How to Expand Your Plant Without Increasing Your Footprint – A Case Study at Käppala WWTP

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Abstract
The Käppala Association has the responsibility to receive and treat wastewater from twelve municipalities situated north of Stockholm, Sweden. By running a 65 km long tunnel system and the Käppala wastewater treatment plant (WWTP) this responsibility is met. The current load to the plant is 550 000 people equivalents (p e) but with an increasing population this number is constantly increasing. In accordance with the Baltic Sea Action Plan (BSAP) and the EU water framework directive more stringent discharge limits are also expected. The current discharge limits are 8 mg/l of BOD₇, 10 mg/l of total nitrogen and 0.3 mg/l of total phosphorous. In some scenarios a reduction by 50 % of these limits are expected which would mean great modifications to the existing plant.

In order to handle the future demands on the plant the Käppala Association has performed a study of existing technologies on the market. A large number of technical solutions have been investigated and evaluated regarding cost efficiency and environmental impact. In this paper two different solutions for the future process layout of the Käppala WWTP are presented. Detailed calculations of the operational and total costs are presented and the economical consequences due to more stringent discharge limits are discussed.

Keywords
Degasification of MLSS, discharge limits, MBBR, storm water treatment

INTRODUCTION
The Käppala Association is the owner of a 65 km long tunnel system and the Käppala WWTP. The plant receives sewage from twelve municipalities north and northeast of Stockholm. Sewage from approximately 550 000 p e is treated at the plant which is situated on the island of Lidingö, a suburb of Stockholm. The plant is located under ground to save space for housing areas. Hence, if the plant must increase its capacity there is no or only little room for expansion sideways. For more information about the history of the Käppala WWTP see also Manhem & Palmgren (2003).

Treated water is released to the Stockholm archipelago in the Baltic Sea. The status of the recipient is in general poor and heavy blooming of algae often occurs during summertime. Especially harmful for humans is the blooming of blue-green algae. The countries surrounding the Baltic Sea have worked together to form a plan to improve the condition of the sea in a project called the Baltic Sea Action Plan (BSAP). In this a certain task for Sweden is to drastically decrease the load of phosphorous and nitrogen to the sea. The EU water framework directive has been implemented in Sweden regulating the ecological status of lakes, rivers and coastal areas. The Swedish water authority has decreed that the ecological status of the recipient of the Käppala WWTP should reach good status by the year 2021. Today the status is moderate to poor.

The Stockholm region is expanding rapidly. Today (2010) about 2 million people are living in 26 municipalities in the county of Stockholm and about 450 000 people are living in areas connected to the Käppala WWTP. In 2030 the anticipated numbers are 2.4 million people living in the Stockholm area and 700 000 people connected to the Käppala WWTP. The
industrial load is expected to be about 125 000 p e giving a total load of approximately 825 000 p e in 2030. With the current discharge limits of 10 mg/l of BOD, 10 mg/l of total nitrogen (N-total) and 0.3 mg/l of total phosphorous (P-total) the capacity of the plant is 700 000 p e. With the future situation of more stringent discharge limits and an increasing load the capacity of the plant must be expanded. Therefore the Käppala Association initiated a project in the year 2009 where conventional and new technologies where investigated. The aim was to find the most cost effective and environmentally friendly solution to handle an increasing load and more stringent discharge limits. A technical report has since then been composed where two different technologies are presented to meet the future demands.

Existing plant
The existing plant was first put in operation in 1969. The plant then consisted of 6 parallel treatment lines with a capacity of 400 000 p e. During the years 1995-2000 the plant was expanded with five additional treatment lines and modified for nitrogen removal. The current capacity is 700 000 p e. The treatment comprises of screenings, pre settling tanks, biological treatment tanks, final settling tanks and sand filters. The process scheme is depicted in Figure 1. The biological step is a conventional activated sludge (AS) process with biological nitrogen and phosphorous removal (UCT-configuration). The nitrogen removal is performed with a pre denitrification process with no addition of external carbon. Anaerobic zones are situated in front of the anoxic zones to carry out biological phosphorous removal (bio-P). In the five new treatment lines phosphorous removal is carried out with simultaneous precipitation where ferrous iron sulphate is added to the return sludge flow. To secure that effluent phosphorous is kept below the discharge limit ferrous iron sulphate is also added to the sand filters as a final barrier. The dose of the precipitant is controlled by an on-line measurement of effluent phosphate. Sludge stabilization is carried out in two mesophilic digesters where the primary sludge is digested separately from the excess sludge to prevent foaming caused by filamentous bacteria of the biological sludge. The produced biogas is upgraded to vehicle fuel quality and sold to a regional bus company. Final dewatering is carried out with a chemical conditioning where sulphuric acid and hydrogen peroxide is added to the sludge followed by a mechanical dewatering with hydraulic filter presses. For further information about this method of sludge dewatering see Thunberg (2010).

**Figure 1** – Process scheme of the Käppala WWTP.
Plant weaknesses
The treatment efficiency of the plant is high seen over the year and existing discharge limits have been kept since the expansion of the plant. However, during winter months when influent water temperatures are low and a long sludge age is required to keep effluent nitrogen below the limit of 10 mg/l poor sludge qualities are common. This can result in solids washout from the final settling tanks during periods of storm water flows. If this occurs the sludge storage capacity of the sand filters can be exceeded rapidly. This will in turn lead to a decrease of the total hydraulic capacity of the plant and overflow can occur. Because of the discharge limit of 0.3 mg/l of total phosporous no more than approximately 2 % of the total influent can be allowed to overflow as a yearly average. During the last overflow in 2010 approximately 1.2 million m³ was by passed out of a total yearly amount of 52 million m³. This corresponds to 2.3 % which was enough to cause the quarterly average of effluent phosphorous to exceed the discharge limit of 0.3 mg/l. Overflow situations are however quite uncommon but when they occur the consequences can be great.

METHODS
The scenario with a growing population and more stringent discharge limits in combination with an expected longer rainy season due to a warmer climate has forced the Käppala Association to review the capacity of the plant. Therefore a project was started in 2009 where four independent consultancies were asked to review the current process configuration of the Käppala WWTP. The consultancies were given a number of conditions that were to be followed.

1. A possible expansion of the plant is only possible downwards. There is no possibility of expanding sideways or upwards and new process solutions are preferred instead of larger volumes.

2. All water coming from the connected municipalities must be treated as it arises. There is no possibility to buffer larger volumes of storm water other than the 40 000 m³ that are available in the tunnel system today.

3. The maximum load to the plant will be 900 000 p e and storm water flows of 9 m³/s can occur.

4. Average effluent concentrations of 4 mg/l of BOD₇, 5 mg/l of total nitrogen and 0.1 mg/l of total phosphorous should be achieved.

RESULTS AND DISCUSSION
In the beginning of 2010 the technical reports were finished and many different process solutions were proposed in order to handle the given scenarios. All of the reports concluded that the existing volumes are more than enough if the organic capacity must be increased. Another conclusion was that the main issues that need to be solved are hydraulic load and sludge separation.

The different solutions that were proposed differed greatly from each other both from an operational stand point but also from an economical one. Some process solutions would ensure that effluent discharge limits would be kept at all times but to a very large cost. Other solutions were less secure but to a much lower cost. During 2010 the different technologies were evaluated to find the most optimal process solution so that effluent discharge limits can be kept to a reasonable cost. Two main solutions were chosen as a first and second hand
choice to increase the organic capacity of the plant. The first hand choice is a very cost effective way of boosting the organic capacity. This is also a technology that has not been tested to a large extent in large waste water treatment plants and must therefore first be tested in full scale. The second hand choice is a more conventional method of increasing the capacity but it is also less cost effective.

The future process configuration

Storm Water treatment

A very important parameter regarding the future process configuration is the hydraulic load. As mentioned earlier storm water flows as high as 9 m$^3$/s are expected. However, one must also consider the frequency of the flows before modifying the existing plant. Today the plant can handle a hydraulic load of 6 m$^3$/s and a reinforcement of the hydraulic capacity is therefore necessary. In Figure 2 the current and the expected future flow frequencies are shown. From here it can be seen that flows exceeding 6 m$^3$/s is expected to occur at less than 1% of the time in the future. Therefore it is not reasonable to increase the hydraulic capacity of the main treatment lines. This would mean that the capacity would be larger than what is needed at 99% of the time. Instead, an effective storm water treatment is a better choice.

![Figure 2 – Current and expected future flow frequencies.](image)

At the Käppala WWTP there are three decommissioned grit chambers that can be used for that purpose. The future process configuration will therefore include a compact unit of storm water treatment in one of the decommissioned grit chambers. The capacity of this unit will be 3 m$^3$/s and with a removal efficiency of more than 90% of total phosphorous, 70% of BOD$_7$ and 10% of total nitrogen. The proposed unit is a high-rate clarifier using lamella sedimentation techniques and microsand as a seed for floc formation. Aluminum based products will be used as a precipitant in combination with anionic polymers for coagulation. This solution would mean that peak flows over 6 m$^3$/s can be withstand over several days without the risk of exceeding the discharge limit of 0.1 mg/l of phosphorous as a one year average. The maximum surface loading rate to the unit is said to be approximately 80 times greater compared to conventional precipitation which makes it possible to fit in one of the decommissioned grit chambers. The solution means that the hydraulic capacity of the main treatment lines can be left as today.

Biological and chemical treatment

Regarding the biological and chemical treatment of the plant all proposed solutions showed that there are many ways of strengthening its capacity. Two different paths have been found
to meet the future. Depending on the outcome of future full scale trials one of the two paths will be chosen.

**Degasification of MLSS**

Since it was concluded that the sludge separation of the final clarifiers is the main issue that needs to be solved a way of improving the settleability of the biological sludge is of key interest. If this could be done the concentration of the MLSS of the bioreactors could be increased and the organic capacity as well without any loss of solids from the final clarifiers. A fairly unknown method has been presented with precisely that purpose, degasification of MLSS. The technique is based on the principle of Henry’s law which states that the amount of a given gas dissolved in a liquid is directly proportional to the partial pressure of that gas. Lowering the pressure of any gas in equilibrium with a liquid will cause the gas to escape the liquid. At the end of the bioreactors the water is saturated with nitrogen, oxygen and carbon dioxide. When the sludge enters the final clarifiers different gases will be entrapped inside the sludge and even more gas can be produced (e.g. due to a continued denitrification). This will counteract the settling of the sludge and sometimes even bring it to the surface. By exposing all of the water from the bioreactors to a very low pressure dissolved gases will be released from the water making it unsaturated. This will in turn prevent additional formation of gas bubbles. The settleability of the sludge is then greatly improved. The degasification is performed by allowing all of the water from the bioreactors to pass through a vacuum tower where the gases are released. At the top of the tower a container is placed where the necessary pressure drop is performed by a vacuum pump. The towers must be approximately 10 m high in order to produce the necessary pressure drop of 9.5 bar. Since the water is transported through the tower by a siphon effect the energy consumption is low, approximately 0.02 kW/m³. The principle is further described in Maciejewski *et al.* (2009).

The Käppala Association has performed pilot scale tests with the technology and with very good results. By improving the settleability of the sludge it is expected that the MLSS of the bioreactors can be increased to 6 g/l. This would increase the organic capacity of the plant enough to handle a total load of 900 000 p e. External carbon is however needed during periods of the year when influent water temperatures are low and long aerobic zones are needed. Because of the simplicity of the technology this is the first hand choice to meet the future scenarios. To test the method one of the eleven treatment lines will be modified for a full scale test during 2012.

**Moving Bed Bioreactors**

Moving Bed Bioreactors (MBBR) has become a quite common way of improving the capacity of conventional biological nutrient removal (BNR) plants. Here, carriers are added to the whole or parts of the bioreactor to induce growth of biofilm. Since the microorganisms are growing on carriers instead of being kept in suspension shorter hydraulic retention times and higher concentrations of sludge is possible (i.e. a high concentration of microorganisms per tank volume). This will increase the capacity of a given volume and reduce the sludge load on the final clarifiers since no return sludge flow is needed. During periods of high flows the risk of wash out and loss of solids from the final clarifiers will be minimized. The effect of high concentrations of filamentous bacteria will also be less pronounced as these will grow in the biofilm as well. With an MBBR solution only five of the eleven treatment lines need to be modified. The remaining lines will be run as an AS process with a maximum concentration of MLSS of 3.5 g/L. One disadvantage with the MBBR technology is that the thickness of the biofilm makes the need of dissolved oxygen (DO) and readily degradable carbon significantly higher compared to a conventional AS process. Therefore an external carbon source such as
methanol or ethanol is required. The existing fine bubble membrane aerators would also have to be replaced with course bubble aerators to keep the carriers of the aerobic zones in suspension. Another disadvantage is that MBBR solutions often cause higher concentrations of fines in the effluent water and a post precipitation with ferric iron would be necessary. Consequently an MBBR process would require larger investment and operational costs compared to the degasification technology.

**Pre and post precipitation**
The focus of the studies that were performed has been the organic capacity and the hydraulic capacity of the plant since these parameters are more dependent of the available volumes. However with effluent discharge limits of 0.1 mg/l of total phosphorous the existing phosphorous removal must also be considered. With this scenario it is unlikely that the biological phosphorous removal process (bio-P) can be kept. The main reason is that a large release of phosphorous from the digesters can occur when bio-P sludge is digested. This gives rise to a substantial internal load of phosphorous from the reject water when the digested sludge is dewatered. Due to the fact that the bio-P process is heavily dependent on the concentration of volatile fatty acids (VFA) in the influent the removal efficiency can also deteriorate under periods of high flows. Today, such periods are compensated by an increased precipitation on the sand filters. However, an increased dose of precipitant on the sand filters can cause them to clog as iron hydroxides is formed. During storm water flows this is highly unwanted since the hydraulic capacity then must be kept high.

The bio-P process is only used in six of the treatment lines. In the five new lines simultaneous precipitation with ferrous iron sulphate is used instead. The removal efficiency of the process is approximately 90 % and it is easy to control. But if 0.1 mg/l of effluent phosphorous is to be achieved the dose of precipitant must be increased. This would also lead to an increased production of sludge in the bioreactors with the risk of overloading the final clarifiers. If the degasification of MLSS works as planned this effect will be counteracted as the maximum solids loading rate of the final clarifiers is said to be increased by approximately 30%. One way of overcoming the problems with an increased production of sludge in the bioreactors is to combine different types of precipitation (i.e. pre- post- and simultaneous precipitation). At the Käppala WWTP this will be done by using the simultaneous precipitation as the main method of phosphorous removal. The dose of precipitant will be as high as the final clarifiers allows regarding the maximum solids loading rate. The second barrier will then be the post precipitation on the sand filters where a relatively small amount of ferrous iron sulphate is used so the filters are not clogged. The last barrier will be a pre precipitation with ferric iron salts to reduce the load of phosphorous to the bioreactors without increasing the production of chemical sludge in the bioreactors.

**Action plan and economical aspects**
The degasification technology would allow for a cost effective and robust way of increasing the capacity of the plant. With this method the present AS process can still be used and modified as new discharge limits arises (e.g. by addition of external carbon if the pre denitrification system is insufficient). The MBBR solution would only be an option if the degasification does not give the expected results. An action plan has been undertaken where detailed calculations of the necessary modifications have been performed. Two paths have been investigated, one where the degasification technology is used and one where MBBR is used instead. In Figure 3 the modifications of the two paths are shown. Here the additional total operational and capital costs of the plant are presented. Some modifications have to be performed regardless of which technology that will be used (illustrated by black arrows in
Figure 3). These are storm water treatment in a decommissioned grit chamber, a new digester and additional dewatering machinery to treat the extra amounts of sludge due to an increased load. When the modifications will be performed depends on the increase of the load to the plant. In Figure 3 it can bee seen how the additional cost of the MBBR solution is higher compared to the degasification. However, this increase of the total additional operational and capital costs does not increase the relative costs for the owners. Or in other words, the total (not additional) yearly cost per p e steadily decreases despite the fact that the total costs as absolute values increases. This effect is also seen in Figure 4 where the treatment costs decreases as the load increases.

**Figure 3** – Additional operational and capital costs with the two technologies.

**Figure 4** – Total treatment costs with the two technologies and marginal costs of more stringent discharge limits.
The treatment costs are described as the total operational and capital costs per kg of oxygen consumption potential (OCP) that is removed. The OCP is a way of describing the total oxygen consumption potential of nitrogen, organic carbon and phosphorous. In Figure 4 the marginal costs due to more stringent discharge limits are also presented. These are the costs of removing the additional amounts of OCP that would be required. It can be seen how these amounts will cost twice as much as the total amount of OCP that is being removed. It has been presumed that more stringent effluent limits will not be introduced before 700 000 p.e which is the reason to why no data for the marginal costs are presented prior to 700 000 p.e.

CONCLUSIONS
To meet an increasing load and more stringent discharge limits the Käppala Association has found two future paths by which the plant can be modified. One of the suggested paths includes the fairly unknown degasification technology where the settleability of the sludge is drastically improved by subjecting the MLSS of the bioreactors to a vacuum before it enters the final clarifiers. The method allows for the MLSS of the bioreactors to be increased to approximately 6 g/l which leads to a large increase of the organic capacity. Compared to the second hand choice, an MBBR process, it is much more cost effective but at the same time less reliable. The technology will first be tested in one treatment line before all of the lines can be modified. Depending on the outcome of such full scale trials one of the two technologies will be implemented. To meet the more stringent discharge limits of phosphorous the Käppala WWTP will have to use a combination of pre-, post-, and simultaneous precipitation. Storm water treatment will also be necessary as no water can be by passed. As the load increases the total operational and capital costs will increase greatly. However, the costs relative the number of p.e connected to the plant will decrease. This means that the owners of the plant, the inhabitants of the municipalities that form the Käppala Association, will have to pay less to treat their waste water. The relative cost to treat the additional amounts of nutrients due to new discharge limits will also be more than twice as high as the overall relative treatment costs. The total environmental and economical impact of such demands should therefore be considered carefully before they are legislated.

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