Control of phosphorus discharges: present situation and trends

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Abstract

The dominating sources of phosphorus in municipal wastewaters are excreta, 1.4 g P/(cap.d) and detergents, 0.6 – 2 g P/(cap.d). Detergent phosphorus can be substituted by nitrilotriacetic acid or zeolites, but if a substantial reduction of phosphorus in municipal waters is to be achieved, modifying the treatment process is necessary. Primary, treatment by sedimentation removes only 10–15% and secondary biological treatment 20–30% of the phosphorus in waste water. If chemicals are added to the primary or secondary treatment stage or to a separate chemical stage, phosphorus can be efficiently removed. An effluent level of 0.8–1.5 g P m^{-3} is easily achieved and with a filtration step it is possible to maintain 0.2 g P m^{-3} in the effluent. Different process configurations are discussed. As precipitants, ferrous and ferric salts, alum and lime are widely used. By introducing anaerobic zones in the activated sludge process, it is possible to promote the growth of bacteria which enhance biological phosphorus uptake. This makes it possible to achieve high phosphorus removal without or, at least, with very small chemical additions. Several emerging physical, chemical and biological phosphorus removal processes are discussed. The removal of phosphorus to a level of 0.8–1.5 g P m^{-3} increases cost 10–20% compared with conventional primary secondary treatment. Higher removal efficiencies will rapidly increase the marginal cost per marginal kg P removed.

Introduction

The major phosphorus inputs to receiving waters come from runoff from agricultural land, from domestic and industrial wastewaters and from atmospheric deposition. The reduction of runoff from agricultural land and of atmospheric deposition is a complex problem involving not only technical but also political and administrative implications and is not discussed here. In densely populated regions the dominating phosphorus load on receiving waters originates from municipal wastewaters. The control of these discharges by treatment started 20 years ago and is today a well established technology. In e.g. Sweden, the first country to apply phosphorus control on a large scale, more than 90% of the urban population is connected to wastewater treatment plants with phosphorus removal.

Phosphorus sources and source control

Phosphorus sources

The dominating sources of phosphorus in municipal wastewater are excreta and detergents. Alexander & Stevens (1976) have measured the phosphorus content in excreta and non-detergent household wastes in various countries and found totals between 1.0 and 1.6 g P/(cap.d) with an average of about 1.4 g P/(cap.d).

In North America and Western Europe each person uses an average of 23 kg of household detergents per year (Stumm, 1985). The phosphorus content varies between countries, due to water hardness, regulations and voluntary agreements between detergent producers and authorities. In most countries the P-content of detergents is between 5 and 8.7%. The per capita load of detergent phosphorus can thus vary from as low as 0.65 g P/(cap.d) in a soft water country like Norway (Vråle, 1983) up to about 2 g P/(cap.d) in countries with hard waters. The total phosphorus in municipal wastewaters varies from 2.2 to 4 g P/(cap.d). In Sweden the amount of phosphorus originating from household detergents has been rather constant with only a small decline between 1970 and 1983. However, before 1970 different manufacturers had reduced the amount of phosphates in their detergents in order to comply with authorities. Studies of municipal wastewater treatment plants in Sweden has shown the per capita load of phosphorus to be rather constant between 1975 and 1983 (Krook, 1986).

In urban areas stormwater will transport air deposited phosphorus, excreta from dogs, birds and other wildlife and other surface deposited phosphorus containing wastes to receiving waters. The total phosphorus concentrations in stormwaters are in the range of 0.2–0.6 g P m^{-3} (Malmqvist, 1983). On an annual basis this means a stormwater phosphorus load two orders of magnitude less than the load from untreated wastewater from the same urban area.

Source control

In most countries the phosphate content of detergents is not regulated by official specifications, although many unofficial agreements exist between authorities and producers in several countries to keep the phosphate concentration below certain values.

In the USSR efforts are being made to reduce the content of sodium tripolyphosphate (STP) in synthetic detergents. New synthetic powders in which synthetic zeolites are partially substituted (about 1/3) for STP have been developed and tested. Their production could reduce STP consumption by 20 000 tonnes in 1990.

More drastic efforts have been made in Canada where detergent phosphorus was limited to 2.2% in 1973, and the state of Michigan which in 1977 limited detergent phosphorus to 0.5% (Hartig & Horvath, 1982). In Switzerland phosphates in home laundry detergents were recently banned (Stumm, 1985). Detergent phosphate bans have also been issued in Maryland and the District of Columbia (Booman & Sedlak, 1986) and in Wisconsin where the ban on phosphate laundry detergents went into force on July 1, 1979. The ban was lifted in 1982 (Pallesen *et al.*, 1985). Booman & Sedlak (1978) estimated the ratio of detergent phosphorus to all phosphorus entering the US environment to 2.5%. In total 12% of the phosphorus originated from municipal and industrial point sources.

Maki *et al.* (1984) have reported that numerous case studies indicate that detergent phosphorus bans represent very small changes in phosphorus loading, and no significant water-quality effects have been related to bans. Lee & Jones (1986) conclude that although detergent phosphorus bans generally will not result in an overall improvement in water quality, there may be some situations where a ban may improve the water quality, for instance where a high percentage of the phosphorus entering a receiving water is derived from domestic wastewaters and a substantial percentage of the phosphorus in the domestic wastewaters is derived from detergents. Lenhart & Steinberg (1986) have indicated that the phosphorus reduction in German detergents since 1980 have given beneficial effects on the water quality in Lake Ammersea, Upper Bavaria.

A strategy to meet phosphorus objectives in lakes should consider possible actions to control all sources. Chapra *et al.* (1983) conclude that an optimal phosphorus management strategy for the Great Lakes should include both point and nonpoint source controls, and zoned rather than uniform treatment. Baccini (1985) finds it important to lower the load of phosphorus from land runoff, wastewater and detergents in order to improve the water quality in Swiss lakes.

If phosphates are removed from detergents some substitute has to be added. Several have been tried but the only viable alternatives seem to be nitrilotriacetic acid (NTA) and zeolites. Although NTA is biodegradable, NTA removal in biological treatment plants is far from complete. NTA has a strong metal complexing capacity and may therefore not be ecologically safe. Producers and authorities have been cautious to substitue phosphates with NTA, the only country using NTA on a large scale is Canada, using 16 000 tons per annum. Zeolites are considered to be ecologically safe. In Japan detergents have been reformulated and 90% of the detergents are now phosphate free, zeolites being the substitute (Stumm, 1985). A replacement of detergent phosphates will also give increased phosphorus removals at biological wastewater treatment plants as this will give a biodegradable organic carbon to phosphorus ratio in the wastewater closer to the metabolic requirements of bacteria.

Phosphorus control methods

Phosphorus control methods for urban areas include:

- Source control
- Diversion of wastewater
- Control of combined sewer overflows, cross connections and other unintended direct discharges
- Wastewater treatment

Source control related to detergents has been discussed earlier. In rural areas low phosphate detergents in combination with waterless toilet systems may be effective. For wastewaters from urban areas diversion of the wastewater by regional intercepting sewers or tunnels and transport to less sensitive receiving waters has been used in some regions (Flögl & Flögl, 1985). In most cases however, this is not possible and wastewaters have to be treated in order to reduce phosphorus discharges.

If effective phosphorus removal methods are applied at a wastewater treatment plant, then the relative importance of other phosphorus discharges increases. Combined sewer overflows may discharge several percent of the annual wastewater flow untreated to receiving waters. Numerical hydraulic models are helpful tools to estimate the amount of overflows and to evaluate alternative measures which reduce overflows. The amount of phosphorus discharged by overflows may be larger than normally calculated since pollutants are deposited in combined sewers during dry weather flow conditions and flushed during storm events. Lindholm (1984) has estimated the phosphorus content in pipe deposits in four catchments. In three catchments the phosphorus in pipe deposits was estimated to be 10–25% of the annual phosphorus load.

Phosphorus in wastewater may be present in three forms: ortophosphate, polyphosphate, and organic phosphorus. Christensen (1976) summarises the distribution of phosphorus in saw sewage:

- ortophosphate: 50%
- polyphosphate: 30%
- organic phosphorus: 20%

Only a minor part of the phosphorus is contained in the settable particles of the wastewater thus phosphorus removal by primary treatment seldom exceeds 15%. Phosphorus removal methods are therefore based on the transfer of soluble phosphorus to the solid phase followed by solid-liquid separation or regeneration of the solid phase (ion exchange or adsorption). Phosphorus removal methods include:

- chemical precipitation and adsorption of phosphorus by the addition of ferrous, ferric and aluminium compounds or lime
- ion exchange and adsorption (activated alumina)
- biological phosphorus uptake mainly due to nonexchangeable phosphorus
- enhanced biological phosphorus uptake by bacteria

Chemical precipitation for phosphorus removal

Removal principles
As most of the phosphorus in wastewater is soluble, an efficient method to remove phosphorus is to precipitate the phosphorus by chemical precipitation agents and to remove the precipitate from the wastewater by some separation method. Important factors to consider are:

- Choice of precipitation chemicals
- Initial mixing conditions
- Surface charge of precipitated particles
- Flocculation conditions
- Separation methods

With aluminium and iron salts the mechanism for phosphorus removal may be interpreted as precipitation of $AlPO_4$ and $FePO_4$ (Leckie & Stumm, 1970) or as metal-hydroxyphosphate complex (Pöpel, 1967) or as adsorption of phosphates on metal hydroxides (Henriksen, 1963). Arvin & Petersen (1980) have proposed a general model for soluble phosphorus removal.

In lime precipitation the thermodynamically stable calciumphosphate compound is apatite (Stumm & Morgan, 1981) but practical experience show that the expected very low phosphate concentrations are not attained. The bulk of the precipitate is however calcium carbonate. Small amounts of magnesium hydroxide formed at pH 11 and above are important as coagulant aids. In Norway some coastal treatment plants use high magnesium content in seawater to facilitate lime precipitation by adding about 5% seawater to the wastewater (Vråle, 1978; Fergusson & Vråle, 1985). The addition of acids and the stripping of carbon dioxide has been used in Japan in order to avoid the formation of large amounts of calcium carbonate sludge (Annaka, 1980). Rapid mixing is often considered as an important factor for the efficient precipitation of phosphates (Klute, 1985) and special devices have been developed in order to improve mixing conditions. In order to from micro-flocs, the surface charge of the precipitated particles should

not be too high. The surface charge is dependant on the pH-value and thus control of pH is important for efficient coagulation-flocculation, which is confirmed by observations in practise (Ulmgren, 1975; Balmér & Fredriksen, 1975). Arvin (1985) has stated that many observed pH-effects may be misinterpretations since the principal effect of a pH-change is the change in hydrogen-carbonate concentration which Arvin has shown to be of great importance. Besides the control of the surface charge, the design of the flocculation is a major factor for building flocs that can be easily separated (Ødegaard, 1975; Hedberg, 1985; Grohmann, 1985). The suitable floc size distribution is dependant on the separation process which follows. Thus, large flocs are desireable for an efficient sedimentation process, while smaller flocs may be suitable in deep-bed filtration in order to avoid blockage of the surface of the filters (Ødegaard, 1985a). Settling characteristics may be improved by use of polyelectrolytes, which can strengthen and enlarge the flocs.

The most common separation methods are sedimentation, flotation and deep-bed filters. Different modifications of these separation method are common e.g. lamella sedimentation and multi media filters.

Process schemes

Pearse *et al.* (1935) have reviewed the earlier developments of chemical precipitation of wastewater. Several plants in England, Germany and USA used chemical precipitation of wastewater before 1900 with the removal of organics as the main objective. The process was not competitive when efficient biological treatment methods were developed around the turn of the century. In the beginning of the 1930's chemical precipitation was used at some plants in the USA. Since the 1960's however, chemical precipitation has been implemented at an increasing number of plants with the main purpose to remove phosphorus, although other side-effects of chemical precipitation such as the removal of organic material and energy savings are also significant. Different

reviews include Nesbitt (1969), EPA (1976) and WPCF (1983). The main process schemes of chemical precipitation (Fig. 1) are:

- Direct precipitation, involving no biological treatment
- Pre-precipitation, in which chemicals are added before the biological step
- Simultaneously precipitation, in which chemicals are added directly to the biological step
- Post-precipitation, in which chemicals are added after the biological step

Direct precipitation is most widely used in Norway where a considerable number of plants have been built using this concept. The largest one in operation is the Oslo plant with a design capacity of over 3 $m^3 s^{-1}$. Pre-precipitation with alum and ferric salts can often be applied with minor alterations at existing biological treatment plants with primary sedimentation. The process has been tested at many medium and large sized plants in Sweden (Hökervall, 1971) and Finland (Kiiskinen, 1985). It is also possible to use lime for pre-precipitation. The carbon dioxide produced in the biological stage reduces the high pH of the primary effluent (Albertson & Sherwood, 1969).

Simultaneous precipitation, pioneered by Thomas (1972) in Switzerland, is applicable at most existing activated sludge treatment plants. Post-precipitation, early studied by Wuhrmann (1964), is a widely applied in Sweden where over 600 treatment plants of this type have been built (Balmér, 1982).
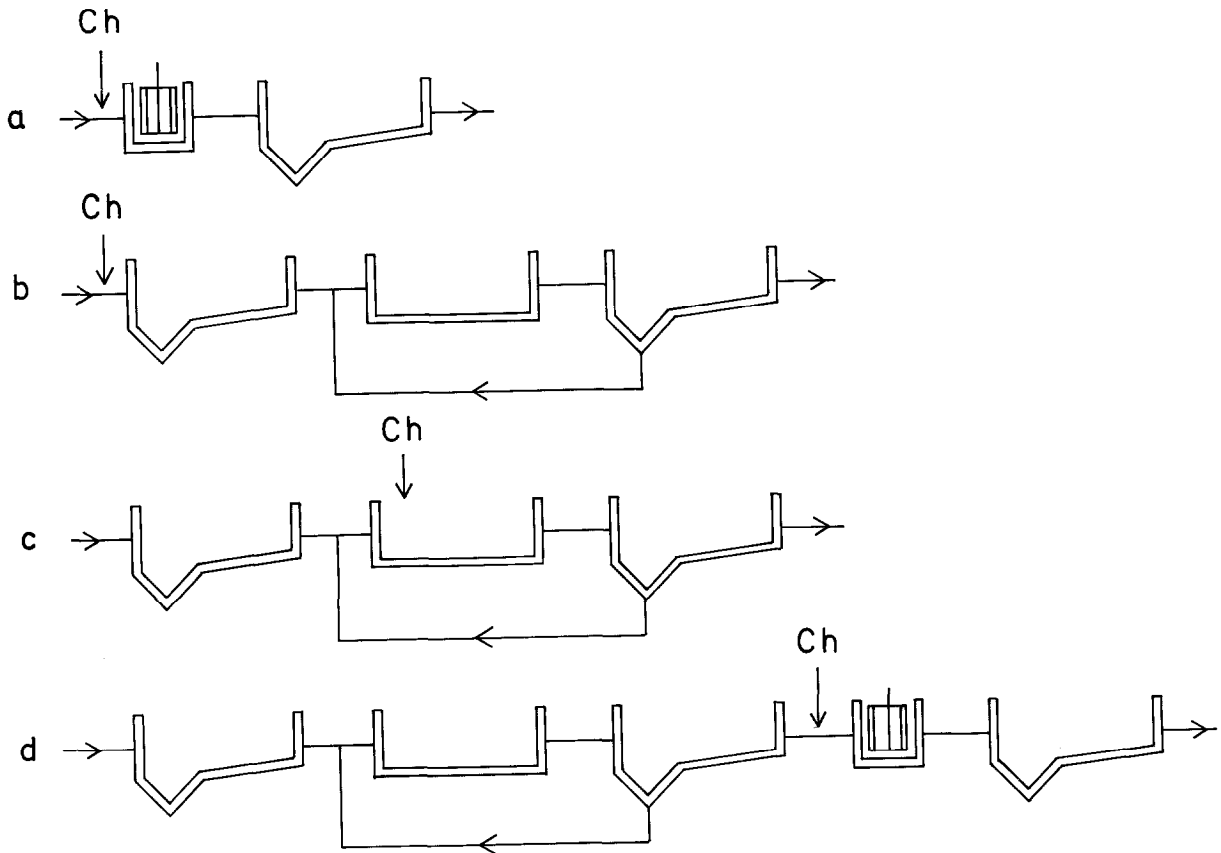

Fig. 1. Process schemes for chemical precipitation a. direct precipitation b. pre-precipitation c. simultaneous precipitation d. post-precipitation. The biological stage shown in activated sludge. In pre- and post-precipitation other biological treatment processes can also be used.
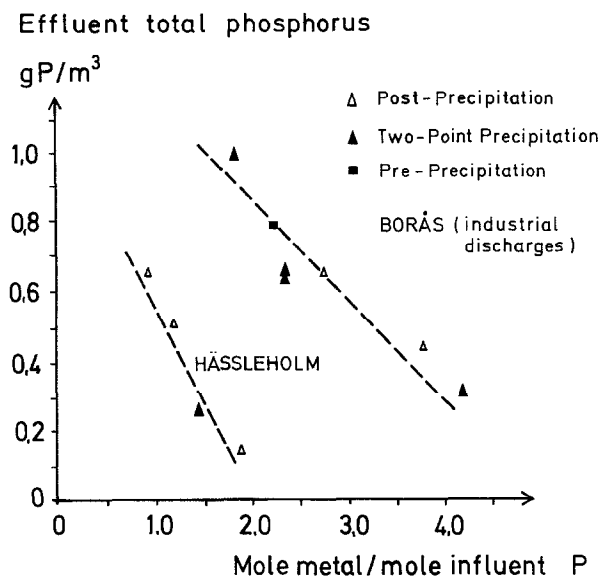
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Effluent total phosphorus

gP/m³

Fig. 2. Effluent total phosphorus concentration versus dose of aluminium or iron salts at two municipal wastewater treatment plants originally built for post-precipitation.

Chemical precipitation plants have now been in operation for 20 years and practical experience have given rise to several modifications of the process schemes outlined above. Two-point chemical addition, recirculation of chemical sludge or both have proved to be advantageous at several plants. Improved phosphorus removal, lowered operation costs and improvements in sludge treatment and handling (Grönquist *et al.*, 1978; Hultman *et al.*, 1984) has been observed with these modified processes.

Chemical precipitation can also be incorporated in simple treatment processes such as oxidation ponds. In Canada it has been demonstrated (Graham & Hunsinger, 1974) that in seasonal retention ponds the whole pond content can be treated with precipitation chemicals before discharge. Balmér & Wik (1978) have reported on successful operation of ponds with continuous addition of chemicals.

Chemical dosages and sludge production

In a large research project in Sweden several plants built according to the post-precipitation

scheme have been carefully studied in different operational modes. From this study Hultman and Nordström (1978) have reported on the effect of dosage of chemicals on effluent total phosphorus. The result of the study can be summarized as:

- No significant difference has been obtained between ferrous, ferric or alum salts, although ferrous salts can not be used efficiently in post-precipitation at pH-values below 8.5.
- The point of addition of the chemicals is of minor importance, although two-point addition seem to be slightly advantageous.
- A linear relationship is normally obtained between the dosage of chemicals expressed as mole metal/mole total influent phosphorus and the total effluent phosphorus concentration (Fig. 2). The slope of this line is dependant on such factors as alkalinity, type of biological treatment, loading of the biological treatment step, hydraulic loading of sedimentation tanks, industrial wastewaters etc.

If low effluent total phosphorus values, e.g. 0.2 g P/m^{-3} are to be attained, Hultman and Nordström (1987) believe that two-point addition is advantageous.

With lime precipitation total effluent phosphorus is mainly a function of pH-value. The lime dose required to achieve a certain pH-value is a linear function of the sum of the molar concentrations of the hydrogen carbonate and ammonium ions in the wastewater (Balmér, 1985).

The addition of precipitating chemicals increases sludge production. With aluminium and iron salts, the increase in sludge total solids can be estimated if the added precipitant is assumed to form $AlPO_4$ and $FePO_4$ respectively and assuming that the surplus of the added precipitants end up as hydroxides. Laboratory data of Veldkamp (1985) and pilot plant data of Balmér & Fredriksen (1975) have shown that these simple models correlate well with experimental results. The increase in sludge solids due to chemical precipitation can be estimated to 20–30% in most cases compared to biological treatment. Reduced effluent suspended solids

losses due to chemical addition can further increase the sludge production at a treatment plant. Sludge digestion can further increase the fraction of chemical sludge. With lime precipitation the bulk of the sludge consists of calcium carbonate. The sludge production is thus closely related to the alkalinity of the wastewater. Using lime significantly increases the amount of sludge solids. With lime precipitation a large proportion of the lime does not dissolve and this adds to the sludge production. The increase compared to biological treatment can vary between 50 and 300%. However, sludges from plants with lime precipitation thicken well, and do not require stabilization and may thus be attractive at small treatment plants. Lime sludges can also be burnt and the lime recovered. Lime recovery is however only practical at large plants.

Operational results

The effluent phosphorus from a wastewater treatment plant is composed of a soluble fraction and a particulate fraction which is associated with the effluent suspended solids. The soluble phosphorus is controlled by the dose of chemicals and the pH. With direct precipitation and post-precipitation, soluble phosphorus levels below 0.1 g $P \, m^{-3}$ can be achieved by careful operation. With pre-precipitation and simultaneous precipitation soluble phosphorus values of 0.1–0.2 g $P \, m^{-3}$ are attainable.

A summary of the effluent phosphorus concentrations of Swedish treatment plants has been compiled by the National Swedish Environmental Protection board (1979) and is reproduced in Table 1.

The higher total effluent phosphorus concentrations from pre-precipitation and simultaneous plants compared with direct precipitation or post-precipitation may be caused by the solubilization of phosphorus due to sludge mineralization, anaerobic conditions in the sedimentation basin and difficulties obtaining low suspended solids concentrations in the activated sludge clarifier effluent. With direct precipitation and post-preci-

Table 1. Average total effluent phosphorus from Swedish waste water treatment plants in 1977.

Type of plant	No. of plants	Effluent phosphorus g $P \, m^{-3}$
Direct precipitation	138	0.70
Pre-precipitation	17	0.98
Simultaneous precipitation	35	1.48
Post-precipitation	554	0.53
Post-precipitation + filtration	16	0.22

pitation the soluble phosphorus concentration is normally low compared with the particulate phosphorus concentration, which implies that the separation efficiency of the sedimentation basin is very important. This is also seen from the improved results when deep-bed filters complement final sedimentation.

With careful control it is possible to achieve a total effluent phosphorus concentration below 0.5 g $P \, m^{-3}$ with all the process configurations discussed here during dry weather flow conditions. However, in the authors opinion, the figures in table 1 quite well reflect the potentials of the different processes.

Trends and emerging technology

If total effluent phosphorus values below 0.2 g $P \, m^{-3}$ are to be achieved, filtration seems to be necessary. A number of Swedish postprecipitation plants also filter the final settler effluent. Filtration has also been employed in combination with simultaneous precipitation (Andersson & Sörensen, 1981). The relatively high soluble phosphorus levels after simultaneous precipitation limit the possibility to achieve very low phosphorus levels with this method. The addition of a filter where precipitation chemicals are added just ahead of the filter (contact filtration) is a promising method. Contact filtration has been used for several years in Sweden (Peterson, 1986) and in Switzerland (Boller, 1984 and Jost, 1986).

If very high effluent qualities are to be achieved

today, it is probably more cost-effective to use pre-precipitation or simultaneous precipitation in combination with filtration or contact filtration, than to use post-precipitation. Post-precipitation still has the advantage of providing very good operational stability.

In the presence of calcium phosphate seed crystals, calcium phosphate can be crystallized from wastewaters on seed crystals if the calcium ion concentration is sufficient and if the pH is not so high that amorphous precipitate is formed in the liquid. This process has been developed in the Netherlands (Eggers & van Dijk, 1986) and in Japan (Joko, 1984). The low sludge production and the attractivity of the sludge as a fertilizer is the main advantages of the process, while effluent phosphorus levels seem to be limited to 1–2 g P m^{-3}. More experience is needed before it is possible to evaluate the cost effectiveness of this process in comparison with established techniques.

Sorption of phosphates on columns of aluminiumoxide can effectively remove phosphate from wastewaters (Brattebø & Ødegaard, 1986). The process has not yet been investigated in a scale that makes technical-economical evaluation possible.

Enhanced biological phosphorus removal

Removal principles

Phosphorus removal by conventional biological treatment is mainly dependant upon the ratio of biodegradable organic carbon (BOD) to phosphorus and the metabolic requirements of the bacteria. Different operational parameters such as solids retention time are also of some importance. Various removal efficiencies are reported in the literature. A survey by Rudolfs (1947), based on averages of twelve wastewater treatment plants in the United States prior to 1947, showed average removals of 75 to 80% for trickling filters and 80 to 90% for activated sludge plants, from wastewater in which the orthophosphate concentration ranged from 1.75 to 4.0 g P m^{-3} and

averaged 2.27. With the introduction of phosphate rich detergents in the 1950's the BOD/P ratio was greatly decreased. Today phosphorus removal efficiencies are therefore lower in biological treatment plants (20–30%).

Early it was demonstrated that bacteria in batch cultures under aerobic conditions can take up more phosphorus than their metabolic requirements. This was later observed for activated sludge in laboratory experiments and at full scale plants, and named 'luxury uptake' (Levin & Shapiro, 1965). Luxury uptake was then reported from many plants. Jenkins (1970) showed that many of those observations could be explained as chemical precipitation and questioned if luxury uptake existed.

Marais et al. (1983) reviewed observations supporting biological mechanisms for excess phosphate removal by bacteria and presented conclusive evidence for enhanced biological phosphorus removal. Marais stated that it was empirically shown that the following conditions must be fulfilled if an enhanced biological phosphorus removal is to be achieved:

– An oxygen and nitrate free zone must be included
– There must be a sufficiently high amount of soluble biodegradable organics supplied to the anaerobic zone from the influent or from anaerobically degraded complex organics
– The bacterial cells must grow under aerobic conditions after the anaerobic zone

The necessary conditions for enhanced biological phosphorus removal are today rather well known although considerable research work is still necessary before the process can be optimized. Marais et al. (1983) have proposed a biochemical model recently detailed by Comeau et al. (1986), that explains most observations. In the anaerobic zone, polyphosphate accumulating organisms (e.g. Acinetobacter) hydrolyze accumulated polyphosphates to use the released bond energy to absorp, complex and store rapidly biodegradable organic material (e.g. acetate) as poly-β-hydroxy-

butyrate within the organisms. In the aerobic zone the stored organic material in the polyphosphate accumulating organisms is used for growth and to synthetize new polyphosphate to be used in the anaerobic zone. In this way the polyphosphate accumulating organisms can efficiently compete with other organisms that have no ability to accumulate phosphate. The mixed liquor suspended solids from the aerobic zone has a high phosphorus content and, in order to avoid release, anaerobic conditions in the settler must be avoided. Phosphorus is removed from the process by the wasted activated sludge which has a high phosphorus content and therefore must be kept under aerobic conditions in order to avoid release of phosphorus.

Arvin & Kristensen (1985) have pointed out that chemical precipitation is an important factor in the treatment of hard waters due to the combined effect of a high concentration of calcium and magnesium ions and the release of phosphates in the anaerobic zone. The role of chemical precipitation may be emphasized by the addition of chemicals such as ferrous iron (Spatzier et al., 1985). Thus, there is a natural link between systems with mainly enchanced biological phosphorus removal and conventional simultaneous precipitations.

Process scheme

Process schemes can be divided in mainstream processes and sidestream processes (Arvin, 1985). A simple principle of the mainstream process is shown in Fig. 3a. The reactor must consist
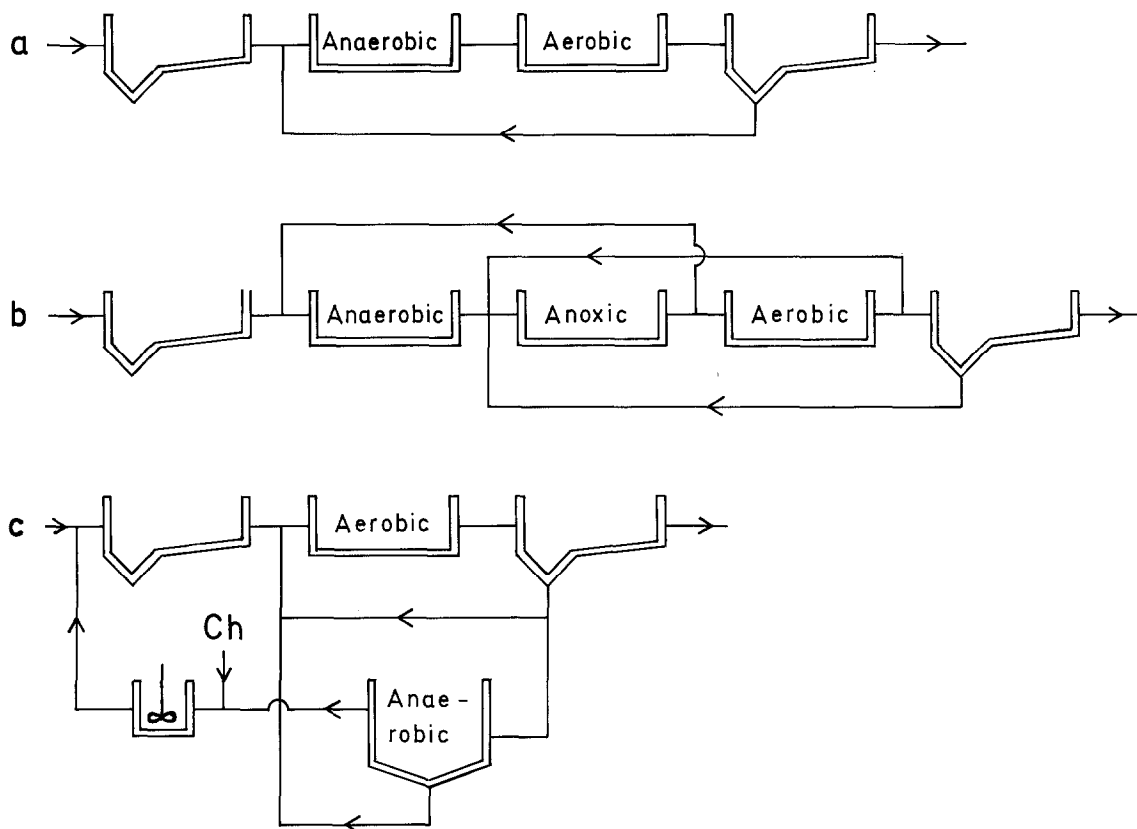

Fig. 3. Process schemes for enhanced biological phosphorus removal. a. simple mainstream process b. mainstream process for phosphorus and nitrogen removal c. side stream process.

of an unaerated and an aerated part. In a system without nitrogen removal the influent wastewater passes an anaerobic zone with a residence time of 1–5 h followed by an aerated zone with a residence time of 2–5 h. It is also possible to achieve both biological phosphorus and nitrogen removal in the same process, Fig. 3b. In addition to the anaerobic zone (without oxygen and nitrate) and the aerobic zone, the system also contains anoxic zones for denitrification. The most studied side-stream process is the Phostrip process (Fig. 3c). In this process phosphorus release is obtained during anaerobic conditions for a fraction of the return sludge in a tank beside the main wastewater stream. Supernatant from the P-stripper is precipitated with lime to remove released phosphorus. The consumption of chemicals is however an order of magnitude less compared to conventional lime precipitation due to the very high phosphorus concentrations in the stripper overflow.

Operational results

As in the case of chemical precipitation it is important to consider both the soluble effluent phosphorus and the phosphorus concentration in the effluent suspended solids when evaluating the treatment efficiency of biological phosphorus removal treatment plants. The soluble phosphorus concentration is often in the range of 0.5–1.0 g $P\,m^{-3}$ (Arvin, 1985) and this is considerably higher than for chemical precipitation. Conventional activated sludge treatment plants normally have a particulate phosphorus content in the suspended solids of 1.5–3% P but this concentration is considerably higher in plants with enhanced biological phosphorus removal, 3–4% in side stream processes and 3.5–6% in mainstream processes (Arvin, 1985). If the effluent suspended solids concentration is 10 to 20 g m^{-3} this means an effluent phosphorus concentration in the suspended solids of 0.3–0.6 g $P\,m^{-3}$ and 0.35–1.2 g $P\,m^{-3}$ for side-stream processes and main-stream processes, respectively. Thus, values of 1–2 g $P\,m^{-3}$ are to be expected

from biological phosphorus removal plants. Only if anaerobic release of phosphates from the sedimentation basin is carefully controlled and a very high separation efficiency is obtained in the sedimentation basin, can a total effluent phosphorus concentration below 1 g $P\,m^{-3}$ be obtained. Biological phosphorus removal followed by, for instance, contact filtration, would however, yield very low total effluent phosphorus values and would require very low dosage of precipitation agents.

Enhanced biological phosphorus removal is still not so well established that the cost-effectiveness of the process can be evaluated. The fact that no or very little chemicals are used and that there is no chemical sludge production makes the process very interesting from an economical point of view.

Trends and emerging technology

Although enhanced biological phosphorus removal is applied at several plants (especially in South Africa) it is still a developing technology. Other areas of development may lie in plant production of easily degradable organics by fermentation of raw primary sludges (Barnard et al., 1985) and different combinations of biological and chemical phosphorus removal processes.

Biological phosphorus removal processes utilizing algae or higher plants do not have the BOD/P-ratio restrictions of bacterial processes. It is well known that oxidation ponds, during warmer seasons can produce low effluent phosphorus values but algaes in the effluent, low wintertime removals in northern areas and difficulties in control reduce the applicability of ponds if efficient phosphorus removal is to be achieved. In recent years, however, new photosynthetically based processes have emerged. In warm climates, water hyacints (Eichornia crassipes) grow very rapidly. By the use of high crop densities in ponds (17 kg m^{-2}) an area of less than 10 m^2 per connected person is claimed to give more than 90% removal of both nitrogen and phosphorus (Stewart, 1986). Recently there has also develop-

ed a large interest in the use of artificial wetlands with plants (e.g. Phragmites australis) for nutrient removal (Brix, 1986).

The use of treated wastewater for irrigation is common in many countries. In such cases the wastewater phosphorus is an asset. Crop uptake and sorption to the soil retains the phosphorus and drainage water generally has low phosphorus concentration.

Costs and cost-effectiveness

Costs for phosphorus removal by chemical precipitation are quite well know. Chemical costs are the easiest to determine. Typical costs for aluminium and iron salts for chemical precipitation are 10–20% of total operation and maintenance costs (Jost, 1985; Barth & Stensel, 1981; Hultman & Nordström, 1987).

Cost calculations are always dependant on a considerable number of assumptions and estimates. Several years ago the National Swedish Environmental Protection Board initiated a cost study of wastewater treatment plants (Andersson & Bornö, 1979). In this study investment costs as well as operation and maintenance costs for the different stages of treatment were calculated in a way that made it possible to hypothetically combine treatment units in various ways and at the same time get the costs of these combinations. This cost study is therefore useful for cost analysis and is used in this section although the data are 10 years old. (More recent data are given by Ødegaard (1985b)). Anderson & Bornö's data are given in 1978 SEK and have been recalculated to 1986 SEK by a factor 2.0. Today, more cost effective process alternatives exist especially where a high quality effluent is to be achieved. However,
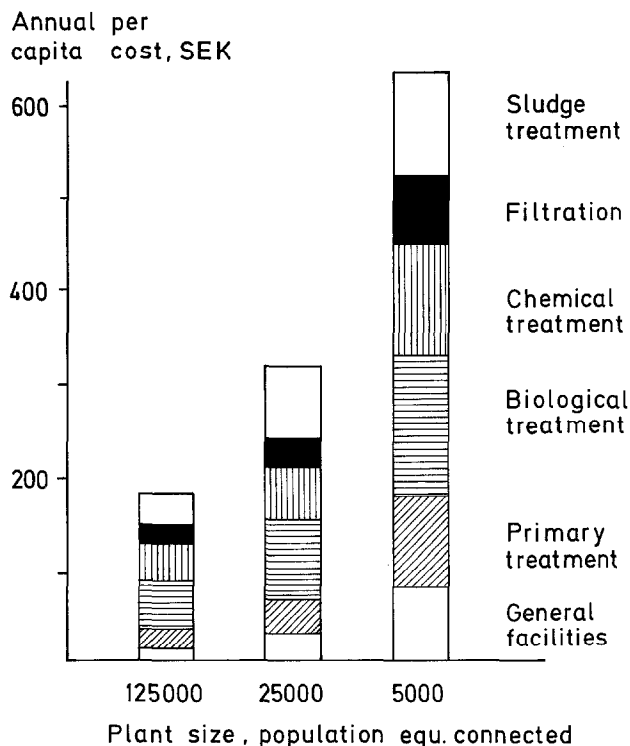

Fig. 4. Annual per capita cost (capital + operation & maintenance) for wastewater treatment plants of three sizes. Data from Andersson & Bornö (1979).
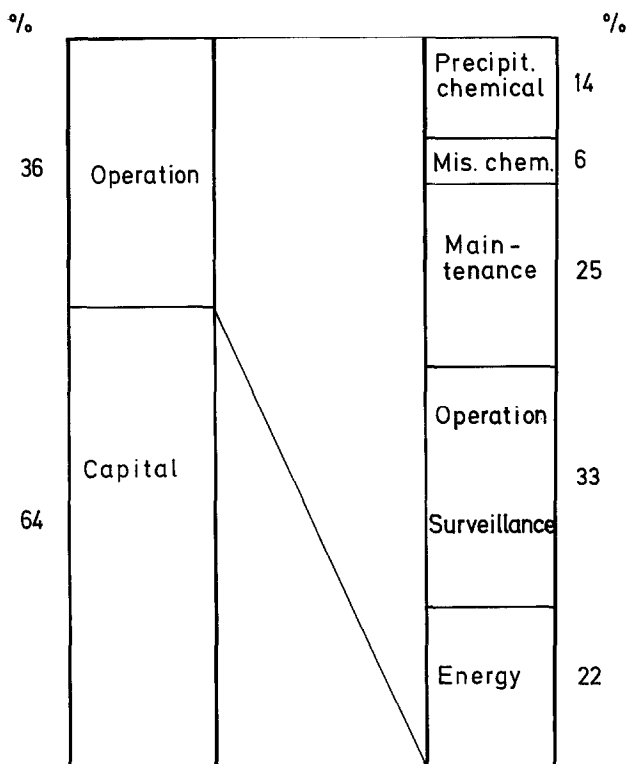

Fig. 5. Distribution of costs on capital and operation & maintenance for a 25 000 population equivalent post-precipitation plant. Operation & maintenance costs are detailed to the right. Data from Andersson & Bornö (1979).

the general tendencies of the cost study are believed to still be relevant but absolute values must be used with caution.

Figure 4 illustrates annual costs per capita for post-precipitation plants of three sizes including the most advanced treatment presently in use in Sweden, i.e. primary biological and chemical treatment and a final filtration step.

In Fig. 5 the total annual costs for a post preci-- pitation plant are separated into capital cost (amortization over 20 years and interest at 10%) and operation and maintenance costs. The operation cost is then broken down into its main components.

The most noteworthy details are in the authors opinion the dominance of capital costs and that costs for chemicals are only about 5% of total costs or 14% of operation & maintenance costs.

There is, of course, a relationship between costs and effluent quality. Primary treatment plus biological treatment can probably be considered as a basic requirement in many industrialized countries today. If phosphorus removal is also required, what are the additional cost to achieve different effluent phosphorus levels?

Based on experience it is assumed that the following mean effluent phosphorus levels are attainable:

- simultaneous precipitation $- 1{,}0$ g P m^{-3}
- post-precipitation $- 0{,}4$ g P m^{-3}
- post-precipitation + filtration $- 0{,}2$ g P m^{-3}

Table 2. Additional annual per capita costs for phosphorus removal after primary and biological treatment for different effluent phosphorus levels. Costs are given in 1986-SEK.

Plant size	Total effluent Phosphorus criterium		
population equivalent connected	1 g P m^{-3}	0.4 g P m^{-3}	0.2 g P m^{-3}
5 000	50	156	228
25 000	40	86	114
125 000	26	54	72

If it also is assumed that two thirds of the sludge treatment costs are incurred by the primary and biological treatment and that costs for chemicals do not differ substantially for the alternatives, then the additional costs for phosphorus removal can be calculated, Table 2.

From a cost-effectiveness point of view the marginal cost per marginal kg phosphorus removed is a more appropriate expression especially if alternative measures in a drainage basin are to be compared. The data is expressed this way in Fig. 6.

If phosphorus level of 1 g P m^{-3} is to be achieved the costs are low. Stendahl (1986) has noted that the cost per kg phosphorus removed is lower than the cost of phosphorus purchased in the form of a commercial phosphate fertilizer. If very low phosphorus values are to be achieved, the marginal cost per kg phosphorus removed is quite high and it must be questioned whether measures other than treatment could be more cost effective.
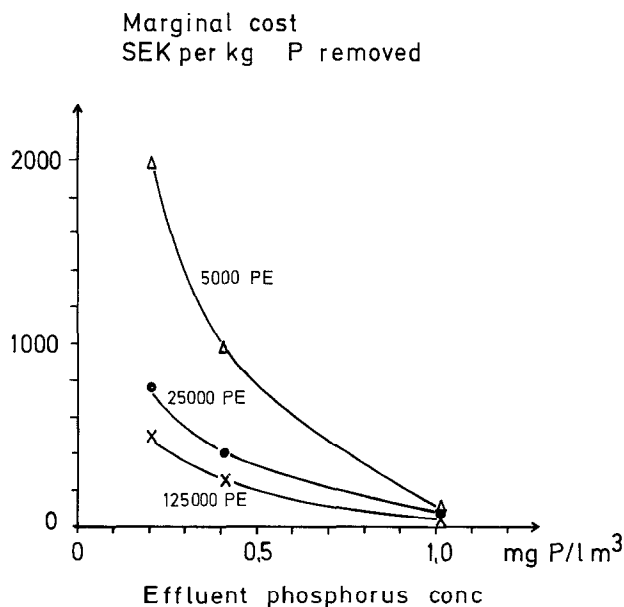

Fig. 6. Marginal cost per marginal kg of phosphorus removed versus effluent phosphorus concentration for 5 000, 25 000 and 125 000 population equivalents.

Conclusions

1. The dominating phosphorus sources in municipal wastewater are human excreta and detergents. The phosphorus load from municipal wastewater treatment plants can be decreased by the substitution of phosphates in detergents. Detergent phosphorus bans alone have normally not resulted in an overall improvement of water quality. However, detergent phosphorus bans may be useful in combination with other measures. In sensitive areas a combination of control measures is necessary.
2. Removal of phosphorus in wastewater treatment plants by chemical precipitation is a well-established technology.
3. Several methods are available for phosphorus removal. The choice of method and process technology depends on such factors as capital and operational costs, process reliability, phosphorus removal requirements, removal requirements for other wastewater constituents, sludge handling and sludge disposal.
4. For a conventional primary and secondary wastewater treatment plant the additional total treatment costs to achieve an total effluent phosphorus of 0.8–1.5 g P m^{-3} are low, about 10–20%.
5. It is possible today to achieve an effluent standard for total phosphorus of about 0.2 g P m^{-3} by the use of a filtration step. The use of pre- or simultaneous precipitation followed by contact filtration seems to be a cost-effective method to reach low effluent phosphorus values.
6. With enhanced biological phosphorus total effluent phosphorus values down to about 1 g P m^{-3} may be obtained. At its present stage of development, biological phosphorus removal seems more sensitive to disturbances than chemical precipitation methods. Enhanced biological phosphorus removal is still not so well established that the cost-effectiveness of the process can be evaluated.
7. When suitable local conditions exist land treatment by irrigation or phytoculture based phosphorus removal may be viable alternatives.
8. Phosphorus removal technology is still developing and new methods are under development. There is, however, no indications that significantly more efficient or economical methods will emerge in the near future.
9. When efficient phosphorus removal is implemented at municipal wastewater treatment plants, the relative importance of other urban phosphorus sources such as combined sewer overflows and storm runoff increases.

Acknowledgment

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