



## Process measurement technology for N and P degradation

In the wake of → *advanced wastewater treatment*, new treatment methods emerged for the parameters → *nitrogen and phosphorus*. Today, due to ever increasing costs, the focus is increasingly on the → *economic use of energy and auxiliary materials*. → *Control technology* alone cannot cope with this challenge. Targeted interventions in the treatment processes, aimed at achieving long-term cost reductions, can only succeed with the help of integrated → *process measurement technology*. On the basis of the → *nitrogen and phosphorus balance in accordance with ATV-DVWK*, this document examines the right process measurement instruments for each individual treatment stage.



**Author:**  
**Uwe Karg**

- Diplom-Ingenieur, chemistry
- Application process measurement technology,  
HACH LANGE



**LANGE** 

# The nitrogen balance in municipal wastewater

## General

Nitrogen is present in wastewater in a variety of compounds, whose properties differ widely. When they are discharged into surface waters, these compounds can deplete the oxygen content of the water and have a toxic effect on fish or serve as a nutrient. It is therefore important to know the composition of the nitrogen compounds in municipal wastewater and how they change during the various wastewater treatment stages.

Additional loads may be imposed by, for example, the sludge liquor (process water) formed during sludge treatment (thickener, mechanical dewatering), or a high level of dilution by infiltration water, which can bring about a reduction in the nitrogen concentration.

In municipal wastewater, human excretions are the main contributors of nitrogen (N). Most of the nitrogen is in the form of urea, which is a constituent of urine. The average amount of nitrogen excreted per person per day is about 11 g. The nitrogen concentration in raw municipal wastewater, expressed as TKN (organic nitrogen +

$\text{NH}_4\text{-N}$ ), is between 50 and 60 mg/l, whereby the  $\text{NH}_4\text{-N}$  content is greater than the proportion of organic nitrogen.

## Inflow to sewage treatment plant

Assuming an average daily inflow of 150 l wastewater and 50 l infiltration water per head of population, the calculated concentration of N per inhabitant is 55 mg/l [1], [2]. Fig. 1, (1). In practice, the nitrogen concentrations are sometimes lower. This is usually attributable to a large volume of infiltration water or a large proportion of industrial wastewater. Urea and other organic nitrogen (org. N) start to degrade to ammonium nitrogen ( $\text{NH}_4\text{-N}$ ) in the sewers. This conversion is referred to as ammonification. The longer the flow path to the sewage treatment plant, the greater the degree of ammonification.

→ See page 8: EVITA INSITU 4100

## After the mechanical treatment stage

The process of ammonification continues during the mechanical treatment stage, so that even more organic nitrogen is converted to  $\text{NH}_4\text{-N}$ . The sludge that settles out during the primary treatment contains about 5 mg/l N, which has therefore been removed from the wastewater. Fig. 1, (2).

→ See page 8: EVITA INSITU 4100, AMTAX sc

## After the biological treatment stage (carbon degradation only)

Virtually all the nitrogen is now present as  $\text{NH}_4\text{-N}$  and is strongly oxygen depleting. In the biological treatment stage, organic material is converted into bacterial mass and drawn off as excess sludge. About 10 mg/l N are needed in order to form this biomass and are removed from the water at this point. Fig. 1, (3).

## After the nitrification stage

In the aeration tank,  $\text{NH}_4\text{-N}$  is oxidised to nitrite ( $\text{NO}_2\text{-N}$ ) and then to nitrate ( $\text{NO}_3\text{-N}$ ) in the presence of an abundance of oxygen. The nitrate acts as a nutrient in surface waters. This also occurs to a similar extent in low-rate trickling filters and rotating biological contactors. This process is called nitrification or nitrogen oxidation. If the sludge has aged sufficiently or the  $\text{BOD}_5$  sludge loading is low and the limiting conditions are favourable, the  $\text{NH}_4\text{-N}$  content in the outflow is less than 3 mg/l, and usually less than 1 mg/l. The N balance in the sludge changes only slightly if the oxygen concentration in the aeration tank exceeds 1 mg/l. Fig. 1, (4).

→ See page 8: EVITA INSITU 4100, AMTAX sc, NH4D sc

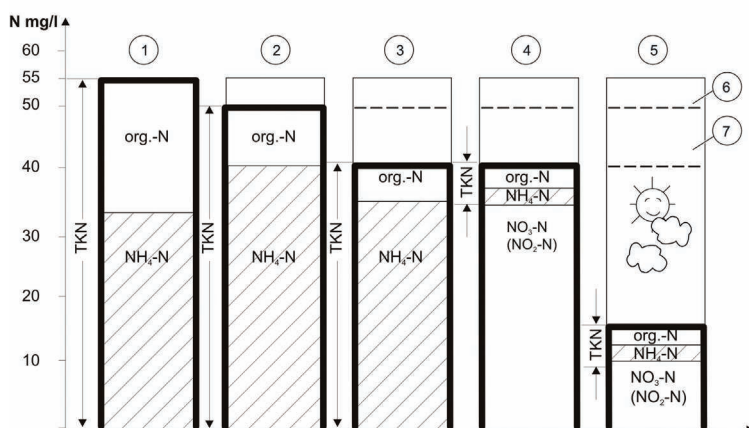


Fig. 1: Nitrogen balance in wastewater [2]

- 1 Raw wastewater
  - 2 Mechanical treatment
  - 3 Biological (carbon degradation only)
  - 4 Biological (with nitrification)
  - 5 Biological (with denitrification)
  - 6 Primary sludge
  - 7 Excess sludge
- /ExD = per inhabitant per day

### After denitrification

In non-aerated (anoxic) tanks or zones, the bacteria are no longer supplied with oxygen and are therefore forced to absorb nitrate ( $\text{NO}_3\text{-N}$ ), which they break down to make oxygen available for respiration. They emit the nitrogen to the water as gas ( $\text{N}_2$ ), which escapes to the air. This process is known as denitrification. Readily degradable carbon compounds play an important role in this, as they are either directly respired or adsorbed, partially incorporated and subsequently processed. Fig. 1, (5).

→ See page 8: AMTAX sc, NITRATAX sc / plus sc

### TKN (Kjeldahl nitrogen)

This is the sum of the organic nitrogen and ammonium-nitrogen (org. N +  $\text{NH}_4\text{-N}$ ). It is of interest with regard to the nitrogen load in raw wastewater or after mechanical treatment.

### Inorganic nitrogen ( $\text{N}_{\text{inorg}}$ )

According to the Wastewater Charges Act (AbwAG), dischargers of wastewater into surface waters must pay a charge for the total discharged nitrogen. Inorganic nitrogen is defined as the sum of  $\text{NH}_4\text{-N}$ ,  $\text{NO}_3\text{-N}$  and  $\text{NO}_2\text{-N}$  – i.e. organic nitrogen is not included. Efficient nitrogen elimination can reduce  $\text{N}_{\text{inorg}}$  below 12 mg/l.

→ See page 8: AMTAX sc, NITRATAX plus sc / clear sc

### Total nitrogen (TN)

To distinguish this from  $\text{N}_{\text{inorg}}$  in the outflow, the sum of organic and inorganic nitrogen is referred to as total nitrogen. The measurement is especially important in the inflow, where the content of organic nitrogen (org. N) can be 20 mg/l or more.

## Optimisation of the biological treatment stage

An example from a sewage treatment plant shows how control measures can have a decisive influence on degradation processes and how savings in wastewater charges can offset the investment costs.

### Starting situation

The wastewater in the inflow to the sewage plant in Markt Schwarzenfeld is a major challenge for the treatment process. The BOD corresponds to a population equivalent (PE) of about 14,000, the nitrogen load corresponds to a PE of about 20,000, and the phosphorus load corresponds

to a PE of about 25,000. The irregular composition of the wastewater is caused by pretreated wastewater from a milk processor. The pretreatment stage releases relatively little BOD, but more than 50 % of the total nitrogen load in the sewage treatment plant inflow. A positive secondary effect is that the water is warm, so that the water temperature in the aeration tank is always above 11 °C. (Fig. 2). After the mechanical treatment in the sewage treatment plant, unfavourable flow conditions in the flow splitter unit the waste water reaches the upstream



Fig. 2: Aeration tank in Markt Schwarzenfeld.

# Perfect aeration through process measurement technology



Fig. 3: Operations manager Thomas Hutz regularly checks the new annular piston valves.

## Markt Schwarzenfeld sewage treatment plant

Technical data:	
BOD	14,000 PE
N	20,000 PE
P	25,000 PE
Qt	3,500 m <sup>3</sup> /d
Qm	10,000 m <sup>3</sup> /d
Aeration tank	8,100 m <sup>3</sup>
Secondary settlement	2 × 1,800 m <sup>3</sup>

Fig. 4: The technical data of the sewage treatment plant

denitrification stages of the 2-channel system in the ratio of 70:30. Furthermore the minimal dwell times and low BOD values prevent efficient denitrification from occurring.

In the following aerated section, a single oxygen line supplies the unequal volumes of wastewater in the two channels with equal amounts of oxygen, with differences of up to 5 mg/l O<sub>2</sub>. The consequence: a total nitrogen value of from 12 to 18 mg/l N in the outflow and a specific energy consumption of 0.40 kWh/m<sup>3</sup> wastewater.

### Today

The composition of the wastewater could not be influenced, of course, but simple structural changes to the flow splitter unit ensure that the wastewater is now evenly distributed over the two channels. The change from upstream denitrification to intermittent operation generates much greater denitrification capacity, so that effective nitrogen degradation takes place during long non-aerated phases, despite the shortage of carbon. Separate oxygen

lines and 2 annular piston valves (Fig. 3) enable a fuzzy controller (an intelligent, self-learning control system) to regulate the oxygen supply in response to the loading.

ELO Consult GmbH is jointly responsible for all these changes.

### No control without process measurement technology

Probes measure the oxygen content in both channels. Ammonium and nitrate are continuously determined in the aeration tank outflow (Fig. 5, plant diagram). The control system can only function effectively thanks to the direct feedback of the measured values from these devices.

### How does a fuzzy controller function?

The time-course curves of 27 and 28 June 2007 (Fig. 5) provide a good insight into differences to time-based and 2-point control systems. A purely time-based control system works on the basis of fixed switch-on and switch-off times, fully independently of the

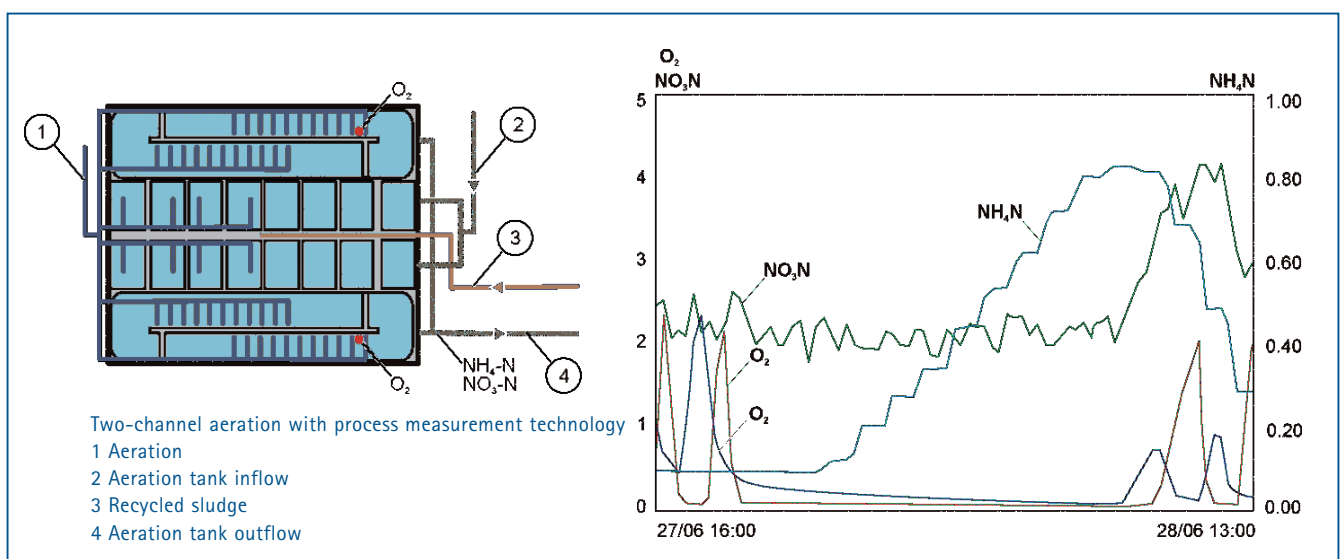


Fig. 5: The oxygen content is determined separately in each channel. Ammonium and nitrate are determined together in the outflow from the biological treatment stage (plant diagram). On the basis of these measured values, the fuzzy controller works out the most economically efficient aeration strategy (diagram).

real-time load situation. The 2-point control system switches on when an upper limit value for ammonium is exceeded and switches off again when the ammonium content falls below a lower limit value (and vice-versa for the parameter nitrate). These limit values are fixed, irrespective of the real-time plant load, and are therefore rarely the ideal switching points. A fuzzy controller takes account of not only the absolute measured value but also the increase in concentration per unit of time (gradient of the time-course curve). In the late evening of 27 June (Fig. 5) the controller switched off the aeration of both channels. However, the ammonium concentration increased very slowly. The nitrate content was very low, at around 2 mg/l NO<sub>3</sub>-N. To save energy, the fuzzy controller now made use of the maximum switch-off time and waited until the next day before it switched on the aeration alternatingly when the concentration reached about 0.8 mg/l NH<sub>4</sub>-N. This alternating method of operation avoids electricity consumption peaks, so that punitive electricity charges are avoided.

### The result:

30 % lower energy costs (from 0.40 kWh/m<sup>3</sup> to 0.28 kWh/m<sup>3</sup> wastewater); < 5 mg/l N in the outflow and a COD below 30 mg/l are impressive figures that clearly express the efficiency of this control system. The cooperation between the Markt Schwarzenfeld sewage treatment plant and ELO Consult GmbH is therefore yielding a long-lasting payoff. In actual fact, the overall cost of the system optimisation was almost zero, as the following list of financial items shows (Fig. 7).

The successful reduction in nitrogen levels by more than 20 % resulted in a repayment of the wastewater charge, which covered about 85 % of the investment costs. A secondary effect of this optimisation measure is that improved biological phosphorus elimination brought about a 50 % reduction in both P<sub>tot</sub> and COD!

### Financing

Investition	-120,158 €
Repayment 2001*	9,806 €
Repayment 2002*	40,388 €
Repayment 2003*	28,676 €
Repayment 2004*	23,368 €
<b>Interim balance</b>	<b>-17,920 €</b>
Annual energy savings approx.	14,600 €
Reduction in wastewater charge	23,450 €

\*through nitrogen reduction of more than 20 %

Fig. 7: Zero-cost optimisation thanks to repayment of wastewater charges

### Performance data

Parameter	Before	After
N <sub>tot</sub> (mg/l)	12-18	<5
COD (mg/l)	50	20-30
P <sub>tot</sub> (mg/l)	2	1
Energy consumption (kWh/m <sup>3</sup> )	0.40	0.28

Fig. 8: The performance data confirm the impressive balance

### ELO Consult GmbH

Manfred Beck (Managing Director)

manfred.beck@elo-consult.de

Tel.: +49 (0) 94 05 / 95 55-20

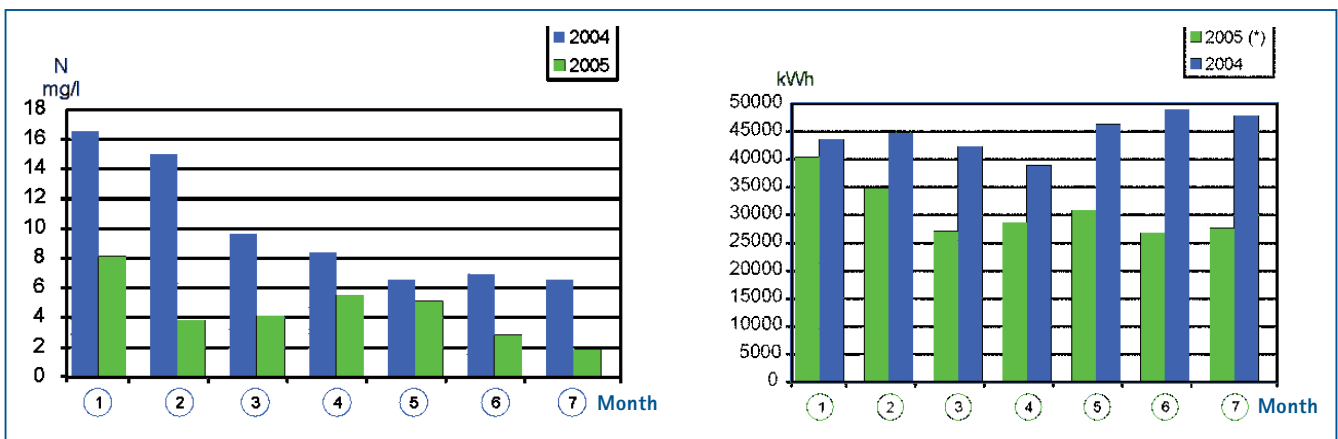


Fig. 6: Clear reduction in nitrogen load in the first seven months of 2004/2005.

At the same time, energy consumption was also reduced. (\*) Calculated on the basis of the wastewater volume in 2004.

# The phosphorus balance in municipal wastewater

## General

In nature, phosphorus (P) only occurs in the form of chemical compounds. The most common is in the form of ortho-phosphates. The phosphorus balance of dissolved phosphorus compounds in water can only be calculated by converting the measured values so that they are expressed in terms of phosphorus. The phosphates discharged into surface waters act as plant nutrients. Fig. 9 shows the forms in which phosphorus occurs in municipal wastewater and how the phosphorus content is reduced during the individual wastewater treatment stages. Potential additional loads e.g. from sludge liquor formed during sludge treatment or mechanical sludge dewatering are not taken into consideration, nor is the problem of phosphorus that redissolves when the excess sludge becomes anaerobic. High levels of dilution due to infiltration water, which can reduce the phosphorus concentration, are also ignored in this balance calculation. These influencing factors can vary from plant to plant and would complicate this simple representation.

Most of the phosphorus in municipal wastewater derives from detergents, household cleaners and human excretions. It is calculated that the daily phosphorus load per head of population is about 1.8 g. The concentration of phosphorus in wastewater has decreased considerably in recent years and is currently between 8.0 and 12.5 mg/l P in municipal and raw wastewater. If no specific wastewater study results are available, the calculations for a sewage treatment plant can be carried out assuming an average concentration of 9 mg/l P [1], [3].

## Sewage treatment plant inflow

Assuming an average daily inflow of 150 l wastewater and 50 l infiltration water per head of population, the calculated concentration of P per inhabitant is 9.0 mg/l P. In practice the phosphorus concentrations are often lower. This is usually attributable to an above-average volume of infiltration water or a large proportion of industrial wastewater. Fig. 9, (1).

→ See page 8: EVITA INSITU 4100

## After the mechanical treatment stage

The bonded phosphorus in the screenings and primary sludge is equivalent to a phosphorus content of about 1.0 mg/l phosphorus, which is removed from the wastewater. Optimal mechanical treatment (e.g. sieve screening) can remove even more phosphorus. Fig. 9, (2).

→ See page 8: EVITA INSITU 4100, PHOSPHAX sc

## After the biological treatment stage (carbon degradation only)

During biological treatment in the aeration tank, about 2.0 mg/l P are bound up in the excess sludge. This also occurs to a similar extent in low-rate trickling filters and rotating biological contactors. Higher levels of efficiency are usually attributable to increased removal of bio-P. Fig. 9, (3).

→ See page 8: EVITA INSITU 4100, PHOSPHAX sc

## After the biological treatment stage (with bio-P)

At higher levels of removal of biological phosphorus (bio-P), which are almost always associated with denitrification, an additional 4 mg/l  $P_{tot}$  can be removed in the excess sludge. Under favourable operating conditions, and using selective bio-P measures, even greater reductions are achievable. Fig. 9, (4).

→ See page 8: EVITA INSITU 4100, PHOSPHAX sc

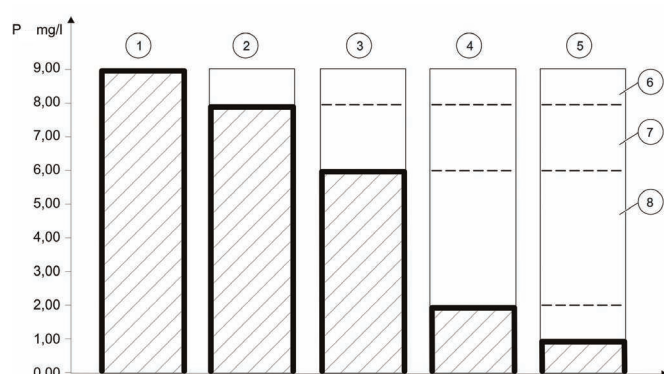


Fig. 9: Phosphorus balance in wastewater [3]

1 Rw wastewater

2 Mechanical treatment

3 Biological (carbon degradation only)

4 Biological (with bio-P)

5 Precipitation with Fe/Al

6 Primary sludge

7 Excess sludge

8 Excess sludge with bio-P

### After the chemical precipitation stage

Only a small amount of phosphorus remains for removal by chemical precipitation. If the various available process options for precipitating phosphate are used properly with the available choice of precipitants, outflow values below  $P_{\text{tot}} = 1.0 \text{ mg/l}$  can be achieved. Sludge volumes can be expected to increase by 20 to 30 %, irrespective of which precipitation method is used. If contact filtration is carried out, values below  $0.3 \text{ mg/l}$  can be achieved. Fig. 9, (5).

→ See page 8: EVITA INSITU 4100, PHOSPHAX sc

### Total phosphorus in the outflow

According to the values specified in the the Wastewater Ordinance, municipalities with a PE above 10,000 must ensure that the value of  $P_{\text{tot}}$  in the outflow never exceeds  $2 \text{ mg/l}$ ; if the PE exceeds 100,000, the equivalent value is  $1 \text{ mg/l}$ .

→ See page 8: PHOSPHAX sigma

### Controlled addition of precipitant

Fig. 10 shows the highly effective control strategy of a large sewage treatment plant in Southern Germany. In general it can be said that the advantages of well controlled addition of precipitant increase in direct proportion to the degree of fluctuation and the magnitude of the P load. "As much as necessary, but as little as possible" – this motto provides for maximum reliability allied to economically efficient handling of the precipitant.

#### How the control system functions (Fig. 10)

To determine the loading, first of all the flow (Q) and the orthophosphate concentration (1) in the inflow to the biological treatment stage are measured. The product of the two values (= precipitable load) is used to control the addition of the precipitant (2) to the recycled sludge. The success at the end of the tank is reflected in the time-course curve (3), which shows the residual orthophosphate concentration after biological absorption and chemical precipitation. Depending on the final residue, the control system corrects the amount of precipitant to be added. Finally, a total phosphorus process photometer (4) monitors actual parameter in the outflow of the sewage treatment plant. Here, too, there is the option of correcting the addition of the precipitant. The adjustment to the current situation could hardly be carried out in a more targeted manner.

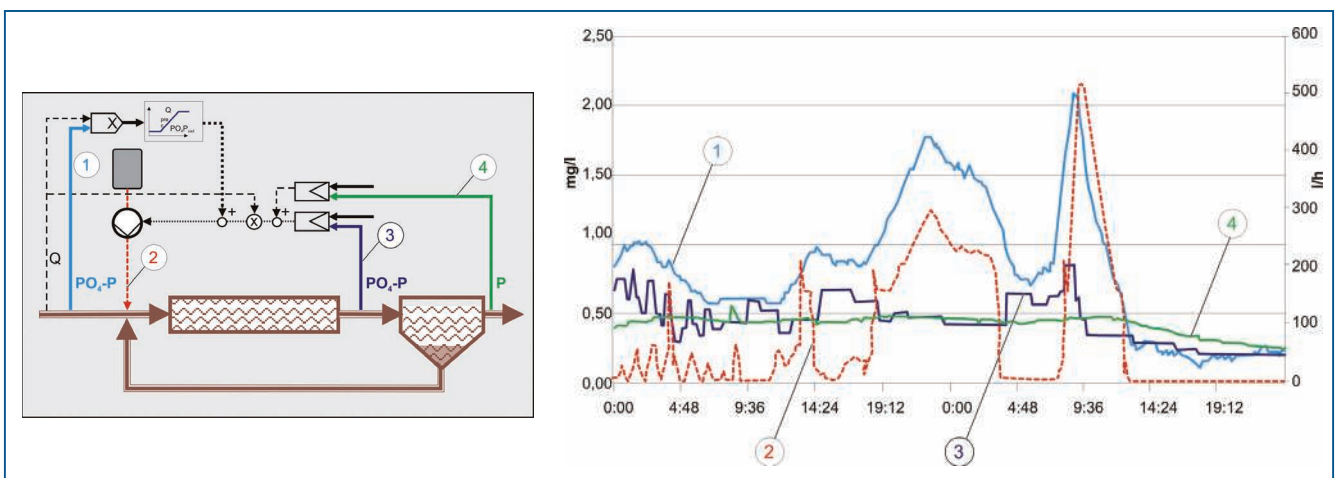


Fig. 10: Optimal control strategy for chemical precipitation of phosphate

1 Orthophosphate concentration before precipitation  
2 Controlled quantity of precipitant

3 Orthophosphate concentration after precipitation  
4 Total phosphorus concentration in the outflow

# Process measurement technology for ammonium, nitrate and phosphate

## NH4D sc ammonium process probe

Affordably priced process probe for continuous direct in-fluid determination of the ammonium concentration. CARTRICAL® cartridge with three mutually calibrated electrodes. Evaluation and operation through SC 100 or SC 1000 controller. Measurement method: ISE (ion-selective electrodes for NH<sub>4</sub>-N and potassium); measuring range: 0.2–1,000 mg/l NH<sub>4</sub>-N

## AMTAX sc ammonium process photometer

High-precision process meter for continuous determination of the ammonium concentration. Sample preparation using integrated filter probe. Isolated, weatherproof enclosure, outdoor or indoor installation. Evaluation and operation through SC 1000 controller. Measurement method: GSE (gas-sensitive electrode); measuring range: 0.05–20 mg/l NH<sub>4</sub>-N

## EVITA INSITU 4100 sc ammonium sensor

Precise ammonium sensor for continuous sampling-free direct in-fluid determination of the ammonium-nitrogen concentration. Patented ion filter. Evaluation and operation through SC 1000 controller with GSM module. Measurement method: photometric measurement by the indophenol blue method; measuring range: 0...20 mg/l NH<sub>4</sub>-N

## PHOSPHAX sc orthophosphate process photometer

Highly precise process photometer for the continuous determination of orthophosphate concentration. The sample is prepared using an integrated filter probe. Insulated weatherproof housing for outdoor or indoor installation. Evaluation and operation through SC 1000 controller. Measurement method: photometric (yellow method); measuring range: 0.05–15 mg/l PO<sub>4</sub>-P

## EVITA INSITU 4100 sc orthophosphate sensor

Orthophosphate sensor for continuous sampling-free direct in-fluid determination of orthophosphate concentration. Patented ion filter. Evaluation and operation through SC 1000 controller with GSM module. Measurement method: photometric measurement using the molybdenum blue method; measuring range: 0–6 mg/l PO<sub>4</sub>-P

## PHOSPHAX sigma total phosphorus process photometer

Process photometer for measuring the total phosphorus and orthophosphate concentration in the wastewater (outflow treatment) and cooling water including solids up to 0.5 mm in size. The DIN-equivalent analysis is carried out in about 10 minutes using the molybdenum blue-method. SIGMATAX 2 for sampling and homogenising samples that contain solids.

## NITRATAX plus/clear sc nitrate process probe

Stainless steel process probe for the sampling-free determination of the nitrate and nitrite content. UV absorption measurement, reagent-free. Evaluation and operation through SC 100 or SC 1000 controller. For in-flow installation, a flow-through cell is absolutely necessary. Measuring range (NO<sub>2+3</sub>-N) plus sc: 0.1–100 mg/l; clear sc: 0.5–20 mg/l; sc: 0.1–20 mg/l

## Literature

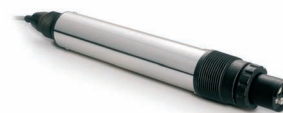
- [1] ATV-DVWK Arbeitsblatt A-131, Bemessung von einstufigen Belebungsanlagen
- [2] ATV-DVWK Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V., Leitfaden Nr. 2-14, Betrieb von Abwasseranlagen, Die Stickstoffbilanz im kommunalen Abwasser 01/2003
- [3] ATV-DVWK Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V., Leitfaden Nr. 2-13, Betrieb von Abwasseranlagen, Die Phosphorbilanz im kommunalen Abwasser 01/2003

## HACH LANGE LTD

Pacific Way  
Salford  
GB-Manchester, M50 1DL  
Tel. +44 (0)161 8721487  
Fax +44 (0)161 8487324  
info@hach-lange.co.uk  
www.hach-lange.co.uk



Phone: (0161) 872 14 87



Process electrode NH4D sc



Process photometer AMTAX sc



Process probe NITRATAX sc

