The impact of sea water flushing on biological nitrification–denitrification activated sludge sewage treatment process


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Abstract The process performance of the two largest activated sludge processes in Hong Kong, the Sha Tin and the Tai Po Sewage Treatment Works (STW), deteriorated in the initial period after the introduction of seawater flushing in 1995 and 1996, respectively. High effluent ammonia nitrogen (NH₄-N) and total suspended solids (TSS) in excess of the discharge standards resulted from incomplete nitrification and changes in floc characteristics. A desktop study on the inhibitory effects of salinity, particularly on nitrification, was subsequently conducted using the Tai Po STW operating data. To assist the upgrade of the Sha Tin STW a five-month extensive bench-scale investigation on a simple but flexible modified Ludzack–Ettinger configuration with bio-selector was conducted to quantify the inhibitory effects due to the saline concentration. The Sha Tin STW upgrade consists of restoration of its original design capacity (conventional process) of 205,000 m³/day from its currently much reduced capacity as a Bardenpho process. Only the volume of the existing biological process and clarifier is to be utilized. The saline concentration ranges from 3,500 up to 6,500 mg Cl⁻/L, both daily and seasonally. High and greatly fluctuating saline concentrations have been known to inhibit nitrification. Design consideration should also be given to the peak daily and seasonal TKN loading of up to three times the average. Although the nitrifiers maximum specific growth rate was significantly reduced to a low 0.25 day⁻¹, the inhibition was considered to be tolerable with effluent NH₄-N and NO₃-N consistently at < 1 and < 6 mg/L. The bio-selector was demonstrated to be efficient in control of sludge foaming and bulking with SVI consistently ≤ 125 mL/g. Results from the IAWQ Model No. 1 and the hydraulic model of the secondary clarifiers allowed overall process capacity maximization. With an anoxic mass fraction of 25–30%, operating sludge age of 9–14 days and SVI ≤ 125 mL/g, both the design requirements and the effluent discharge standards could be met. Without these investigations, an unnecessarily large reaction basin and secondary clarifier volume, and hence capital investment, would have resulted.

Keywords Activated sludge process; biological nitrogen removal; bio-selector; denitrification; modified Ludzack–Ettinger configuration; nitrification; saline concentration

Introduction

The Sha Tin Sewage Treatment Works (STW) are generally regarded as the largest biological STW in Hong Kong. The existing Stage I/II was upgraded from a conventional configuration to the current 5-stage Bardenpho process to achieve biological nitrogen (N) and phosphorus (P) removal. The configuration modification resulted in a reduction in treatment capacity from 205,000 m³/day to 150,000 m³/day. The Sha Tin STW needs to be upgraded in the near future to treat 342,000 m³/day with the Stage III extension, while the existing Stage I/II will need to handle the original 205,000 m³/day using the existing aeration tank and secondary clarifier hydraulic volume. A much more space-efficient activated sludge process configuration, with biological foaming and bulking control, will be utilised for biological N removal only. The future effluent discharge standards are more stringent as regards nitrogen. Thus, a higher process treatment capacity than that of the current 5-stage
Bardenpho process is necessary. The present and future effluent standards are given in Table 1.

However, it is not easy to determine the maximum treatment capacity of the Sha Tin Stage I/II facility with the future selected process due to the unknown magnitude of the adverse impact of the high salinity levels on the performance of biological N removal activated sludge systems. The high salinity levels result from the introduction of seawater flushing into the catchment areas since 1995. Similarly, deterioration in process performance had been experienced at the Tai Po STW during the initial introduction period of seawater flushing in the Tai Po catchment areas. It was believed that the kinetic rates of nitrification and denitrification were further affected by the variation (daily and seasonal) in salinity levels, particularly during the rainy season due to the influx of rainwater into the sewage system.

After the initial desktop studies on the Tai Po STW performance before and after seawater flushing was introduced, extensive bench-scale investigations were conducted for the performance and design review of Sha Tin Stages I, II and III. The key design parameters, biokinetic constants and optimal operating conditions of the future selected biological process configuration were determined. This paper details implications of the high and greatly fluctuating saline concentrations on the biological nitrification-denitrification process and thus, the activated sludge process design.

**Background**

Seawater flushing was introduced into the catchment areas of two large-scale municipal treatment works in Hong Kong, the Sha Tin and Tai Po STWs, in 1995 and 1996, respectively. For the Tai Po STW, a study was conducted covering the period before and after the seawater flushing was introduced (Yu et al., 1997). The crude sewage chloride (Cl–) level increased from < 500 to approximately 5,000 mg Cl–/L. An increase in the total suspended solids (TSS) concentration of up to 25% was also observed. This was due to inorganic salt precipitation such as PO4-P and supernatant recycling from the solids treatment process wherein ferric salt was added for removal of sulphide. Consequently, more solids were removed from the primary clarifiers. The sludge characteristics changed significantly. The foaming problems became less intense and the sludge volume index (SVI) level decreased.

**Table 1** Influent and effluent characteristics and discharge standards

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Cl–</td>
<td>3356</td>
<td>3238</td>
<td>3253</td>
</tr>
<tr>
<td>TCOD</td>
<td>341</td>
<td>97</td>
<td>104</td>
</tr>
<tr>
<td>SCOD</td>
<td>193</td>
<td>61</td>
<td>67</td>
</tr>
<tr>
<td>BOD5(3)</td>
<td>154</td>
<td>18.6</td>
<td>17.4</td>
</tr>
<tr>
<td>TSS</td>
<td>105</td>
<td>40</td>
<td>45</td>
</tr>
<tr>
<td>VSS</td>
<td>74</td>
<td>29</td>
<td>32</td>
</tr>
<tr>
<td>NH3-N</td>
<td>30</td>
<td>1.3</td>
<td>0.7</td>
</tr>
<tr>
<td>TKN(3)</td>
<td>34</td>
<td>1.8</td>
<td>1.6</td>
</tr>
<tr>
<td>NO3-N</td>
<td>–</td>
<td>5.9</td>
<td>5.6</td>
</tr>
<tr>
<td>TN(4)</td>
<td>34</td>
<td>7.7</td>
<td>7.2</td>
</tr>
</tbody>
</table>

(1) From 24-hour composite samples from Aug. 12–Oct. 18 1998
(2) From 24-hour composite samples from Nov. 7–Dec. 16 1998
(3) Infrequent data
(4) Sum of other nitrogen species
(5) Compliance must be 95% statistically
dramatically from up to 350 mL/g to ≤ 100 mL/g consistently. The majority of the effluent TSS was pin floc rather than precipitate or foam particles.

More importantly, the nitrification capacity decreased substantially. During the transient period, both the effluent TN and TSS levels were in excess of the Discharge License limitations. Effluent NH₄-N and TSS concentrations of up to 15 and 55 mg/L, respectively, were recorded. Although the biological systems eventually became acclimatized to the saline influent, and the performance and effluent quality improved to a satisfactory level, there were still incidences of high effluent NH₄-N concentration and uncontrolled foaming problems.

For the Sha Tin STW, significant daily and seasonal saline concentration variation was recorded (Figure 1). This variation was due to the change in salinity of the seawater intake and in the frequency of toilet usage during the day. From the experience of the Tai Po STW, the salinity variation may impact the Sha Tin biological treatment process considerably, particularly the nitrification and floc characteristics, leading to deterioration in the quality of the effluent.

Salinity has been known to inhibit nitrification. However, the nitrifiers can acclimatize to saline concentrations as high as that of seawater, as long as the saline concentration does not vary significantly. The nitrification rate under both high and greatly fluctuating saline concentrations is uncertain. To treat the peak daily TKN loading under such saline conditions, a long operating sludge age is normally employed to achieve complete nitrification and also sufficient denitrification for alkalinity control. The large process volume and clarifier capacity is not compatible with the limited land availability of the existing Sha Tin STW sites. In addition, the long sludge age, or low F:M ratio, also leads to potential filamentous foaming and bulking problems.

Consequently, a well-proven biological process with simple configuration – the modified Ludzack–Ettinger (MLE) process with bio-selector – was chosen for the bench-scale investigation. The goal is to develop a process design with optimal treatment capacity/anoxic mass fraction, mixed liquor recycle ratio, operating sludge age/MLSS concentration, and sludge volume index for the existing aeration tank and secondary clarifier volume capable of handling the required flows for Stages I and II works as well as the new Stage III extension works.

**Materials and methods**

An on-site laboratory was set up at the Sha Tin STW. Two identical, but fully independent, bench-scale MLE systems with and without bio-selector (MLE1 and MLE2) were used (Figure 2). The actual settled sewage from the existing primary clarifiers was automatically collected on-line and pumped directly into the bench-scale systems according to the diurnal flow pattern, i.e. there was a variable flowrate into the systems. The salinity (or chloride concentration
concentration) in terms of total dissolved solids was measured on-line. The computer for the control of the bench-scale units was also used to control the influent feed pumps for the diurnal and wet weather flow patterns.

Each system consists of one bio-selector with plug-flow configuration, two anoxic reactors (10 L), four aerobic reactors (12 L), one secondary clarifier with a variable speed scraper, variable speed sludge recycle pumps, and an effluent holding tank.

An IBM compatible computer installed with a commercial control system was used for the process control of the bench-scale system. The parameters which can be varied include influent feed rate, floc loading in the bio-selector, hydraulic retention time, sludge age via volumetric control, mixed liquor recycle ratio, operating dissolved oxygen (DO) concentration and anoxic mass fraction.

The investigation was divided into two phases. In Phase 1, MLE1 and MLE2 were operated at winter (20 ± 2°C) and summer (30 ± 2°C) temperatures, respectively. To maintain 20°C, the influent could be routed through a refrigerated water bath. To maintain 30°C, fish tank water heaters were used in the bioreactors. The air temperature was maintained at 25 ± 2°C. In Phase 2, both MLE1 and MLE2 were operated at 20 ± 2°C and the bio-selector in MLE2 was eliminated to evaluate the ability of the bio-selector to control biological foaming and bulking.

Twenty-four hour composite settled sewage and effluent samples were collected daily for laboratory analyses. In-reactor soluble parameters (SCOD, NH₄-N, NO₃-N, PO₄-P, DO, ORP, SVI, MLSS and MLVSS) were determined at least once a week after two sludge ages of successful operation. At the end of three operating sludge ages, extensive sampling and analysis was performed for detailed performance analyses, determination of kinetic constants, and database development for computer simulations (IAWQ Model No.1). Methods of kinetic constant determination are given in Table 2.

Mixed liquor samples were collected manually at recorded time intervals and filtered immediately, or as required. Analyses were performed in the on-site laboratory as soon as possible after sampling. Only total and soluble BOD₅ and TKN were analyzed by an independent laboratory.

A HACH analyzer and HACH methods were used for analysis of TCOD, SCOD, NH₃-N, NO₃-N, PO₄-P and TP. The other analyses were in accordance with Standard Methods for the Examination of Water and Wastewater (APHA, 1992). SVI was measured using a 1,000 mL graduated measuring cylinder and a 30-minute settling period. DO concentration readings were taken using a YSI oxygen probe / YSI DO meter. The DO probes were calibrated weekly or as required. The pH levels were measured using a TPS pH analyzer.

**Results and discussion**

The average settled sewage and effluent pollutant concentrations during the Phase 1 and 2 studies are summarized in Table 1. The average daily concentration of Cl⁻, TCOD, TKN and NH₄-N in the settled sewage is shown in Figures 1 and 3. Note that the daily difference in Cl⁻ concentration was frequently more than 1,000 mg/L. The diurnal flow and pollutant concentration...
The inhibitory effects on the key kinetic constants determined, together with the default values for the IAWQ Model adopted by the University of Queensland (Australia), are given in Table 2.

<table>
<thead>
<tr>
<th>Bio-kinetic constant</th>
<th>Determination method</th>
<th>MLE 1 values Phase 1</th>
<th>MLE 1 values Phase 2</th>
<th>IAWQ Values</th>
<th>Inhibition level*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum specific autotrophic growth rate [\mu_{\text{A}}_{\text{max}} \text{ day}^{-1}]</td>
<td>WRC</td>
<td>0.28</td>
<td>0.25</td>
<td>0.80</td>
<td>Very significant</td>
</tr>
<tr>
<td>Autotrophic biomass yield coefficient [\text{mg VSSN/mg NH}_3-\text{N}]</td>
<td>IAWQ</td>
<td>0.14</td>
<td>–</td>
<td>0.16</td>
<td>Moderate</td>
</tr>
<tr>
<td>Autotrophic endogenous decay coefficient [\text{day}^{-1}]</td>
<td>IAWQ</td>
<td>0.03</td>
<td>–</td>
<td>0.10</td>
<td>Very significant</td>
</tr>
<tr>
<td>Maximum specific heterotrophic growth rate [\mu_{\text{H}}_{\text{max}} \text{ day}^{-1}]</td>
<td>WRC</td>
<td>2.2</td>
<td>–</td>
<td>6.0</td>
<td>Very significant</td>
</tr>
<tr>
<td>Heterotrophic biomass yield coefficient [\text{mg cell COD/mg COD}]</td>
<td>IAWQ</td>
<td>0.41</td>
<td>0.37</td>
<td>0.66</td>
<td>Significant</td>
</tr>
<tr>
<td>Heterotrophic endogenous decay coefficient [\text{day}^{-1}]</td>
<td>WRC</td>
<td>0.10</td>
<td>–</td>
<td>0.20</td>
<td>Significant</td>
</tr>
</tbody>
</table>

* Moderate = decrease from IAWQ value of 0–25%
Significant = decrease from IAWQ value of 25%–50%
Very significant = decrease from IAWQ value of 50%–75%

The inhibitory effects on the key kinetic constants determined, together with the default values for the IAWQ Model adopted by the University of Queensland (Australia), are given in Table 2.

The TKN peak loading and Cl\(^{-}\) concentration occurred at 10 a.m–12 p.m., from frequent toilet usage, whereas the peak hydraulic and TCOD loading occurred at 10 p.m–12 a.m. mainly from cooking, etc. The highest peak factor of TKN loading recorded was close to 2.5.

**Figure 3** TCOD, TKN and NH\(_4\)-N of settled sewage during Phase 1 and Phase 2 bench-scale testing

**Figure 4** Phase 1 diurnal patterns for flowrate and chloride concentration

**Figure 5** Phase 1 diurnal patterns for pollutant loadings
These peak loading patterns had a significant implication in selecting the optimal sludge age during the Phase 1 investigation. During the initial start-up period, the activated sludge seed from the full-scale Bardenpho process was not nitrifying and sludge from another plant not receiving seawater was used. Although initially a sludge age of ≥ 15 days was selected for MLE1, occasional increases in effluent NH₄-N concentration (from < 1 mg/L to ~5 mg/L), particularly during the peak hours, was observed. It was then decided to increase the sludge age to ≥ 25 days for MLE1.

After the operating sludge age had been increased, the effluent NH₄-N concentration was consistently < 1 mg/L. Because of a favorable TCOD:TKN ratio of ~10, the effluent NO₃-N concentration was consistently low (average: 6 mg/L). The extensive bi-hourly sampling programme was conducted from 24/9/98–1/10/98. Coincidentally, the influent Cl⁻ concentration increased dramatically from 2,363 mg/L on 23/9/98 to 5,525 mg/L on 26/9/98. The low effluent NH₄-N concentration, however, remained unchanged. From the in-reactor data, nitrification was complete in either Aerobic Reactor 2 or 3, which indicated that MLE1 had spare nitrogen removal capacity.

After a number of batch experiments and detailed in-reactor parameter analyses were conducted, the inhibitory effect of Cl⁻ on the key kinetic constants was established (Table 2). The maximum specific growth rate of the nitrifiers was 15–20% of that reported by WRC (1984) and was significantly lower than the IAWQ Model default value. Based upon the Tai Po STW experience, an acclimatization period is predicted for the nitrifiers. Although the other key kinetic constants were also affected by the saline conditions, the inhibitory effects were much smaller than that for the nitrifiers.

During the data evaluation, it was also found that the existing Sha Tin STW was operating at > 90% of design flow. The secondary clarifiers were also operating at their peak capacity with an operating MLSS concentration of close to 3,000 mg/L. It was then decided to extend the bench-scale investigation to a second phase to determine the potential maximum treatment capacity of the MLE process. From IAWQ Model No. 1 simulation results, a flowrate of 133% of the design flow of 205,000 mg/L could be achieved with a 25% reduction in the anoxic mass fraction and a 50% reduction in the sludge age without affecting the effluent N quality. The flow and load to the MLE systems were increased stepwise to 133% while the operating MLSS concentration was maintained at ≤ 3,300 mg/L. The operating conditions for MLE2 were modified so that it was similar to MLE1 except the bio-selector was eliminated.

Both MLE1 and MLE2 performed well after the modifications (Figure 8 and Table 1). Only during the stepwise increases in flow were there transient slight increases in effluent NH₄-N concentration.

However, it was subsequently found by computer modeling that the existing clarifiers could not handle the increase in flow and load of 33% with the design requirement of three
times the average dry weather flow, even with modifications such as Crosby and inlet baffles. However, the modified clarifiers could handle the design flow of 205,000 m$^3$/day provided that the MLE process with bio-selector (with reduced anoxic mass fraction and sludge age) was employed due to its low MLSS and SVI. Winter is the dry season in Hong Kong and a 3ADWF flow to the STW is very unlikely.

The bio-selectors worked satisfactorily with almost complete absorbable soluble COD removal. The SVI values during Phase 1 were generally lower than 100 mL/g, with MLE2 always lower than that of MLE1 (Figure 9). With the 33% increase in flow and load, and the resulting increase in MLSS/MLVSS concentration in Phase 2, the SVI levels of MLE1 increased slightly to an average and a maximum of 119 mL/g and 125 mL/g, respectively. This indicated that the floc-load should be fine-tuned to control biological bulking.

The capability of the bio-selector in controlling bulking was demonstrated in Phase 2. The MLE without a bio-selector exhibited high sludge blanket levels and SVI values. The highest SVI level recorded was 300 mL/g. The predominant filaments responsible for the bulking were identified as Types 1851 and 0041/0675. While the full-scale 5-Stage Bardenpho process was suffering from foaming problems caused by *Nocardia amarae*, the two bench-scale MLE systems did not experience any foaming problems at all. This might also be due to the plug flow configuration, i.e. two anoxic and four aerobic reactors, of these bench-scale systems.

**Conclusions**

The extensive bench-scale studies successfully quantified the unknown inhibitory effects of the high and greatly fluctuating saline concentration on biological nitrification-denitrification. With a relatively higher operating temperature during the winter months (≥ 20°C) as compared to that (≤ 10°C) of most European and North American countries, this inhibitory effect on nitrification was considered to be tolerable although the inhibition was considered...
to be significant. The kinetic parameters determined allowed accurate computer simulation using IAWQ Model No. 1, which was subsequently verified by the bench-scale testing. Together with the hydraulic model simulation results of the secondary clarifiers and the performance of the bio-selector in controlling biological floc characteristics, this made the selection of the most optimal process configuration and operating conditions possible. These optimal conditions not only allow the effluent discharge standards, particularly the \( \text{NH}_4^+ \)-N and TN, to be met consistently, but more importantly, they allowed capacity optimization between the biological process and the secondary clarifiers to meet the design requirements. Otherwise, a conservative estimation of the maximum growth rate of the nitrifiers would have been used, resulting in an unnecessarily long sludge age, high operating MLSS concentration and large reaction basin and secondary clarifiers, which is, essentially, an under estimation of the overall maximum treatment capacity.

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References