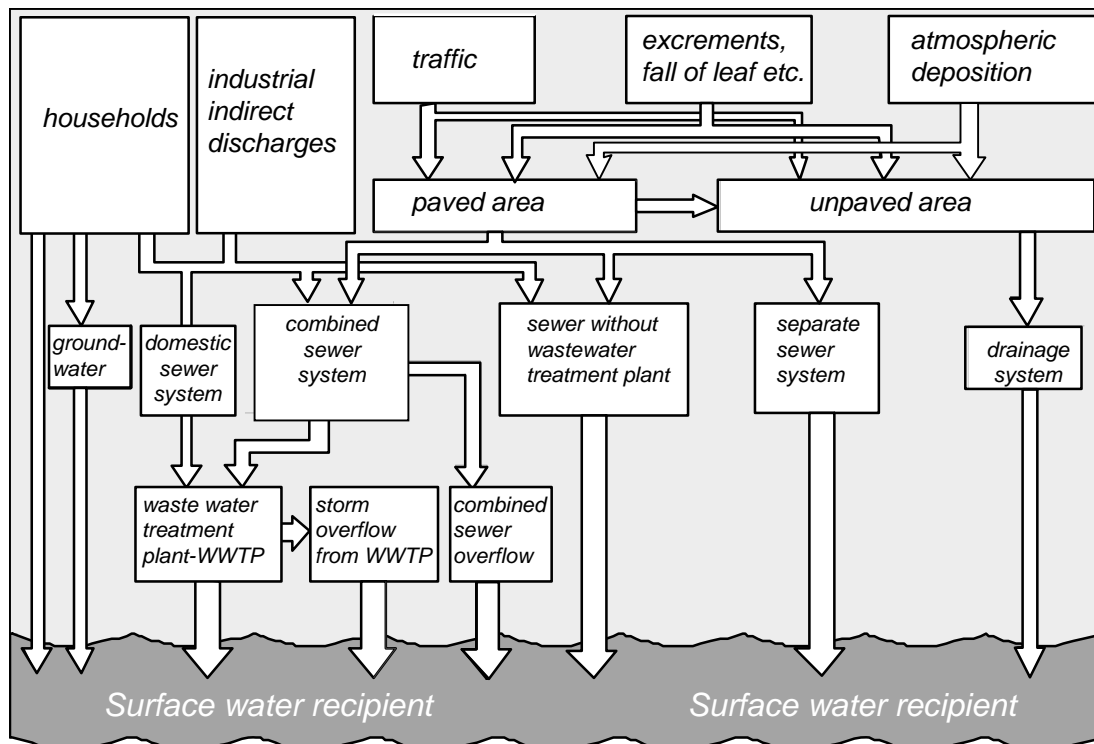
where

- $Q_{WWTP_{in}}$  = total influent of WWTPs,
- $Q_{WW_{URB}}$  = total collected waste water in Berlin, and
- $Q_{SF_{in}}$  = quantity of inflow waste water to the sewage farms.

Since establishment, the WWTPs of Berlin have been technologically upgraded many times, according to each technology level different nutrient removing capacities have to be considered.

## 6.2.2 Nutrient emissions from diffuse sources

### 6.2.2.1 Nutrient emissions from surface runoff in impervious urban area



**Figure 6.3:** Sources and pathways of nitrogen and phosphorus discharges and losses in urban areas (BEHRENDT, 1993)

Nutrients in surface runoff from impervious area will be calculated in three ways:

- Whenever the area is sewered by a combined system (old Berlin city), the nutrient emissions from surface runoff from impervious area will mix with waste water from household and indirect industrial discharges before flowing to sewage farms or into waste water treatment plants.
- The surface runoff from impermeable area without sewer system is finally transported to soil and then absorbed or leached. In this case, it can be assumed that no directly nutrient emissions from this source reach the surface water bodies.
- Whenever the area is drained by a separated system (new urban area), the nutrient emissions from surface runoff on impermeable area flows directly into the surface water bodies:

$$E_{runoff} = A_{IMP_S} \cdot D_{N,P} \quad (\text{eq. 6.8})$$

where

$E_{runoff}$  = nutrient emissions from surface runoff on impervious area connected to the separate drainage system [t/a],

$A_{IMP_S}$  = impervious area connected to separate sewer system and the total surface water area [ha], and

$D_{N,P}$  = area specific nutrient emissions [kg/(ha·a)].

$$\text{or } E_{runoff} = A_{IMP_S} \cdot q_R \cdot C_{D_{N,P}} \quad (\text{eq. 6.9})$$

where

$A_{IMP_S}$  = impervious area connected to separate sewer system and the total surface water area [ha],

$q_R$  = rainfall runoff [mm/a], and

$C_{D_{N,P}}$  = nutrient concentrations in runoff water [mg/l].

The area specific emission of phosphorus into surface waters includes inputs from the atmospheric deposition, animal and plant wastes (excrements, fallen leaves etc.) and traffic. Atmospheric P-deposition comprises 25% of the total P-content of urban area and the rest of the P-content is originated from animal excrements and traffic (BEHRENDT et al., 1999).

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)). The specific nutrient deposition from the atmosphere is a function of energy consumption development in the region. Since the industrial revolution, the nutrient inputs from the atmosphere deposition have increased continuously (BEHRENDT et al., 1998). Data on the paved urban area was calculated and derived from statistic yearbooks of Berlin.

**Table 6.1:** Comparison of measured phosphorus concentrations in the precipitation of European urban areas and in separate sewers

	TP in precipitation	TP in rain drains	Ratio TP drains/TP pre.	Sources
	(mg P/l)	(mg P/l)		
1	0.037	0.10	2.70	Malmqvist (1983)
2	0.025	0.19	7.60	Malmqvist (1983)
3	0.080	0.28	3.50	Hogland U. Niemczynowic (1980)
4	0.090	0.45	5.00	Van Dam et al (1986)
9	0.143	0.52	3.64	Klein & Wassmann (1986)
10	0.030	0.28	9.03	Dauber et al (1978)
11	0.240	1.10	4.58	Weibel et al (1966)

(Source: BEHRENDT, 1994)

### 6.2.2.2 Nutrient emissions from combined sewer overflow

In the case of storm events, the sewer system is rapidly filled and can not even discharge all of the waste water (storm water mixed with domestic waste water and indirect industrial discharge) into the waste water treatment system. An over-capacity volume of the sewer system will be directly discharged into the surface water bodies.

In Berlin area, the capacity of the combined sewer system is most limited because this system was established in the inner city areas with highest population density (high domestic waste water) and highest sealed degree of urban area (high surface runoff from rainfall).

The nutrient emissions from overflow water is the product of the nutrient concentration in the combined sewer system during the storm events and the quantity of overflowing water.

$$E_{OE} = Q_O \cdot C_{C_{N,P}} \quad (\text{eq. 6.10})$$

where

- $E_{OE}$  = nutrient emissions from overflow water [t/a],
- $Q_O$  = discharge of combined sewer overflow [m<sup>3</sup>/a], and
- $C_{C_{N,P}}$  = nutrient concentration in the combined sewer system during overflow [mg/l].

The nutrient concentration in the combined sewer system can be calculated from the area specific emission rate of the impervious urban area, the inhabitant specific nutrient emissions as well as nutrient inputs from industrial sources:

$$C_{C_{N,P}} = \frac{((EIN_{N,P} \cdot P_{SEWC} + C_{IND_{N,P}} \cdot Q_{IND_C}) \cdot Z_{RD} + ES_{IMP_{N,P}} \cdot A_{IMP} \cdot a_{IMP} \cdot 100) \cdot RE \cdot 10^{-2}}{Q_{IMP_C}} \quad (\text{eq. 6.11})$$

where

- $C_{C_{N,P}}$  = nutrient concentration in the combined sewer system during overflow [mg/l],
- $EIN_{N,P}$  = specific nutrient output per inhabitant [g/(inh-d)],
- $P_{SEWC}$  = population connected to the combined sewer system [inh.],
- $C_{IND_{N,P}}$  = nutrient concentration in industrial and commercial waste water [mg/l],
- $Q_{IND_C}$  = runoff from commercial areas connected to the combined sewer system [m<sup>3</sup>/d],
- $Z_{RD}$  = number of days with storm water overflows,
- $ES_{IMP_{N,P}}$  = specific nutrient emissions from impermeable urban area [t/(ha·a)],
- $A_{IMP_C}$  = impervious urban area connected to combined sewer system and the total surface water area [ha],
- $a_{IMP}$  = share of precipitation realized as surface runoff from paved urban area [%],
- $Q_{IMP_C}$  = total water runoff from combined sewer system [m<sup>3</sup>/a], and
- $RE$  = discharge rate of combined sewer overflows [%].
- $N_{DEP}$  = area specific nitrogen deposition [kg TN/(ha·a)]; and
- $P_{DEP}$  = area specific phosphorus deposition [kg TN/(ha·a)],
- $a_p$  = area specific phosphorus emission from animal excrements and traffic wastes [kg TN/(ha·a)].

**Table 6.2:** Parameters used for nutrient load calculation in combined sewer system  
(BEHRENDT, 2000)

Nutrient	$C_{IND_{N,P}}$	$ES_{IMP_{N,P}}$
	(g/m <sup>3</sup> )	(kg/(ha·a))
Nitrogen	1.0	$4 + N_{DEP}$
Phosphorus	0.1	$a_P + P_{DEP}$

The quantity of overflow water during storm water events depends on the specific runoff from the paved urban areas, the number of people connected to the combined sewer system, the inhabitant specific waste water discharge, the share of industrial area and the area specific runoff from these industrial zones and the number of days with storm water events (MOHAUPT et al., 1998; BROMBACH & MICHELBAACH, 1998; BEHRENDT, 1999). The total water runoff from combined system during the days of storm water events can be calculated as:

$$Q_{IMP_C} = q_{URB_C} \cdot A_{IMP_C} \cdot a_{IMP} + Z_{RD} (P_{SEW_C} \cdot q_{inh} + q_{IND} \cdot a_{IND} \cdot 100 \cdot A_{URB}) \quad (\text{eq. 6.12})$$

where

- $Q_{IMP_C}$  = total water runoff from combined sewer system [m<sup>3</sup>/a],
- $q_{URB_C}$  = surface runoff from urban area with combined sewer system [l/m<sup>2</sup>·a],
- $A_{IMP_C}$  = impermeable urban area with combined sewer system [ha],
- $a_{IMP}$  = the share of precipitation realized as surface runoff from paved urban area [%],
- $P_{SEW_C}$  = population connected to the combined sewer system [inh.],
- $Z_{RD}$  = the number of days with storm water overflows,
- $q_{inh}$  = daily waste water output per inhabitant [m<sup>3</sup>/(inh·d)],
- $q_{IND}$  = specific runoff from industrial and commercial areas [m<sup>3</sup>/(ha·d)],
- $a_{IND}$  = the percentage of the industrial and commercial areas within the total urban area,
- $A_{URB}$  = urban area (ha).

### **The discharge rate of combined sewer overflows**

The rate of waste water discharged into rivers via overflows is dependent on the annual precipitation and the storage volume of the combined sewer system. It can be estimated by using an empirical formula, developed by MEISSNER (1991). The storage volume of the combined sewer system keeps back a portion of the total waste water during a storm event, before finally directing in to the sewage treatment system:

$$RE = \frac{4000 + 25 \cdot q_r}{V_s + \frac{0.551 + q_r}{36.8 + 13.5 \cdot q_r}} - 6 + \frac{P_Y - 800}{40} \quad (\text{eq. 6.13})$$

where

- $RE$  = percentage of waste water discharged into rivers via overflows [%],
- $V_s$  = volume of the specific storage of the combined sewer system [m<sup>3</sup>/ha],
- $q_r$  = rainfall runoff rate [l/(ha·s)], and
- $P_Y$  = annual precipitation [mm/a].



MEISSNER (1991) and BROMBACH & MICHELBAACH (1998) give out a threshold retention volume of 23 m<sup>3</sup>/ha for a discharge rate of 100% in a combined sewer system. The value of 1 l/(ha·s) for rainfall runoff rate can be used based on the research on the Lake Constance catchment area of BROMBACH & MICHELBAACH (1998).

$$RE_r = \frac{2595}{V_s + 33,5} - 6 + \frac{P_Y - 800}{40} \quad (\text{eq. 6.14})$$

The value of  $V_s$  varies in German rivers between 2 and 21 m<sup>3</sup>/ha (5.0 m<sup>3</sup>/ha for Eastern Germany). Depending on precipitation and volume of storage, the percentage of wastewater discharged into rivers via overflows ( $RE_r$ ) varies between 40 and 70%.

For German river system, the effective number of storm water days ( $Z_{RD}$ ) is assumed depend on the level of precipitation as follow (BEHRENDT et al, 1999):

$$Z_{RD} = 13 \cdot 10^{-7} \cdot P_Y^{2.55} \quad (\text{eq. 6.15})$$

where  $P_Y$  = annual precipitation [mm/a].

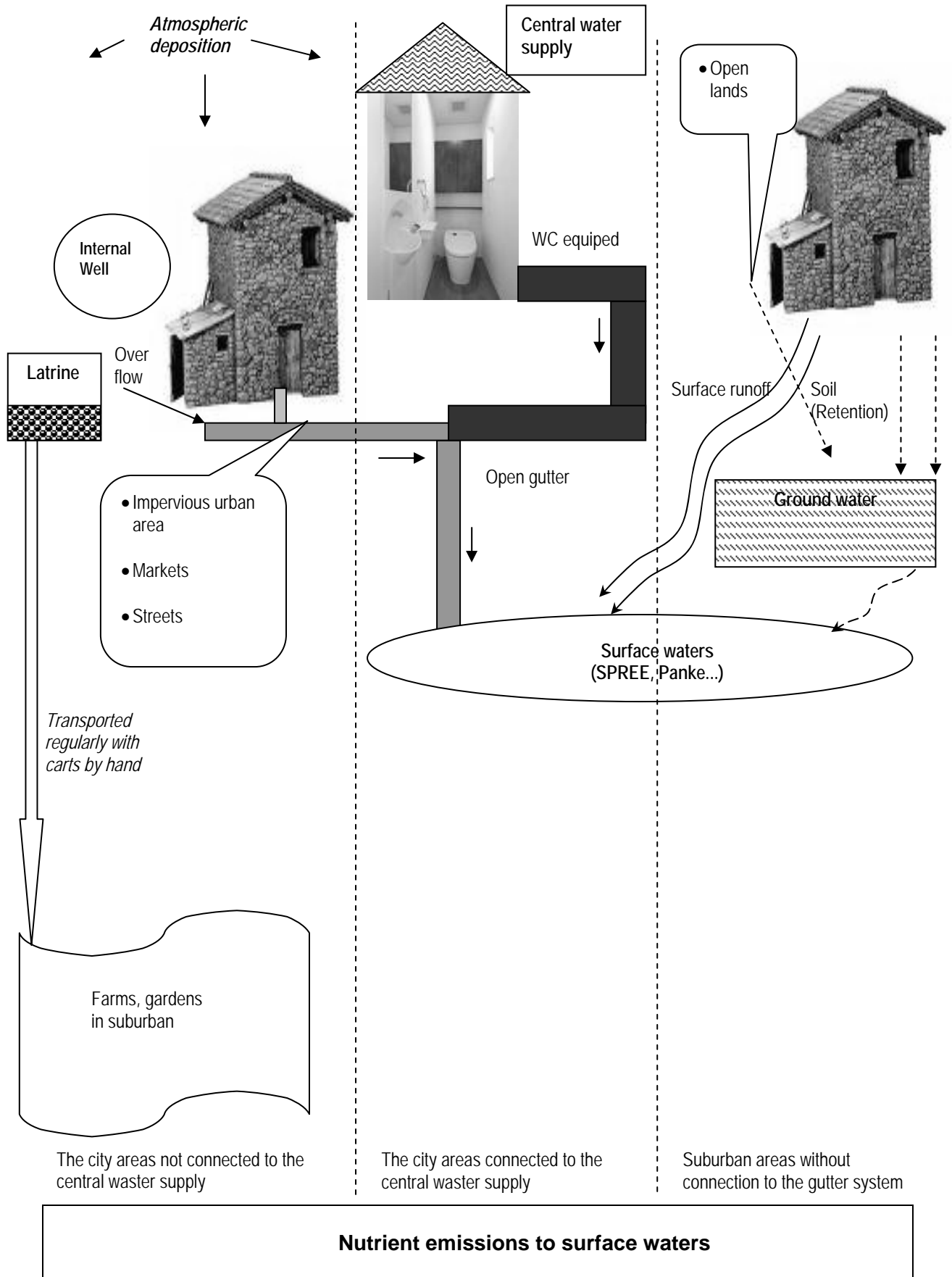
From a mean precipitation in the region of 589 mm/a, a number of effective storm water days of 8 is calculated.

Due to the different in living standards, the specific phosphorus emissions per inhabitant are different in West-Berlin and East-Berlin in the time of separation. In addition, combined sewer system is located mostly in western part of Berlin (70%) (Figure 2.20). These conditions need to be integrated into the formula as:

$$C_{C_p} = \frac{((EIN_{P_{WEST}} \cdot P_{SEWC_{WEST}} + EIN_{P_{EAST}} \cdot P_{SEWC_{EAST}} + C_{IND_{N,P}} \cdot Q_{IND_C}) \cdot Z_{RD} + ES_{IMP_{N,P}} \cdot A_{IMP} \cdot a_{IMP} \cdot 100) \cdot RE \cdot 10^{-2}}{Q_{IMP_C}} \quad (\text{eq. 6.16})$$

where

- $C_{C_p}$  = phosphorus concentration in the combined sewer system during overflow [mg/l],
- $EIN_{P_{WEST}}$  = specific phosphorus emission per inhabitant in West Berlin [g/(inh·d)],
- $EIN_{P_{EAST}}$  = specific phosphorus emission per inhabitant in East Berlin [g/(inh·d)],
- $P_{SEWC_{WEST}}$  = population connected to the combined sewer system in West Berlin [inh.],
- $P_{SEWC_{EAST}}$  = population connected to the combined sewer system in East Berlin [inh.],
- $C_{IND_{N,P}}$  = nutrient concentration in industrial and commercial waste water [mg/l],
- $Q_{IND_C}$  = runoff from commercial areas connected to the combined sewer system [m<sup>3</sup>/d],
- $Z_{RD}$  = number of days with storm water overflows,
- $ES_{IMP_{N,P}}$  = specific nutrient emissions from impermeable urban area [t/(ha·a)],
- $A_{IMP_C}$  = impermeable urban area connected to combined sewer system and the total surface water area [ha],
- $a_{IMP}$  = share of precipitation realized as surface runoff from paved urban area [%],
- $Q_{IMP_C}$  = total water runoff from combined sewer system [m<sup>3</sup>/a], and
- $RE$  = discharge rate of combined sewer overflows [%].



**Figure 6.4:** Nutrient emissions from households and impervious areas connected to the gutter system without treatment

### 6.2.2.3 Nutrient emissions from households and impervious urban areas connected to sewers without treatment

In Berlin, the estimation of nutrient loads from households not connected to public sewerage systems without treatment is mostly applied for the period of 1850 -1876. At that time, households in the Old Berlin city and other old towns like Charlottenburg, Neuköln, Schöneberg, Spandau, Wilmersdorf were connected to sewer system (via open gutters) and discharged directly to the open water bodies (the river Spree) without any treatment.

Nutrient emissions, in this case, included nitrogen and phosphorus discharges from the proportion of impervious urban area, population and indirect industrial sources having connection to the sewer system, but not to a waste water treatment plant (OSPAR, 2000; BEHRENDT et al., 2000, 2003).

It is assumed that only the dissolved part of the nitrogen and phosphorus outputs per inhabitant is fully discharged into the sewer systems (open gutters). The particulate fraction of the human nutrient output from inhabitants only connected to sewers, in the case of Berlin in the period of 1850-1876, was transported to the suburban area and agricultural farms by carts (OSPAR, 2000; BEHRENDT, 2003; BÄRTHEL, 2003, MOHAJERI, 2005).

The nitrogen and phosphorus discharges from this pathway can be calculated according to the following formula:

$$EUSO_{N,P} = D_{N,P} \cdot A_{IMP_{SO}} \cdot a_{IMP} \cdot 100 + 0.365 \cdot IN_{SO} \cdot EIN_{D_{N,P}} + C_{IND_{N,P}} \cdot Q_{IND_{SO}} \quad (\text{eq. 6.17})$$

where

- $EUSO_{N,P}$  = nutrient input via paved urban areas and people connected only to sewers [t/a],
- $A_{IMP_{SO}}$  = urban area connected to sewers only [km<sup>2</sup>],
- $D_{N,P}$  = area specific nutrient emissions [kg/(ha·a)],
- $IN_{SO}$  = people connected only to sewers,
- $EIN_{D_{N,P}}$  = inhabitant specific output of dissolved nutrients [g/(inh·d)],
- $Q_{COM_{SO}}$  = annual runoff from industrial area only connected to sewers [m<sup>3</sup>/s], and
- $a_{IPM}$  = the share of precipitation realized as surface runoff from paved urban area.

The specific human dissolved nitrogen output was assumed to 9 g N (inh·d) for all inhabitants in the Danube basin (BEHRENDT, 2003) and in other Europe catchments (OSPAR, 2000). For phosphorus it has to be assumed that the dissolved emissions are different by countries due to the varying amount of phosphorus used in detergents. The inhabitant specific P-emissions in Germany was identified by SCHMOLL (1998) at a level of 1.62 g P /(inh·d) if no phosphorus is used for detergents and dish washers. The dissolved phosphorus emission per inhabitant was estimated of 1 g/(inh·d) for Berlin in the period of 1850-1876 (BEHRENDT, 1994, 2003).

#### 6.2.2.4 Nutrient emissions from impervious urban areas and households not connected to sewer into surface waters

In Berlin, households not connected to public sewerage systems include both scattered dwellings and households within urban areas that are not connected to the combined or separate sewer systems. The diffuse anthropogenic nitrogen and phosphorus losses from households encompass the phosphorus and nitrogen losses from sanitary waste water. Nutrient emissions via this pathway depend on the level of water consuming equipment, nutrient retention in soil, ways of discharge and distance from water bodies and indicative specific loads of phosphorus and nitrogen (OSPAR, 2000). According the approach of HARP-NUT guideline 5 the inputs of materials from these area are, in the case of households with water flushed toilets, with no specific external treatment (except sedimentation tanks): 0.43 kg/(inh·a) P and 3.1 kg/(inh·a) N (OSPAR, 2000).

The following formula according to BEHRENDT et al. (2000) was used in this study:

$$EUN_{N,P} = (100 - R_{S_{N,P}}) \cdot (D_{IMP_{N,P}} \cdot A_{IMP_{N,P}} \cdot 100 + IN_N \cdot EIN_{D_{N,P}} \cdot 0.365 \cdot (100 - W_{TR})) \quad (\text{eq. 6.18})$$

where

- $EUN_{N,P}$  = nutrient input via people and impervious areas not connected to sewers [t/a],
- $R_{S_{N,P}}$  = nutrient retention in soil (80% for nitrogen and 90% for phosphorus),
- $A_{IMP_{N,P}}$  = paved areas not connected to sewers [km<sup>2</sup>],
- $IN_N$  = people not connected to sewers, and
- $W_{TR}$  = proportion of dissolved human nutrient output transported to WWTPs or other activities [%].

It is assumed that 40% of the dissolved human phosphorus and 20% of the dissolved human nitrogen output is transported to a waste water treatment plant or other facilities with the particulate part (OSPAR, 2000).

#### 6.2.2.4 Nutrient emissions via groundwater

Nutrient inputs by groundwater are calculated from the product of the groundwater flow and the nutrient concentrations in groundwater. In this study, groundwater flow was calculated from the product of the urban area (includes paved urban area and natural ground), the precipitation and the share of precipitation realized as ground water from urban paved urban area. Groundwater concentrations of soluble reactive phosphorus (SRP) in Berlin were taken from BEHRENDT et al. (2000, 2003) as the level of sandy soil (0.1 mg P/l).

The nitrogen concentrations in the groundwater were derived from the potential nitrate concentration in the soil. Nitrogen concentrations in the ground water depend on the nitrification process, that is can be depend on the residence time of the groundwater, the mineralization and immobilization capacity and substances of soil. Berlin belongs to the unconsolidated rock region (close to groundwater and far groundwater), where the nitrogen

concentrations in groundwater are generally low. According to the median of the residence time in ground water for German river catchments, the retention time of groundwater in Berlin area was estimated as 50 years (BEHRENDT et al., 2003). Nitrogen in ground water flowing into surface waters is related to the N-surpluses in the past rather than present. Therefore, in this study, N-surpluses were calculated as averages of previous years based on retention time. According to BEHRENDT (2003), N-retention in the unsaturated zone and in ground water in Berlin is 90-80% of the total N in percolating water. The N concentration in percolating water was calculated from nitrogen emissions via inhabitants not connected to sewers and the atmospheric nitrogen precipitation and percolating volume.

Over the last 150 years, the nitrogen surpluses in Berlin were changed over periods and mostly originated from seeping waters around the open pits in yard during the storm events (in the period before water closet application) and deposition from the atmosphere. Total nutrient surpluses to soil was estimated as the sum of nutrient emissions from people connected with sewer but not treatment plants, and emissions from people with connection to neither sewers nor WWTPs, nutrient depositions on open lands and in the share of precipitation realized as seeping water from paved urban area.

### 6.3 Quantification of nutrient loads by monitoring data

In general, the total nutrient inputs into Berlin surface water bodies are the sum of nutrient emissions from inflow rivers, from surface runoff on impermeable urban area with separate sewer system, nutrient load from combined sewer overflow water, people and impervious urban area not connected to sewer system, nutrient loads from point sources (sewage farm and WWTP) and also nutrient emissions from air deposition.

The nutrient loads in the rivers were calculated by a method favoured by OSPAR (1996), LITTLEWOOD (1995), BEHRENDT (2003) and EUROHARP (2006), in which the river load can be estimated by the following formula:

$$L_y = a \cdot \frac{Q_y}{\sum_{i=1}^n q_i} \cdot \sum_{i=1}^n q_i \cdot c_i \quad (\text{eq. 6.19})$$

where

$L_y$	= annual nutrient load via inflow river [t/a],
$a$	= unit conversion factor,
$n$	= number of data,
$Q_y$	= mean annual river flow [ $\text{m}^3/\text{s}$ ],
$q_i$	= measured flow [ $\text{m}^3/\text{s}$ ], and
$c_i$	= measured nutrient concentration in river water [mg/l].

The mean load for a specific time period can be calculated as follow:

$$L_p = \frac{1}{p} \cdot \sum_{i=1}^p L_y \quad (\text{eq. 6.20})$$

where

$$\begin{aligned} L_p &= \text{average annual nutrient load in the specific period [t/a], and} \\ p &= \text{number of years with measuring data in the specific period.} \end{aligned}$$

#### 6.4 Nutrient retention in the water bodies

Surface waters in Berlin are low land flow systems, with typical widening water bodies and a continuous and intensive nutrient input loading from urban area over the last 150 years. The river system has a high potential of nutrient loss and retention processes due to low flow and lakes. With those natural and historical conditions, the retention capacities of Berlin water bodies were considered. The retention and loss processes within a water system: sedimentation, denitrification and plant uptake,... are the causes of the differences between the input load and output load of the Berlin city (in the case, there are no underestimate of input load or overestimated of output load).

From the data of nutrient emissions and loads in 100 catchment areas in different sizes (100 to 200.000 km<sup>2</sup>), an empirical model was developed (BEHRENDT & OPITZ, 1999), in which the observed nutrient load for a specific time period is the sum of all inputs from point and diffuse sources and the sum of all retention and loss processes:

$$L_{N,P} = ET_{N,P} - R_{N,P} = \sum EP_{N,P} + \sum ED_{N,P} + \sum R_{N,P} \quad (\text{eq. 6.21})$$

where

$$\begin{aligned} L_{N,P} &= \text{nutrient load [t/a],} \\ ET_{N,P} &= \text{total nutrient input [t/a],} \\ R_{N,P} &= \text{loss or retention of nutrients [t/a],} \\ EP_{N,P} &= \text{nutrient input via point source [t/a], and} \\ ED_{N,P} &= \text{nutrient input via diffuse sources [t/a].} \end{aligned}$$

From eq. 6.21 we can adjust to:

$$\frac{L_{N,P}}{ET_{N,P}} = \frac{1}{1 + RL_{N,P}} \quad \text{or} \quad L_{N,P} = \frac{ET_{N,P}}{1 + RL_{N,P}} \quad (\text{eq. 6.22})$$

$RL_{N,P}$  = load weighted nutrient retention.

By regression method, a power function was selected for description of possible relationship between retention and the possible driving forces:

$$RL_{N,P} = a \cdot x^b$$

where a, b = model coefficients.

The following models were used for calculation of retention of TN, DIN and TP.

$$\text{TN:} \quad RL_N = 1.9 \cdot HL^{-0.49} \quad n=56, r^2=0.52 \quad (\text{eq. 6.23})$$

$$\text{DIN:} \quad RL_N = 5.9 \cdot HL^{-0.75} \quad n=100, r^2=0.654 \quad (\text{eq. 6.24})$$

$$\text{TP:} \quad RL_P = 13.3 \cdot HL^{-0.93} \quad (\text{eq. 6.25})$$

$$\text{where } HL = \text{hydraulic load [m/a] and } HL = \frac{Q_{flow}}{A_{SW}} \quad (\text{eq. 6.26})$$

where

$$Q_{flow} = \text{mean annual river flow [m}^3/\text{s], and}$$

$$A_{SW} = \text{area of surface waters within the river catchment [km}^2\text{].}$$

$$\text{TP:} \quad RL_P = 26.6 \cdot q^{-1.17} \quad n=89, r^2=0.81 \quad (\text{eq. 6.27})$$

With  $q$  = specific runoff divided by the area of the river basin [ $l/(s \cdot km^2)$ ]

Surface waters of Berlin belong to the lowland river system with typical riverine lakes. Therefore, the retention capacity of riverine lakes plays an important role. Because that lakes having long water renewal times are much more sensitive to phosphorus loading than would appear from mean depth only. In this case, the residence time of water in lakes should be taken into account in phosphorus retention estimation by methods given by VOLLENWEIDER (1975).

$$\frac{L_p}{ET_p} = \frac{1}{1 + a \cdot \tau^b} \quad (\text{eq. 6.28})$$

where

$$L_p = \text{load weighted phosphorus retention [\%],}$$

$$a = 0.7$$

$$b = 0.5$$

$$\tau = \text{residence time of water [year], and}$$

$$ET_p = \text{total phosphorus input [t/a].}$$

The residence time of water in lakes can be estimated from the total water volume of lakes in Berlin and the annual flow:

$$\tau = \frac{V_{Lake}}{Q_{flow} \cdot 86400 \cdot 365} \quad (\text{eq. 6.29})$$

where

$$\tau = \text{residence time of water [year],}$$

$$V_{Lake} = \text{total water volume of surface water bodies [m}^3\text{], and}$$

$$Q_{flow} = \text{mean annual river flow [m}^3/\text{s].}$$

VENOHR (2003) developed a method for estimating of nitrogen retention in surface water bodies taking into account the hydraulic load as well as water temperature.

$$RL_{N,DIN} = \frac{1}{1 + a \cdot e^{b \cdot t_w} \cdot HL^c} \cdot ET_{N,DIN}, \quad RL_{DIN} = \frac{1}{1 + 8.58 \cdot e^{0.67b \cdot t_w} \cdot HL^c} \cdot ET_N \quad (\text{eq. 6.30})$$

where

$RL_N$	= load weighted nitrogen retention [%],
a	= 4.74 for TN; 8.58 for DIN
b	= 0.067
c	= -1
e	= Euler's number [2.718281],
$HL$	= hydraulic load [m/a],
$t_w$	= annual mean of water temperature [°C],
$\tau$	= residence time of water [year], and
$ET_p$	= total nitrogen input [t/a].

## 6.5 Reconstruction of the urban development of Berlin and secondary data method

### 6.5.1 Reconstruction of the development of impervious area in Greater Berlin

#### *Existing data*

The impervious area is the sum of impermeable areas: houses, yards, industrial and commercial centers and paved roads. This information is extracted from the statistic yearbooks of the Old Berlin for the period of 1875-1919, and Greater Berlin after 1920. In the period of 1850-1920, this data is available in some years for the Old Berlin city only (Table 6.3). The data on impervious area in the extension parts of Greater Berlin in this period does not exist.

**Table 6.3:** Population, urban area and impervious area of the Old Berlin city, 1875-1919

Year	Population (inh.)	Urban area (ha)	Impervious area (ha)
1875	966845	5924	1421
1880	1123749	6061	1764
1885	1315665	6337	1997
1890	1578794	6338	2150
1895	1677034	6338	2559
1900	1888848	6333	2745
1905	2040148	6337	2966
1910	2071257	6341	3168
1914	1945684	6345	3263
1915	1835094	6346	3282
1916	1770061	6567	3308
1917	1743034	6566	3310
1918	1822782	6566	3312
1919	1902530	6580	3317

(Source: *Statistisches Jahrbuch der Stadt Berlin, 1875-1919*)

#### *Required data*

The impervious area is an important input data for estimating the rain water volume to be realized as surface runoff. Therefore, the data on the impervious area are required not only in the Old Berlin city but also for the extension parts of Greater Berlin in the period of 1850-2000.



### Transformation procedures

The information on impervious area does not exist for the whole Berlin area as well as the studied period. This data need to be filled by estimation.

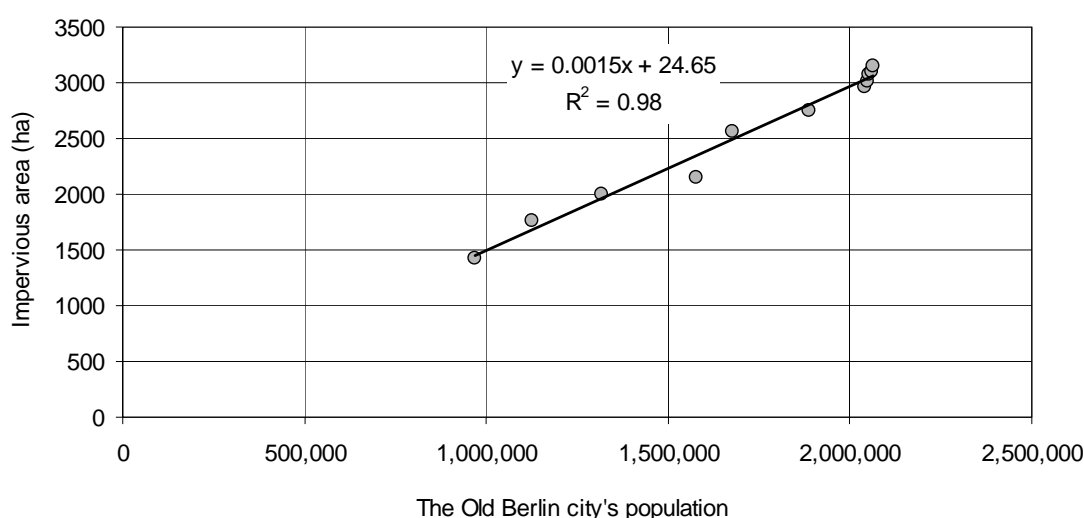
For the Old Berlin area in the period of 1850-1920, the constructed area can be estimated from the urban area by an empirical formula:

$$A_{IMP-old} = 0.0015 \cdot P_{OB} + 24.65 \quad n=12, r^2=0.98 \quad (\text{eq. 6.31})$$

where

$A_{IMP-old}$  = Impervious area in the Old Berlin city [ha],

$P_{OB}$  = Population of the Old Berlin city [inh.].



**Figure 6.5:** Relationship between the impervious area and population of the Old Berlin city, 1875-1920 (Source: *Statistisches Jahrbuch der Stadt Berlin, 1875-1924*)

For the extension parts of Greater Berlin, the constructed area can be estimated by the product of the population and the proportion between the impervious area and the population in 1920.

$$A_{IMP-ext} = \frac{A_{IMP-ext-1920}}{P_{ext-1920}} \cdot P_{ext} \quad (\text{eq. 6.32})$$

where

$A_{IMP-ext}$  = impervious area in the satellite towns and communities of Greater Berlin [ha],

$A_{IMP-ext-1920}$  = impervious area in the extension parts of Greater Berlin in 1920 [ha] and

$P_{ext-1920}$  = population in the extension parts of Greater Berlin in 1920.

The impervious area of Greater Berlin can be estimated from the sum of the constructed area in the Old Berlin area and in suburban and surrounding cities:

$$A_{IMP} = A_{IMP-old} + A_{IMP-ext} \quad (\text{eq. 6.33})$$

### 6.5.2 Reconstruction of the sewerage development

#### Existing data

The sewer system development can be estimated via the number of houseblocks connected to the sewer system. The number of houseblocks connected to the sewer system can be extracted in the statistic yearbooks for the Old Berlin city in the period of 1875-1919 and Greater Berlin after 1920 (Figure 6.6). The data on sewer connection does not exist for some extension parts of Greater Berlin in the period of 1875-1919. Information on sewerage area in combined and separate sewer system of Greater Berlin is available only since 1920.

#### Required data

Sewer connection is an important input data for estimating the total waste water to be collected. Therefore, the data on sewer connection is needed also for the extension parts of Greater Berlin in the period of 1875-1920. The information on the area and population connected to sewer system is also needed for estimation of waste water and rain water volume.

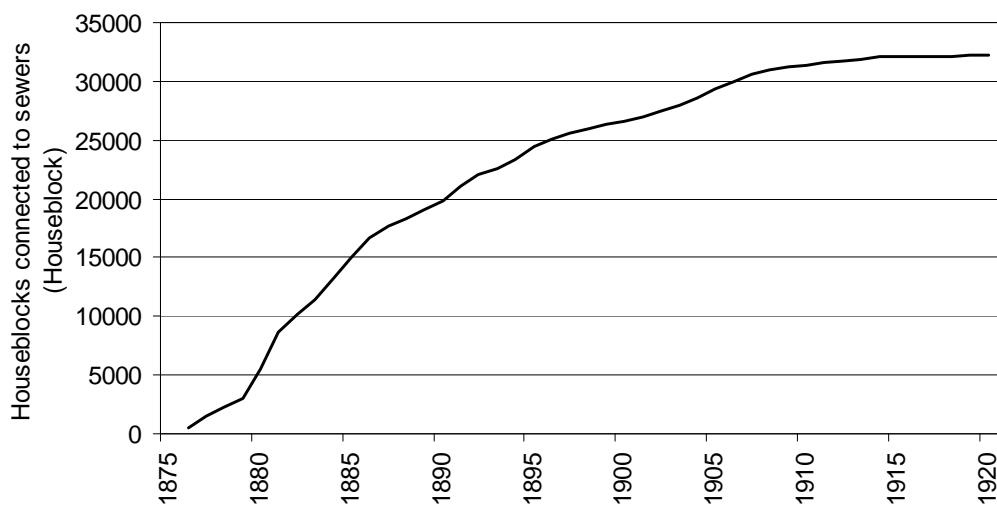
#### Transformation procedures

Assuming that the surrounding areas have the same construction progress like the Old Berlin area, the constructed area of the cities and towns surrounding Berlin was estimated by using the following formula:

$$H_{SEW-ext} = \frac{H_{SEW-old} \cdot P_{ext}}{P_{old}} \quad (\text{eq. 6.34})$$

where

- $H_{SEW-ext}$  = number of houseblocks connected to the sewer system in extension parts,
- $H_{SEW-old}$  = number of houseblocks connected to the sewer system in the Old Berlin city,
- $P_{ext}$  = population in the extension parts.



**Figure 6.6:** Sewer connections in the Old Berlin city, 1875-1920

(Source: Statistisches Jahrbuch der Stadt Berlin, 1875-1921)

### 6.5.2.1 Area connected to the sewer system of Greater Berlin

The total sewered area of Greater Berlin is the sum of the sewered areas in the Old Berlin city, satellite towns and communities:

$$A_{SEW} = A_{SEW-old} + A_{SEW-ext} \quad (\text{eq. 6.35})$$

where

- $A_{SEW}$  = total sewered area of Greater Berlin,
- $A_{SEW-old}$  = total area serviced by the combined sewer system in the Old Berlin city at estimated year [ha], and
- $A_{SEW-ext}$  = total area serviced by the combined sewer system in the extension part [ha].

The total sewered area of Greater Berlin can be estimated from the total impervious area by the following empirical formula:

$$A_{SEW} = -2275 + 1.9003 \times A_{IMP}, n = 43, r^2 = 0.978, \text{ period of 1875-1919} \quad (\text{eq. 6.36})$$

#### a. The sewered area in the Old Berlin city

Sewered area is an important parameter for the water balance and nutrient emission calculating. The sewer coverage level decides the volume of waste water from domestic and industrial sector as well as rain water to be collected and purified in the sewage farms and WWTPs. For the Old Berlin city, total area serviced by the combined sewer system was calculated by the following formula:

$$A_{SEW-old} = \frac{A_{SEW-old-1920}}{H_{SEW-old-1920}} \cdot H_{SEW-old} \quad (\text{eq. 6.37})$$

where

- $A_{SEW-1920}$  = total area serviced by the combined sewer system in the Old Berlin city in 1920 [ha],
- $H_{SEW-old-1920}$  = number of houseblocks connected to the sewer system in the Old Berlin city in 1920, and
- $H_{SEW-old}$  = number of houseblocks connected to the sewer system in the Old Berlin city

#### b. The sewered area in the extension parts

The sewered areas in the extension part of Berlin were estimated as follow:

$$A_{SEW-ext} = \frac{A_{SEW-ext-1920}}{H_{SEW-ext-1920}} \times H_{SEW-ext} \quad (\text{eq. 6.38})$$

where:

- $A_{SEW-ext-1920}$  = total area serviced by the combined and separate sewer system in the extension part in 1920 [ha],
- $H_{SEW-ext-1920}$  = number of houseblocks connected to the sewer system in the extension part in 1920, and
- $H_{SEW-ext}$  = number of houseblocks connected to the sewer system in the extension part.

**6.5.2.2 Area connected to the combined sewer system.**

The combined sewer system mostly located in the old quarter of Berlin and some satellite towns. The total area connected to combined sewer system can be estimated by the sum of the area serviced by combined sewer system in the Old Berlin city, the satellite towns and communities:

$$A_{SEW-C} = A_{SEW-old} + A_{SEW-Ext-C} \quad (\text{eq. 6.39})$$

where:

$A_{SEW-C}$  = total area connected to combined sewers of Greater Berlin [ha],

$A_{SEW-old}$  = sewered area in the Old Berlin city [ha], and

$A_{SEW-ext-C}$  = area connected to combined sewers in the extension parts [ha].

***The impervious area in the combined sewer system***

The impervious area in the combined sewer system is the sum of the impervious area of the Old Berlin city and the impervious area connected to combined sewers in the extension parts of Greater Berlin. It can be estimated from the total sewered area, based on the proportion of the impervious area and the total sewered area of the Old Berlin in 1920:

$$A_{IMP-C} = \frac{A_{IMP-old-1920}}{A_{SEW-old-1920}} \cdot A_{SEW-C} \quad (\text{eq. 6.40})$$

where:

$A_{IMP-C}$  = total impervious area connected to combined sewers of Greater Berlin [ha],

$A_{IMP-old-1920}$  = total impervious area connected to combined sewers in the Old Berlin city in 1920 [ha],

$A_{SEW-C}$  = total area connected to combined sewers of Greater Berlin [ha], and

$A_{SEW-old-1920}$  = total area connected to combined sewers in the Old Berlin city in 1920 [ha].

**6.5.2.3 Area connected to the separate sewer system**

Since 1905, sewers constructed in Greater Berlin have been separate systems and almost no new combined sewers have been built (Figures 6.7, 6.8). Therefore, the new urbanization areas in satellite towns and communities are mainly serviced by the separate sewer system. The area connected to separate sewers can be estimated by the difference of the total sewered area of Greater Berlin and the area sewered by the combined system:

$$A_{SEW-S} = A_{SEW} - A_{SEW-C} \quad (\text{eq. 6.41})$$

where:

$A_{SEW-S}$  = total area connected to the separate sewer system of Greater Berlin [ha]

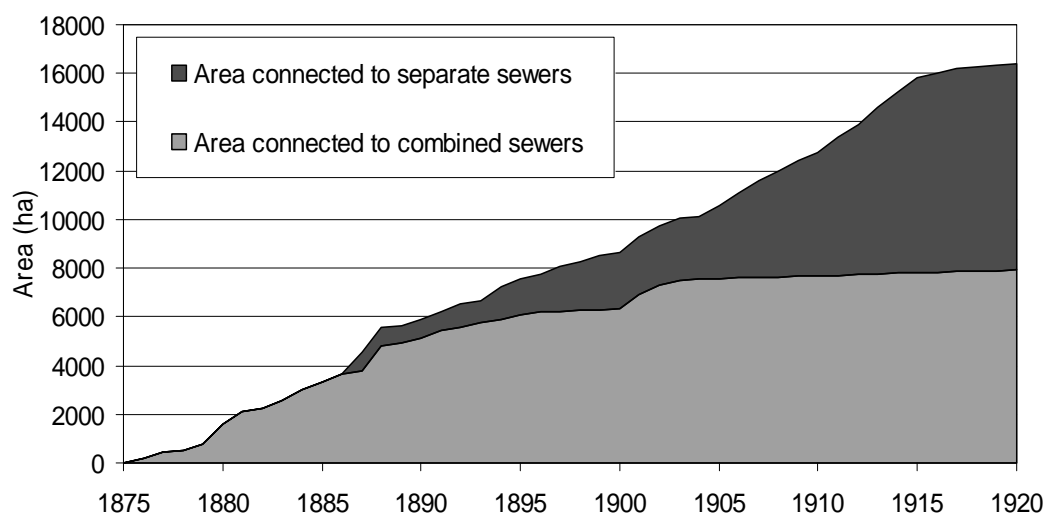
***The impervious area in the separate sewer system***

The impervious area serviced by the separate sewer system can be estimated by the product of the total area connected to separate sewers and the proportional between the impervious area and the total area serviced by the separate sewer system in 1920:

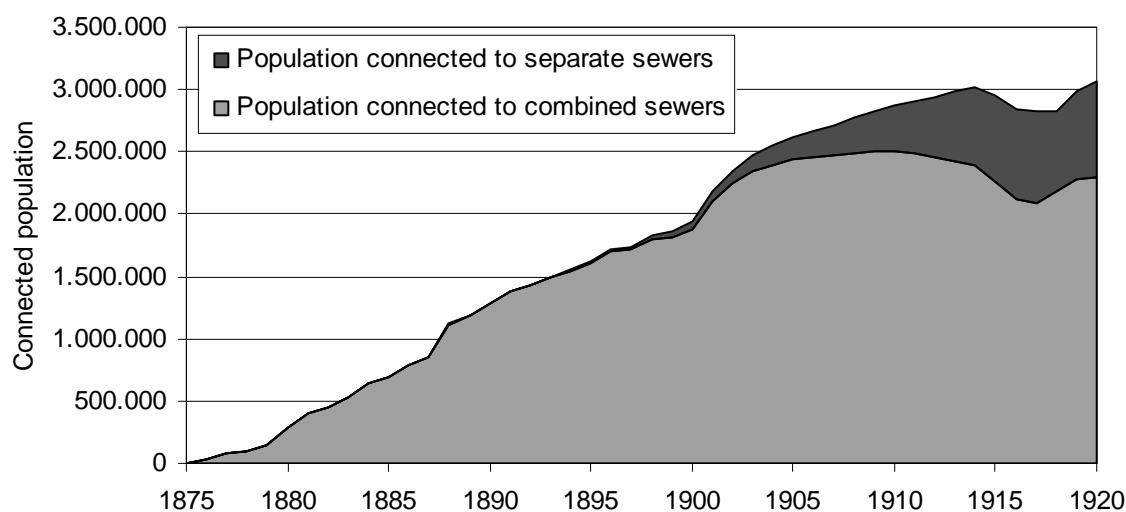
$$A_{IMP-S} = \frac{(A_{IMP-ext-1920} - A_{IMP-ext-C-1920})}{A_{SEW-S-1920}} \cdot A_{SEW-S} \quad (\text{eq. 6.42})$$

where:

- $A_{IMP-S}$  = total impervious area connected to separate sewers of Greater Berlin [ha],
- $A_{IMP-ext-1920}$  = total impervious area connected to separate sewers in the extension parts of Greater Berlin in 1920 [ha],
- $A_{IMP-ext-C-1920}$  = total impervious area connected to combined sewers in the extension parts of Greater Berlin in 1920 [ha], and
- $A_{SEW-S}$  = total area connected to the separate sewer system of Greater Berlin [ha].



**Figure 6.7:** Area connected to sewers in Greater Berlin city, 1875-1920



**Figure 6.8:** Population connected to sewers in Greater Berlin, 1875-1920

**6.5.2.4 Population connected to sewers of Greater Berlin**

The total population serviced by the sewer system of Greater Berlin was calculated by the sum of the total population serviced by the combined sewer system (mainly the Old Berlin city) and the total population serviced by the separate sewer system (in extension parts only):

$$P_{SEW} = P_{SEW-C} + P_{SEW-S} \quad (\text{eq. 6.43})$$

where:

- $P_{SEW}$  = total population connected to the sewer system of Greater Berlin,
- $P_{SEW-C}$  = total population serviced by the combined sewer system of Greater Berlin,
- $P_{SEW-S}$  = total population serviced by the separate sewer system of Greater Berlin.

*Population connected to combined sewers*

Population serviced by the combined sewer system can be estimated by sewer population in the Old Berlin city and the surrounding town having the combined sewer system:

$$P_{SEW-C} = P_{SEW-old} + P_{SEW-ext-C} \quad (\text{eq. 6.44})$$

where

- $P_{SEW-old}$  = sewer population in the Old Berlin city, and
- $P_{SEW-ext-C}$  = population connected to combined sewers in the extension parts.

Assuming that population connected to combined sewers is a proportion of the total area serviced by the combined sewer system, population connected to combined sewers of Greater Berlin can be estimated by the following formula:

$$P_{SEW-C} = \frac{P_{SEW-C-1920}}{A_{SEW-C-1920}} \cdot A_{SEW-C} \quad (\text{eq. 6.45})$$

where

- $P_{SEW-C-1920}$  = population serviced by combined sewers of Greater Berlin in 1920,
- $A_{SEW-C-1920}$  = area connected to combined sewers of Greater Berlin in 1920.

*Population connected to the separate sewer system*

The separate sewer system is only located in the extension parts: the satellite towns and communities. Population connected to separate sewers of Greater Berlin can be estimated by the following formula:

$$P_{SEW-S} = \frac{P_{SEW-S-1920}}{A_{SEW-S-1920}} \cdot A_{SEW-S} \quad (\text{eq. 6.46})$$

where

- $P_{SEW-S-1920}$  = population serviced by the separate sewer system of Greater Berlin in 1920,
- $A_{SEW-S-1920}$  = area connected to separate sewers of Greater Berlin in 1920 [ha]

### 6.5.3 The development of collected waste water volume

#### *Existing data*

The collected waste water volume of the Old Berlin city can be extracted from the statistic year books for the Old Berlin city in the period of 1875-1919. Data on collected waste water volume for Greater Berlin are available in the period of 1920-1952 and after 1990. This data does not exist for the extension parts of Greater Berlin for the period of 1875-1919. In the period of 1953-1989, collected waste water volume of West Berlin can be extracted from the Statistic year books and does not exist for East Berlin.

#### *Required data*

Data on waste water volume is needed for the extension parts of Greater Berlin in the period of 1875-1920. Waste water volume for the Eastern part of Berlin in the period of 1953-1989 is also need to be estimated.

#### *Transformation procedures*

The total collected waste water volume of Greater Berlin is the sum of the collected waste water in the Old Berlin city and the collected volume in the surrounding cities, towns and communities in the extension parts:

$$V_{SEW} = V_{SEW-old} + V_{SEW-ext} \quad (\text{eq. 6.47})$$

where:

$$\begin{aligned} V_{SEW} &= \text{total collected waste water volume of Greater Berlin per year [1000 m}^3\text{/a]}, \\ V_{SEW-old} &= \text{annual total collected waste water volume of the Old Berlin city [1000 m}^3\text{/a]}, \\ V_{SEW-ext} &= \text{annual total collected waste water volume of the extension parts of Greater Berlin [1000 m}^3\text{/a]}. \end{aligned}$$

#### **6.5.3.1 Collected waste water volume in the Old Berlin city**

Waste water collected in the Old Berlin city is a mixture of the sewage from the houses and businesses but also storm water runoff from streets and roofs in the drainage basin. The total waste water collected by the radical system in the Old Berlin city can be extracted from the statistic yearbooks of Berlin.

The total collected waste water volume can be estimated from the number of houseblocks connected to the sewers by an empirical formula:

$$V_{SEW-old} = 0.1646 \cdot H_{SEW-Old}^{1.2860} \quad n=42, r^2=0.99 \quad (\text{eq. 6.48})$$

where

$H_{SEW-Old}$  = number of houseblocks connected to the sewer system in the Old Berlin city

Waster water collected in the Old Berlin city can be determined by the formula:

$$V_{SEW-old} = P_{SEW-old} \cdot q_{inh} + A_{IMPC} \cdot a_{IMP} \cdot P_Y \quad (\text{eq. 6.49})$$

where

$q_{inh}$  = daily waste water output per inhabitant [l/(inh-d)],

$a_{IMP}$  = the share of precipitation realized as surface runoff from paved urban area,

$P_Y$  = annual precipitation [mm/a].

According to HEANEY et al (1976) the share of precipitation realized as surface runoff from impervious urban area can be calculated as the following Equation:

$$a_{IMP} = 0.15 + 0.75 \cdot \frac{A_{IMP}}{A_{URB}} \quad (\text{eq. 6.50})$$

where

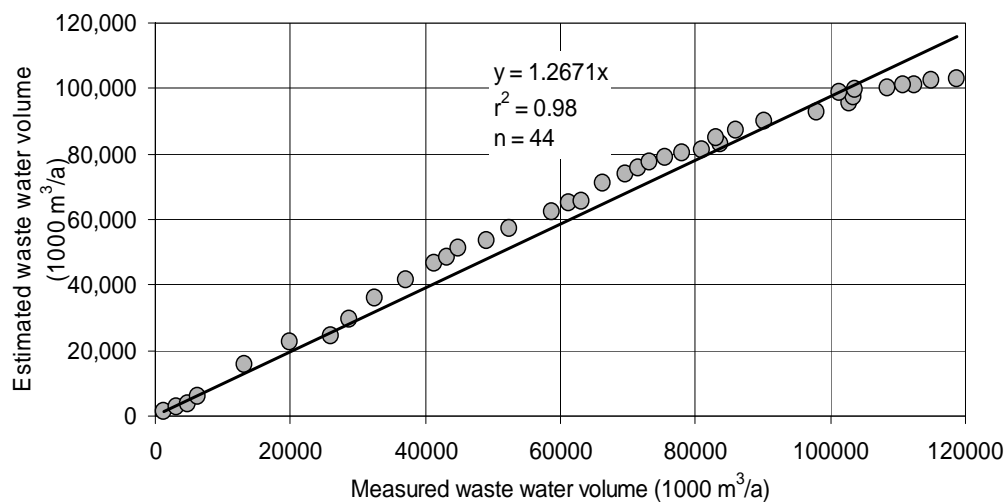
$a_{IMP}$  = the share of precipitation realized as surface runoff from paved urban area,

$A_{IMP}$  = impermeable urban area [ha], and

$A_{URB}$  = total urban area [ha].

The period of 1876-1920:

$$a_{IMP_C} = 0.15 + 0.75 \cdot \frac{A_{IMP-old}}{A_{URB-old}} \quad (\text{eq. 6.51})$$



**Figure 6.9:** Estimated waste water volume and statistical data on collected waste water volume of the Old Berlin city (Source: *Statistisches Jahrbuch der Stadt Berlin, 1875-1921*)



The period of 1921-2003

$$a_{IMP_c} = 0.15 + 0.75 \cdot \frac{A_{IMP-old-1920}}{A_{URB-old-1920}} \quad (\text{eq. 6.52})$$

$$a_{IMP_s} = 0.15 + 0.75 \cdot \frac{A_{IMP-ext} - A_{IMP-old-1920}}{A_{GB} - A_{URB-old-1920}} \quad (\text{eq. 6.53})$$

where  $A_{GB}$  = total area of Greater Berlin.

In the period of 1850-1920, the main volume of collected waste water originated from the Old Berlin city and surrounding towns, therefore in the term of the share of precipitation realized as surface runoff from paved urban area, the  $a_{IMP}$  factor from the Old Berlin city can represent to Greater Berlin.

$$A_{IMP_c} = \frac{A_{IMP-old}}{A_{URB-old}} \cdot A_{SEW_c} \quad (\text{eq. 6.54})$$

### 6.5.3.2 Collected waste water volume in the extension parts

In the satellite towns and communities, the separate sewer system is the dominant sewerage. The total collected waste water volume mainly comprises domestic and commercial sewage, and it can be estimated via the number of houseblocks connected to the sewers by two methods:

*By the connection rate of houseblocks to sewer:*

$$V_{SEW-ext} = \frac{V_{SEW-ext-1920}}{H_{SEW-ext-1920}} \cdot H_{SEW-ext} \quad (\text{eq. 6.55})$$

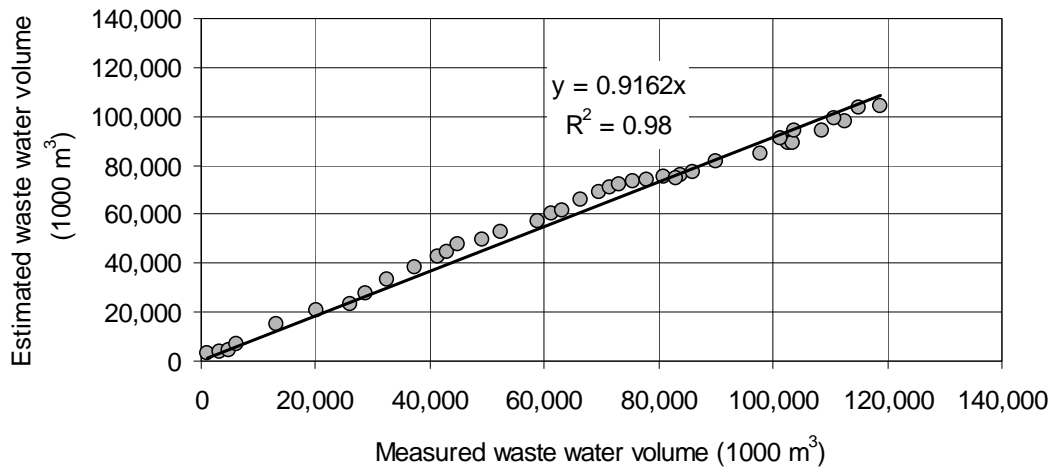
where:

- $V_{SEW-ext-1920}$  = The total collected waste water volume of the extension parts in 1920,
- $H_{SEW-ext}$  = number of houseblocks connected to sewers in extension parts, and
- $H_{SEW-ext-1920}$  = number of houseblocks connected to sewers in the extension parts of Greater Berlin in 1920.

*By regression method:*

With assumption that the extension parts have the same relationship between the collected waste water volume and the number of houseblocks connected to the sewers as in the Old Berlin city, the total collected waste water volume in this area can be estimated by the

$$\text{formula: } V_{SEW-ext} = 0.1546 \cdot H_{SEW-ext}^{1.2860} \quad (\text{eq. 6.56})$$



**Figure 6.10:** Estimated waste water volume and measured data in the Old Berlin city in the period of 1876-1920