Estimations of municipal point source pollution in the context of river basin management

M. Zessner and S. Lindtner
Institute for Water Quality and Waste Management, Vienna University of Technology, Karlsplatz 13/226, 1040 Wien, Austria (E-mail: mzessner@iwag.tuwien.ac.at; lindtner@iwag.tuwien.ac.at)

Abstract Integrated presentation of total emissions on catchment scale is prerequisite for many tasks in integrated management of point and diffuse sources of pollution. This paper will focus on emissions of nutrients from municipal point sources. Based on calculations of discharges of N, P from households into wastewater and on the detailed evaluation of data from 76 municipal wastewater treatments plants, this paper presents ranges of specific loads of inhabitants and population equivalents in the raw wastewater. In addition data of these treatment plants have been evaluated in respect of the treatment efficiency for nitrogen and phosphorus (average reduction rates) dependent on the design characteristic (with or without nitrification, denitrification or enhanced phosphorus removal). The results of the investigation show that the specific N and P loads from households in Austria lie within the range 1.6–2.0 g P/(inhabitant.d) and 11–13 g N/(inhabitant.d). The specific contribution of industries to municipal wastewater varies between 0.3 and 2.0 gP/(pe.d) and 0 and 13 gN/(pe.d) with average values of 1.3 gP/(pe.d) and 6.5 gN/(population equivalent (pe)/d). As average values for municipal wastewater (contributions from household and industry) this leads to specific influent loads of 1.5 gP/(pe.d) and 8.8 gN/(pe.d). Average treatment efficiencies of treatment plants are for instance 50% nitrogen removal in treatment plants with nitrification and 80% in treatment plants with nitrification/denitrification. For phosphorus a removal of about 85% can be expected where the treatment plant was designed for enhanced phosphorus removal. Finally a method for load estimations based on standard values as mentioned above was tested for the estimation of emission from municipal point sources of selected regions.

Keywords Management plans; nitrogen; phosphorus; specific loads; treatment efficiency; wastewater

Introduction
Aggregated presentation of wastewater emissions from municipalities (e.g. N, P) for whole regions and countries is necessary in several cases: e.g. for integrated management of point and diffuse sources on catchment scale, for reporting to the European Union as well as for management plans according to the water framework directive (WFD). In general this information should be based on the measurements from single treatment plants. In many cases those data will not be available, cannot be collected with an acceptable effort for all treatment plants or settlements in a region or data are not of acceptable quality. Thus it will be necessary to make assumptions and estimations based on the information available in order to derive realistic emission loads for whole regions. In such cases it cannot be the goal to calculate accurate values for every single treatment plant or settlement with a high temporal resolution but to derive appropriate estimates to describe the average situation as realistically as possible. Based on the calculation of nitrogen and phosphorus discharges to wastewater produced per inhabitant and the evaluation of a detailed data set of 76 municipal treatment plants in Austria, this contribution will develop a method for the estimation of nitrogen and phosphorus loads in the influent and the effluent of municipal wastewater treatment plants. Further on the accuracy of the method will be evaluated on a set of data from an additional 29 treatment plants.
Materials and methods
For calculation of the specific nitrogen and phosphorus discharges from inhabitants to the wastewater system two approaches have been used. On the one hand the input of nitrogen and phosphorus into households has been calculated based on the consumption of food, detergents and water in Austria (statistical data) and the related average concentrations of the nutrients in these goods. On the other hand these inputs into households have been balanced with data from literature on the production of faeces, dish wash residuals, solid waste discharges and emissions to the air. Further on data from 76 wastewater treatment plants with a average loadings between 5,000 and 350,000 pe (population equivalent = 60 g BOD₅/d) have been used to derive the variation of population equivalent specific influent loads of nutrients as well as of nutrient elimination rates in the treatment plants. The data sets were collected by Lindtner et al. (2002) and consist of information on design values of the treatment plants (e.g. design capacity in pe, volumes of aeration tanks, of primary and secondary clarifiers and sludge treatment devices), connected inhabitants, sludge production and composition, discharge as well as BOD, COD, N, P influent and effluent concentrations and loads (monthly averages from two to seven measurements every week over one year). In a first step the consistency of the data was checked using detailed P, COD and N balance for every treatment plant. Only treatment plants with complete and consistent data have been used for further evaluation. The drop out rate was somewhere around 50% with a dependency on the parameter considered. For the remaining treatment plants the distribution and relation of different parameters were investigated in order to derive standard values that can be used for estimation of yearly averages of effluents and influent loads for nitrogen and phosphorus of other treatment plants where these data are missing. For calculation of population equivalent specific nitrogen and phosphorus influent loads, a method developed by Andreottola et al. (1994) with presentation of these specific values dependent on the relation between connected inhabitants and actual BOD influent loads (expressed as pe) was used. As reference a population equivalent (pe) with 60 g BOD₅/d was assumed. In addition another set of 41 treatment plant data has been used for the validation of the method for load estimations that was developed based on the standard values derived before. Again the first step was a plausibility check of the data set. Data from 29 treatment plants remained for further consideration. For these treatment plants estimation for yearly effluent and influent loads of nitrogen and phosphorus have been done based on basic information of different detail and on standard values, for example specific nutrient loads in the influent and removal rates. Results of the estimation have been compared with the measured values and the average deviation for all treatment plants, and the standard deviation of the deviations for single treatment plants have been calculated. Further on clusters of different numbers of treatment plants have been formed and the average deviation of the measured values and the estimated ones for these clusters have been calculated in order to derive information on how many treatment plants have to be considered together to get realistic results of estimations based on standard values.

Development of standard values
Influent loads
13 to 15 g N/(inh.d) and 1.8 to 2.4 g P/(inh.d) are consumed by households in Austria, mainly by food but to some extent by detergents and water (nitrogen only) (for details see Lindtner and Zessner, 2003). Most of this amount is discharged to the wastewater mainly via urine but via faeces and dish wash residuals as well. Altogether the discharge to the wastewater can be assumed to be 11–13 g N/(inh.d) and 1.6–2.0 g P/(inh.d). The rest is discharged to solid waste or released to the air (nitrogen only).
Figures 1 and 2 show the nitrogen and phosphorus loads per pe of different treatment plants dependent on the relation between connected inhabitants (inh) and average loading of the treatment plant expressed as pe (based on Andreottola et al., 1994). An inh/pe relation of 1 would indicate discharges from inhabitants (households) only. An inh/pe relation of 0 indicates only industrial discharges. Values in between show a mixture of household and industrial discharges as usually found in municipal wastewater.

The following conclusions can be drawn from these figures in order to derive standard values for load estimations.

- In wastewaters stemming mainly from households, average values of 11 g N/(pe.d) and 1.6 g P/(pe.d) are found. This is well in line with the calculations of inputs from households to wastewater of 11–13 g N/(inh.d) and 1.6–2.0 g P/(inh.d).
- The specific contribution of industries to municipal wastewater varies from 0.3 to 2.0 gP/(pe.d) and 0 to 13 g N/(pe.d) with average values of 1.3 g P/(pe.d) and 6.5 g N/(pe.d).
- As average values for municipal wastewater (contributions from household and industry) this leads to specific influent loads of 1.5 g P/(pe.d) and 8.8 g N/(pe.d). These values are close to values that Nowak (2000) derived from data of 73 treatment plants (1.53 g P/(pe.d) and 9.3 g N/(pe.d)).

These standard values can be used for estimation of N- and P-influent loads if the actual pe (BOD, COD)-loading (and the connected inhabitants) of treatment plants is known. In case this information is not available, additional assumptions have to be made. The design loads of a treatment plant will be known in most of the cases, and the number of connected inhabitants can be derived from statistical data. Figure 3 shows which relation between the design capacity or the number of connected inhabitants with the actual loading (pe) of a treatment plant can be expected in the Austrian situation.

The relation between inhabitants and actual pe-loading as well as the relation between the actual pe-loading and design capacity expressed as pe varies in a way that 80% of the treatment plants lie in the range 0.4 to 0.9. The average values that can be assumed as standard values for estimations of the pe-loading are 0.63 and 0.64 respectively.

Effluent loads

If no data on effluent loads exist they can be estimated based on influent loads (measured or estimated) and typical removal rates. In the following the data set of treatment plants was used to derive those typical removal rates for nitrogen and phosphorus based on
information on specific volume of the aeration tank and treatment target (carbon removal only = C-wwtp, nitrification = N-wwtp, nitrification/denitrification = ND-wwtp, phosphorus removal = P-wwtp).

Figure 4 shows the relation between nitrogen removal rates and the available volume of the aeration tank per design capacity expressed as pe. The following conclusions can be drawn.

- A nitrogen removal of more than 60% can be expected if the specific volume of the aeration tanks is more than 65 l/pe. The removal rate for nitrogen shows an increasing tendency with increasing specific aeration tank volume. For treatment plants designed for nitrification/denitrification an average removal rate of 80% N as yearly average can be expected.
- The nitrogen removal rates for treatment plants designed for carbon removal or nitrification only vary in a wide range. No relation to specific aeration tank volume can be seen. For treatment plants designed for carbon removal only, an average removal of nitrogen of 35% has been observed. This is significantly more than is removed by excess sludge. Partial nitrification and denitrification can be expected.
- For treatment plants designed for nitrification an average removal rate of 50% was observed. Again partial denitrification happens in most of these cases as well.
Phosphorus evaluation of treatment plant data in respect of removal rates can only be done for treatment plants with additional P-removal (P-precipitation and/or bio-P). Treatment plants without P-removal hardly exist in Austria anymore, thus no representative data set was obtained. On the basis of information from the literature a removal of P of 0.6 g/(pe.d) can be assumed. For treatment plants with P-removal two approaches can be used. Either removal rates as a percentage of the influent load can be used or the effluent load is calculated based on estimated effluent concentrations and the discharge volume. The evaluation of the data set from treatment plants showed that both approaches lead to the same variation of results. In respect of removal rates an average value of 85% P-removal was obtained. In respect of typical effluent concentrations an average value of 0.75 can be assumed. In both cases the variance of results is relatively small. 90% of the treatment plants lie within a range of ±10% of these values.

Validation of estimations based on standard values

Influential loads

For validation of the approach for load estimation based on standard values a data set of 29 treatment plants has been used. The following assumptions have been made in order to calculate influent loads based on different basic information and standard values and to compare the results of this estimation with the measured loads:

1. Only the design capacity (pe) of a treatment plant is known: the influent loads to the treatment plants are calculated based on an average loading of 63% of the design capacity and specific loads of 8.8 g N/(pe.d) and 1.5 g P/(pe.d).
2. Design capacity and connected inhabitants are known: an average pe-loading of the treatment plant is calculated from the average of 0.63 of the design capacity and 1/0.64 of the connected inhabitants. The N and P influent loads are calculated based on the formulas derived from Figures 1 and 2: g N/(pe.d) = 4.5 (inh/pe) + 6.5 and g P/(pe.d) = 0.3 (inh/pe) + 1.3.
3. The BOD-influent load (actual pe-load) is known from measurements: N and P loads can be estimated based on specific of 8.8 g N/(pe.d) and 1.5 g P/(pe.d).
4. The nitrogen or the phosphorus influent loads are known from measurements: phosphorus or nitrogen loads can be estimated based on the relation of N:P = 6:1 (= 8.8 gN/d / 1.5 gP/d).
5. The BOD-influent load (actual pe-load) and the connected inhabitants are known: N and P influent loads can be estimated based on the formulas derived from Figures 1 and 2: g N/(pe.d) = 4.5 (inh/pe) + 6.5 and g P/(pe.d) = 0.3 (inh/pe) + 1.3.
Table 1 shows the deviations between measured influent loads and the loads that were estimated based on the different assumptions specified above. Deviations are expressed as average deviation of all treatment plants and as standard deviation of the deviation for single treatment plants.

<table>
<thead>
<tr>
<th>Assumed basic information:</th>
<th>Average ± standard deviation</th>
<th>Average ± standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. design load</td>
<td>0.2 ± 3.1 g N/(pe.d)</td>
<td>0.0 ± 0.6 g P/(pe.d)</td>
</tr>
<tr>
<td>2. design load and inhabitants</td>
<td>−0.2 ± 2.5 g N/(pe.d)</td>
<td>0.0 ± 0.5 g P/(pe.d)</td>
</tr>
<tr>
<td>3. BOD load</td>
<td>−0.7 ± 1.7 g N/(pe.d)</td>
<td>−0.1 ± 0.2 g P/(pe.d)</td>
</tr>
<tr>
<td>4. N or P load</td>
<td>0.1 ± 1.7 g N/(pe.d)</td>
<td>0.0 ± 0.3 g P/(pe.d)</td>
</tr>
<tr>
<td>5. BOD load and inhabitants</td>
<td>−0.8 ± 1.9 g N/(pe.d)</td>
<td>−0.1 ± 0.2 g P/(pe.d)</td>
</tr>
<tr>
<td>Average of measured loads</td>
<td>9.5 g N/(pe.d)</td>
<td>1.6 g P/(pe.d)</td>
</tr>
</tbody>
</table>

Table 1 shows the deviations between measured influent loads and the loads that were estimated based on the assumptions specified above. The table shows the average deviation of the whole set of treatment plants as well as the standard deviation of the deviations for single treatment plants. For comparison the absolute values of the measured loads are shown as well.

It can be seen that the average deviation between estimated and measured values for the whole set of treatment plants is relatively small (≤10% of total measured load) for all different basic assumptions. For single treatment plants the deviation may be much higher (20–40%). Estimations are significantly better if at least one from BOD-load, P-load or the N-load in the influent is known.

Effluent loads

For estimation of effluent loads the same assumptions for the estimation of influent loads have been used as described before. Based on this estimated influent load, effluent loads have been estimated and compared with the measured effluent loads. For estimation of the effluent loads elimination rates for nitrogen and phosphorus have been assumed dependent on the treatment target of the plant. For treatment plants designed for carbon removal only, elimination rates for nitrogen of 35% have been assumed; for treatment plants with nitrification 50% and for plants with nitrification/denitrification of 80%. For plants operated with additional P-removal, removal rates of 85% have been assumed. For plants without additional P-removal, the removal was estimated with 0.6 g P/(pe.d).

Table 2 shows the average deviations between estimated and measured values as well as the standard deviation of the deviation of single treatment plants and for comparison the absolute value of the average of the measured effluent loads. Again the estimations based on different basic assumptions specified above are compared.

Again the estimation for all treatment plants fits the measured value well. The deviations are less than 13% of the measured values. For single treatment plants the deviations might be very high (up to more than 70% to the measured value). This result is independent of the basic information that has been used for estimation of influent loads.

Table 2 shows the deviations between measured effluent loads and the loads that were estimated based on the different assumptions as specified above. Deviations are expressed as average deviation of all treatment plants as well as standard deviation of the deviation for single treatment plants.

<table>
<thead>
<tr>
<th>Assumed basic information:</th>
<th>Average ± standard deviation</th>
<th>Average ± standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. design load</td>
<td>0.1 ± 1.3 g N/(pe.d)</td>
<td>−0.01 ± 0.17 g P/(pe.d)</td>
</tr>
<tr>
<td>2. design load and inhabitants</td>
<td>0.0 ± 1.2 g N/(pe.d)</td>
<td>0.00 ± 0.16 g P/(pe.d)</td>
</tr>
<tr>
<td>3. BOD load</td>
<td>0.1 ± 1.3 g N/(pe.d)</td>
<td>−0.03 ± 0.15 g P/(pe.d)</td>
</tr>
<tr>
<td>4. N or P load</td>
<td>0.3 ± 1.3 g N/(pe.d)</td>
<td>−0.01 ± 0.16 g P/(pe.d)</td>
</tr>
<tr>
<td>5. BOD load and inhabitants</td>
<td>0.0 ± 1.3 g N/(pe.d)</td>
<td>−0.03 ± 0.15 g P/(pe.d)</td>
</tr>
<tr>
<td>Average of measured loads</td>
<td>2.4 g N/(pe.d)</td>
<td>0.25 g P/(pe.d)</td>
</tr>
</tbody>
</table>
loads. An estimate based on the design capacity and treatment target only has the same accuracy as an estimate based on measured BOD-loads in the influent and the treatment target of the plant.

If the average estimation for 29 treatment plants fits the measured values well and the estimations for single plants do not fit, the question rises how many plants have to be considered together in order to achieve reliable results. Therefore clusters of different numbers of treatment plants have been formed and the deviation between estimated and measured values for these different clusters has been calculated. Figure 5 shows these calculations, for example of BOD-load and connected inhabitants as basic data for the calculation of the effluent loads. It clearly can be demonstrated that the deviation decreases with the increasing number of plants considered together in a cluster. If we take more than 10 plants together (e.g. of a river basin or a region) the deviation of these calculations compared with measurements can be expected to stay below ±20% in 90% of the cases.

Finally, for the whole of Austria an estimate only based on the design capacity and design targets (with or without nitrification/denitrification or P-removal) as well as standard values derived above was done. The calculations in most of the cases fitted very well with the reported data from the different federal states. For the whole Austria (without Vienna) our own estimations matched official data from authorities with a deviation of less than 10% for N and P in influent and effluent. Details are published in Lindtner and Zessner (2003).

**Conclusions**

In order to obtain completed data sets on yearly N and P influent and effluent loads of wastewater treatment plants in catchments, regions or countries it will be necessary in many cases to make estimations for treatment plants, where no measured data exist.

In this paper standard values for N and P influent loads have been derived. As average values for municipal wastewater (contributions from household and industry) this leads to specific influent loads of 1.5 g P/(pe.d) and 8.8 g N/(pe.d). Further relations between actual loadings and design capacity and between connected inhabitants and actual loadings as well as nutrient elimination rates are presented. All these relations may vary in a wide range.

If averages of relations of different parameters are used as standard values for estimation of influent or effluent loads, deviations between estimates and measured values

---

**Figure 5** Deviation of estimated from measured specific nitrogen loads dependent on the number of treatment plants considered together in a cluster (estimations of influent loads were based on BOD-load in the influent and connected inhabitants)
may be significant for single treatment plants. Nevertheless, if estimates are done for a higher number of plants together, the reliability of estimates increases significantly. If more than 10 plants are considered together the expected deviation between estimations and measurements stays beyond ±20% for the estimation of yearly effluent loads.

Estimates of influent or effluent loads will never be able to replace measurements at the different treatment plants. But for regional studies estimates based on the method presented are an efficient tool to complete data sets and to check the plausibility of existing data.

References

