住房和城乡建设部 中国给水排水

Workshop on wastewater treatment plants up-grading

污水处理厂提标改造高级研讨会

9月16日—19日, 2017, 鑫江温德姆酒店, 青岛

200 000m³/d主流部分短程硝化和氨氮厌氧氧化: 反应器构型, 运行和与传统的生物脱氮工艺的比较

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IWA Grand Applied Innovation Award 2014 together with DC Water, HRSD and Strass WWTP

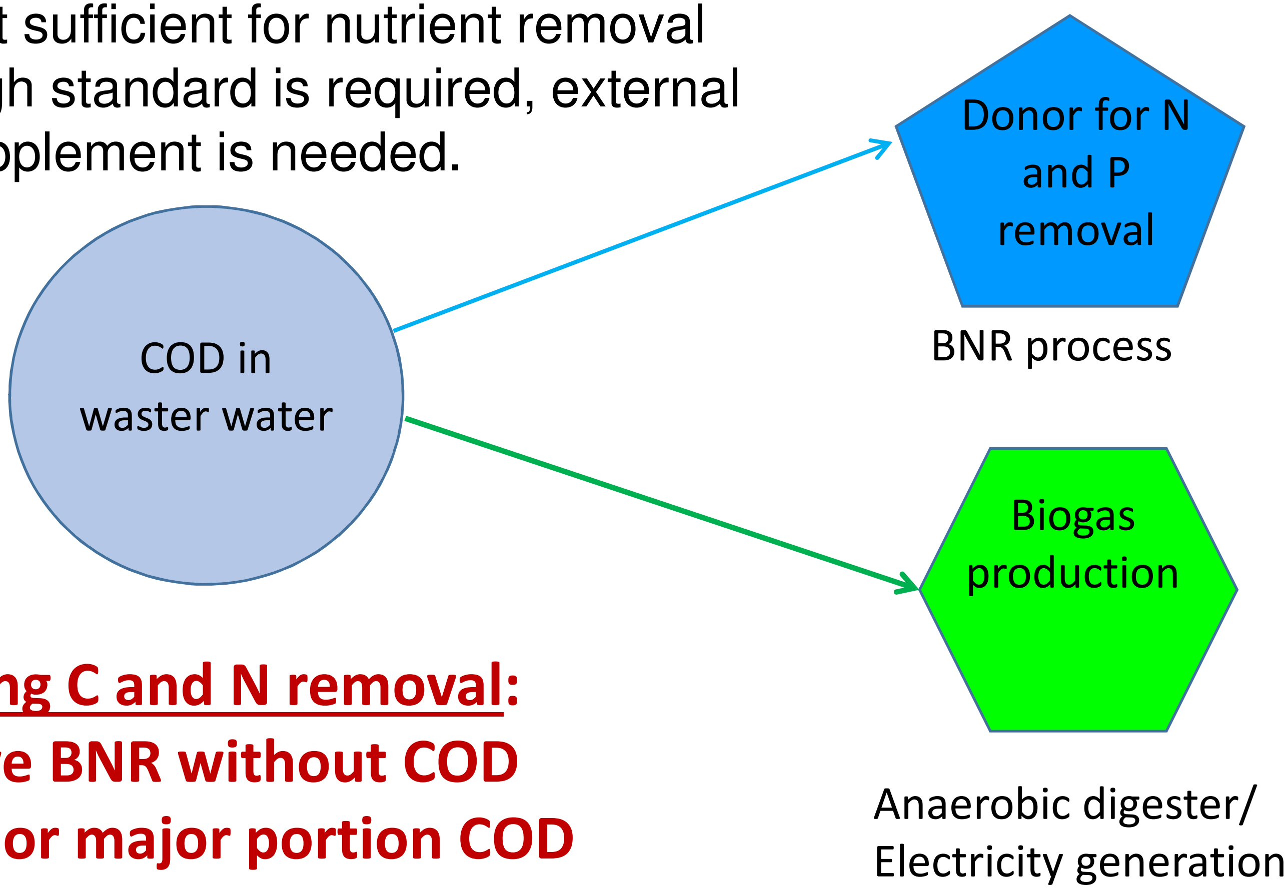
樟宜主流氨氮厌氧氧化项目和美国DC Water, HRSD和奥地利Strass废水处理厂在同一主题项目下一起获得2014年度国际水协(IWA)应用创新大奖

Outline 提纲

- Mainstream PN/A: an innovative process : 主流部分短程硝化和氨氮厌氧氧化: 一个创新的工艺技术
- Mainstream PN/A in Changi WRP, Singapore 樟宜回收水厂主流部分短程硝化和氨氮厌氧氧化
  - Configuration 反应器构型
  - Nitrogen profiling 氮浓度沿程分布
  - NOB suppression and Anammox activity 亚硝化氧化菌的限制和氨氮厌氧氧化活性
  - Nitrogen fate and balance 氮的分配和平衡
- What are the main benefits? 先进性/效益
  - Effluent inorganic nitrogen 出水氮和pH
  - Aeration energy 曝气能耗
- To try from the South part of China? **先在南方地区尝试**
- Summary 总结

A fundamental dilemma in WWT: Carbon Management
污水处理中的根本难题：碳管理

For conventional BNR, carbon in wastewater is often not sufficient for nutrient removal when a high standard is required, external carbon supplement is needed.



<u>Decoupling C and N removal</u>: Innovative BNR without COD need. All or major portion COD goes for energy recovery ?!!!

Cao, 2016

Autotrophic pathways for nitrogen removal
自养脱氮的反应途径

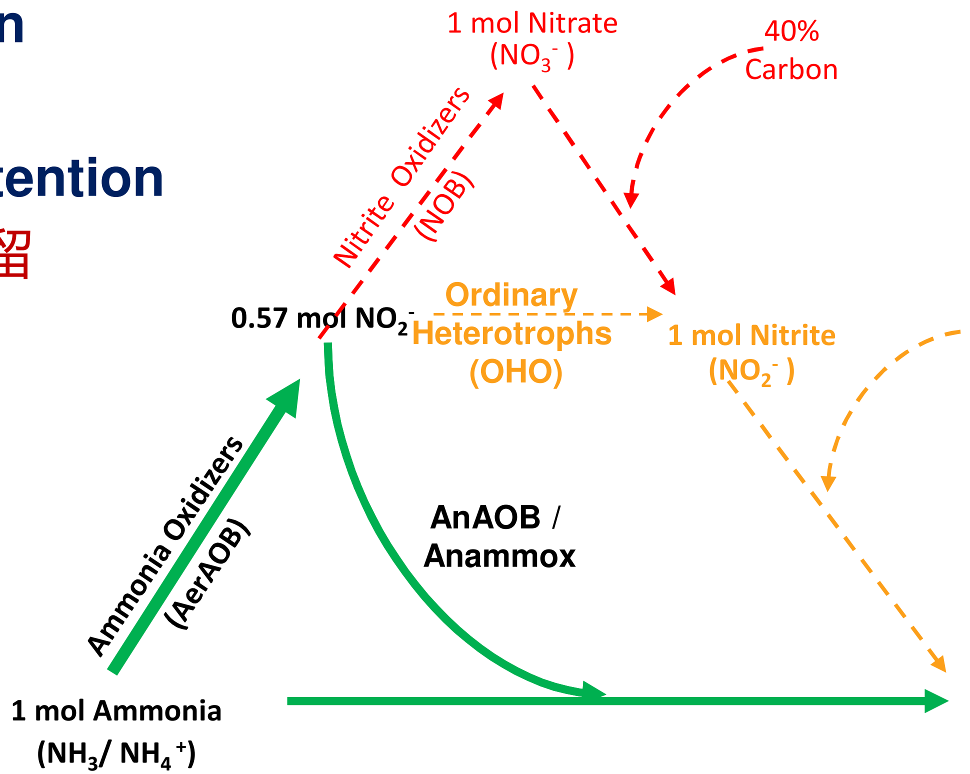
✓ **1. AOB Growth & Retention**
氨氧化菌的生长与截留

✓ **2. Anammox Growth & Retention**
厌氧氨氧化菌的生长与截留

✗ **3. Limit NOB Growth**
限制亚硝化氧化菌的生长

✗ **4. Control OHO Activity**
抑制普通异养菌的活动

? **5. PAO and GAO**
聚磷菌PAO和GAO



Stinson et al., 2013

ANAMMOX
"Anaerobic" Ammonia Oxidation - (New Planctomycete - Strous et al, 1999)

$$NH_4^+ + 1.32\ NO_2^- + 0.066\ HCO_3^- + 0.13\ H^+ \rightarrow$$
$$0.26\ NO_3^- + 1.02 N_2 + 0.066\ CH_2O_{0.5}N_{0.15} + 2.03\ H_2O$$

Technology innovation
技术创新

- 60% of aeration saving
  60%曝气能耗减少
- Little carbon needed for nitrogen removal
  不需要碳的氮去除
- Little excess sludge production
  很少剩余污泥产量

- Decoupling carbon and nitrogen removal, which allows direct carbon for energy generation
  使得碳和氮去除可以分开，因此碳可首要地用以能源回收发电
- Significant saving on the cost of aeration energy and sludge treatment and disposal
  大大的节省曝气能源和污泥处理与处置的成本

Revolutionary changes of wastewater treatment

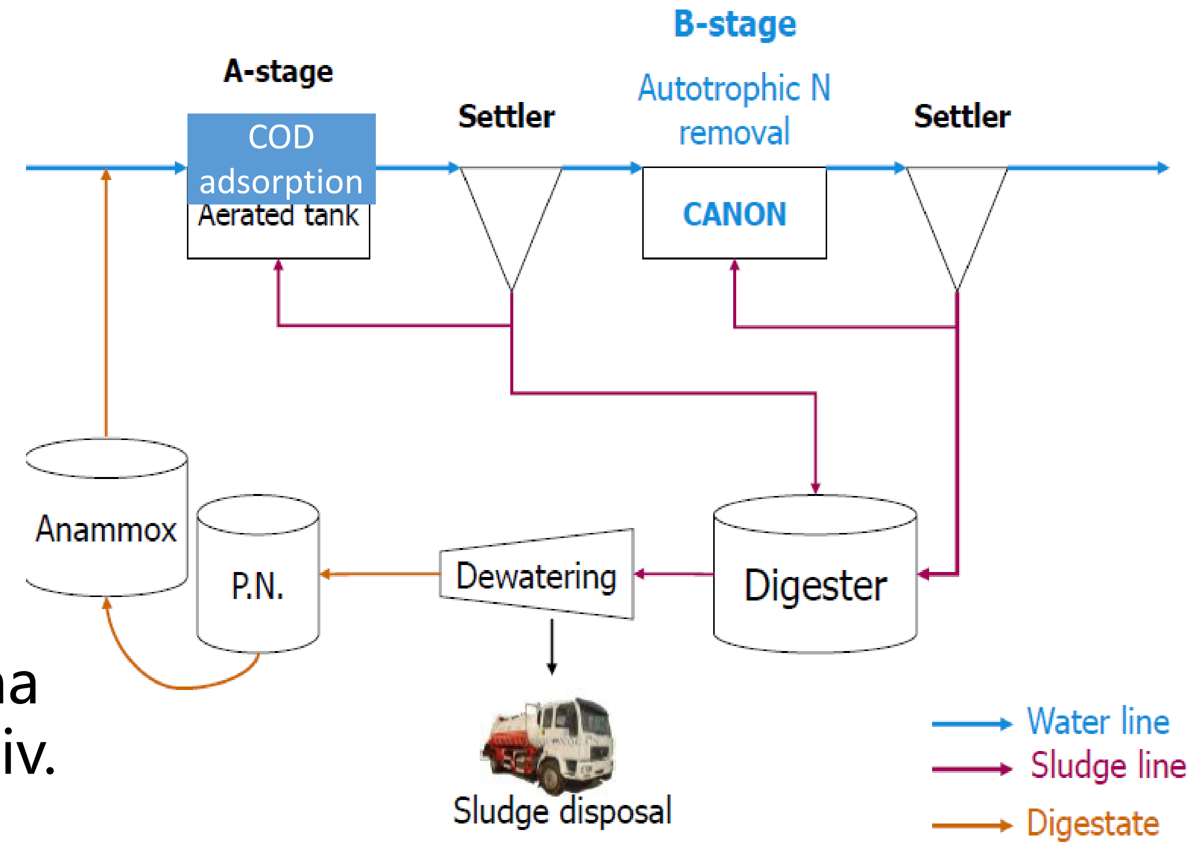
污水处理的革命性变革！

Future Plant 未来污水厂 Mainstream Anammox 主流厌氧氨氮氧化

Strass, Austria
Changi WRP, SG

Dokehaven, Rotterdam
DC Water, USA
Veolia, Paris
BDG, Beijing

BTU, Beijing, China
Ecolab, Ghent Univ.

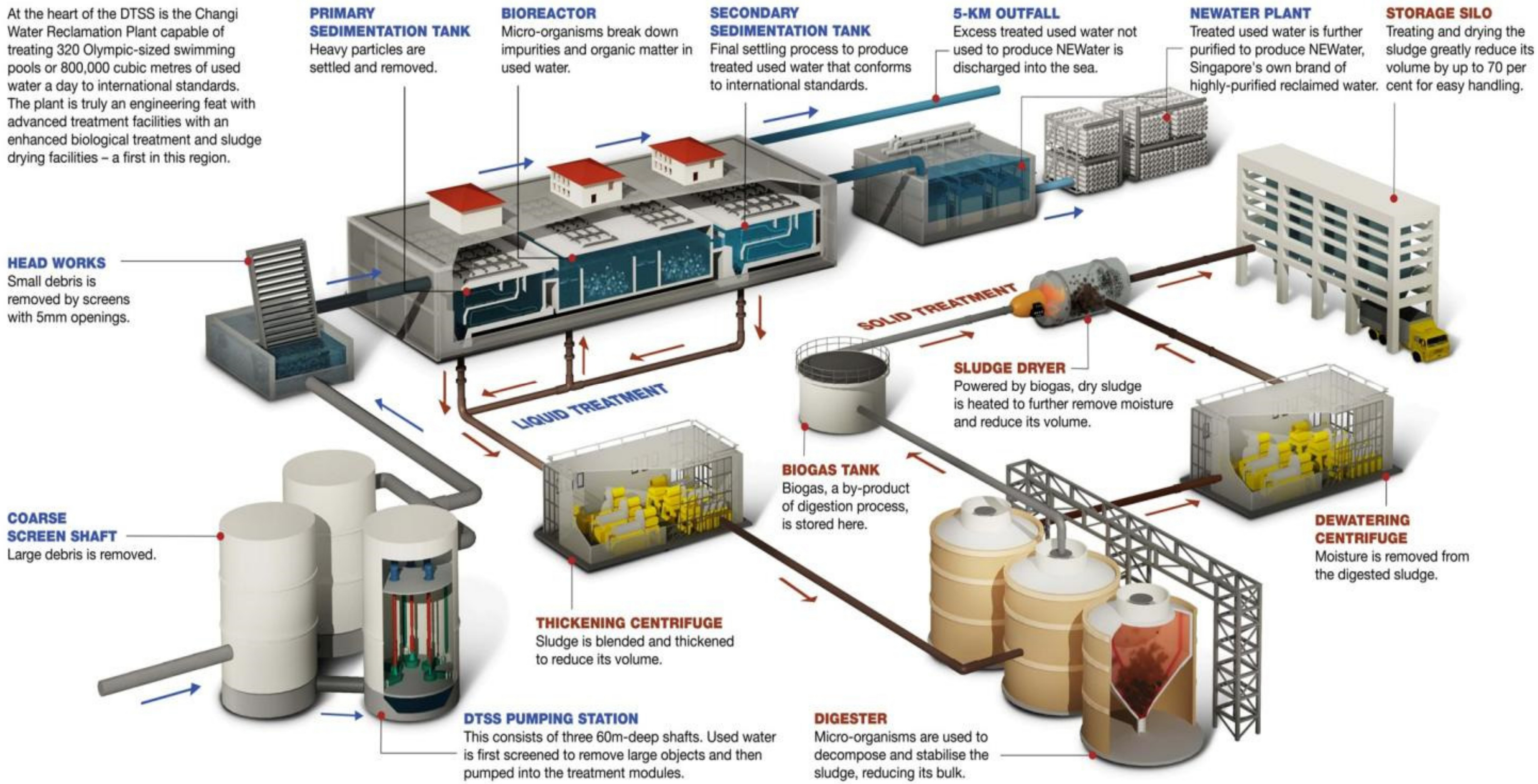


Lotti, 2013

A solution to conduct nutrient removal under the carbon limitation (low C/N ratio) of wastewater in China

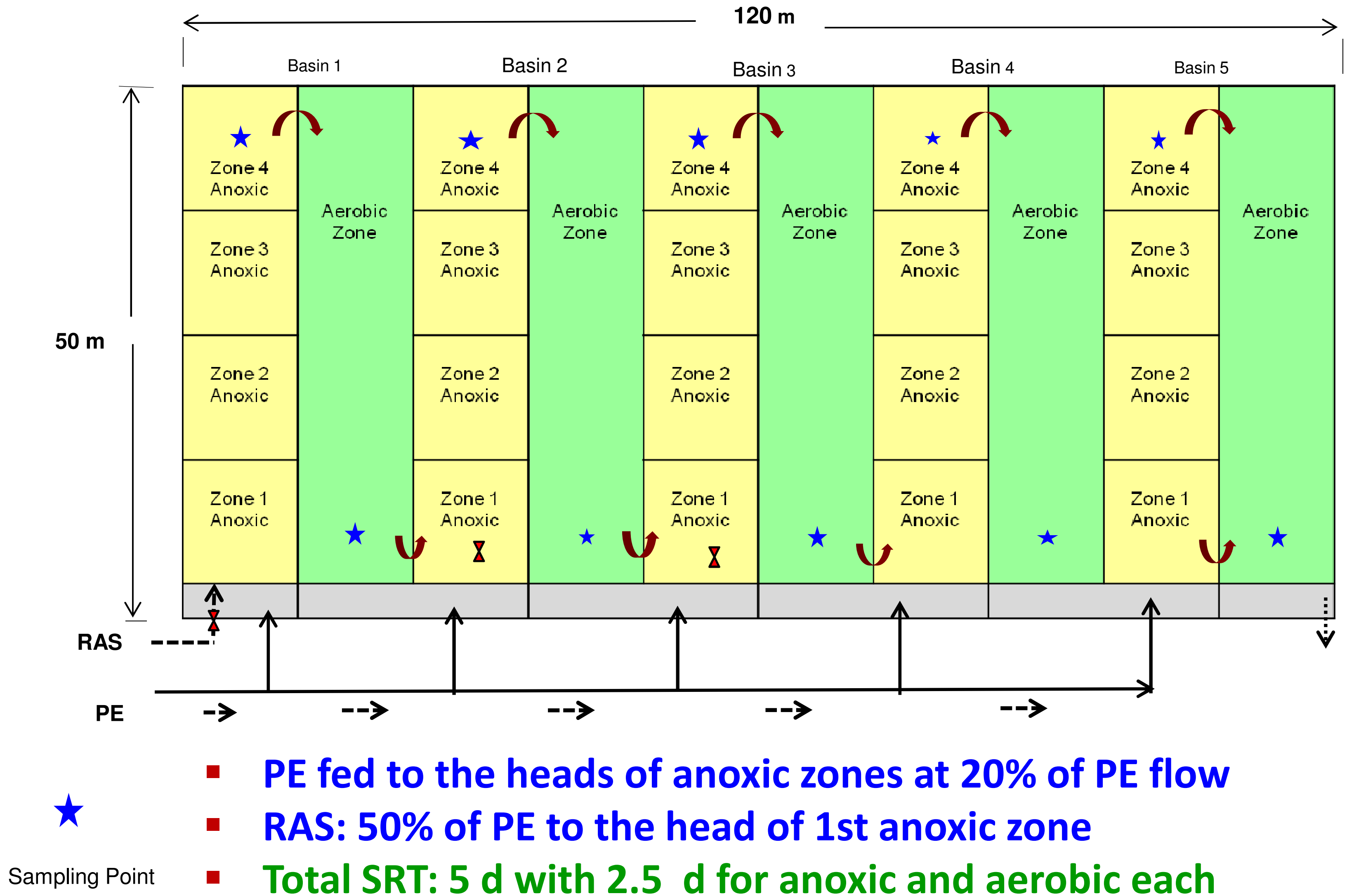
提供碳限制的条件下低碳氮比污水的脱氮除磷可能性

Changi Water Reclamation Plant
樟宜回收水厂



Step-feed activated sludge configuration and process

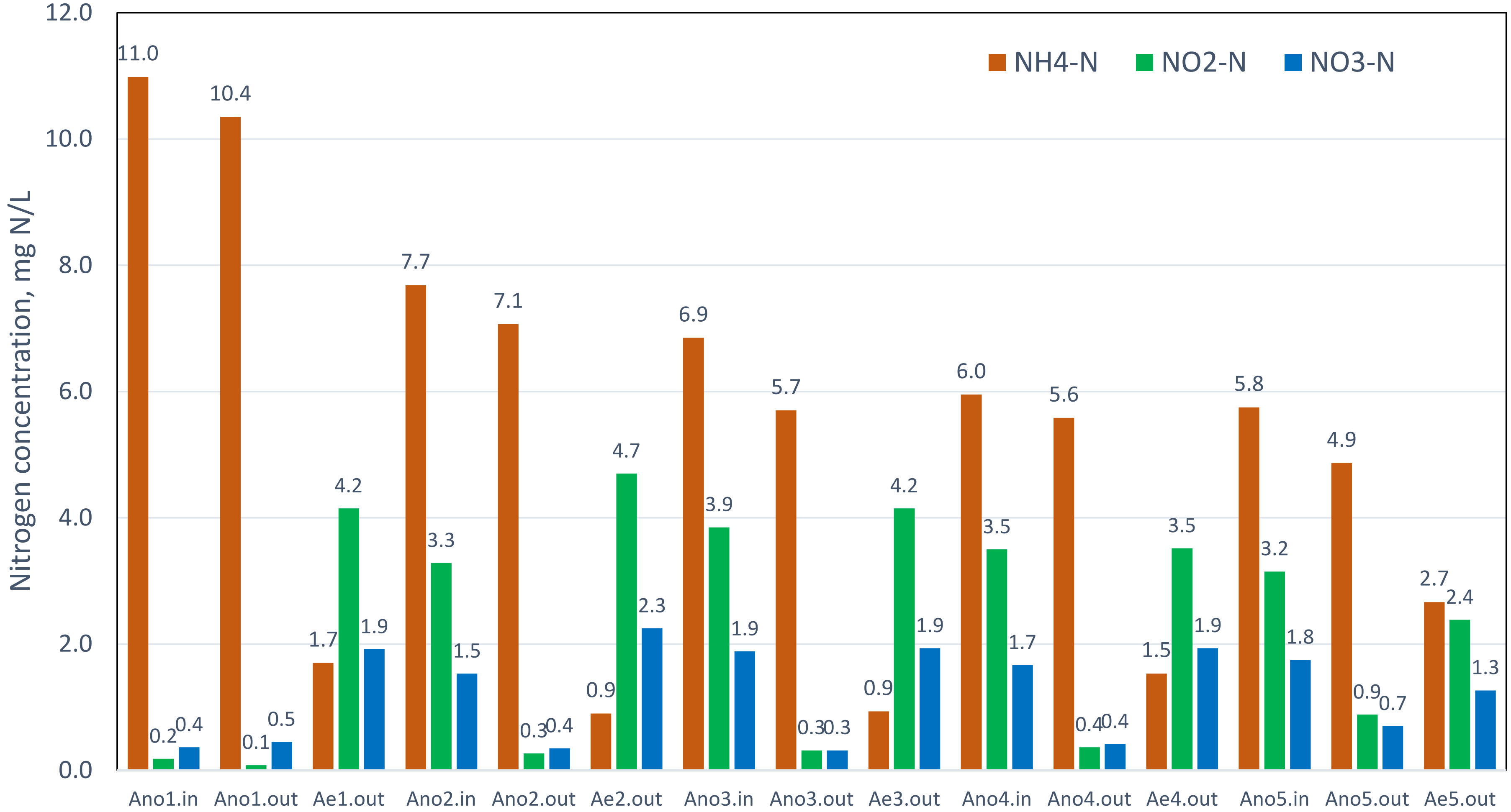
分段进水活性污泥法反应器构型和工艺



- **PE fed to the heads of anoxic zones at 20% of PE flow**
- **RAS: 50% of PE to the head of 1st anoxic zone**
- **Total SRT: 5 d with 2.5 d for anoxic and aerobic each**
- **HRT: 5.7 h, treatment capacity of single train: 200 000 m3/d**

Cao et al., 2013

Nitrogen profiling 氮浓度沿程分布 (2011-2015)



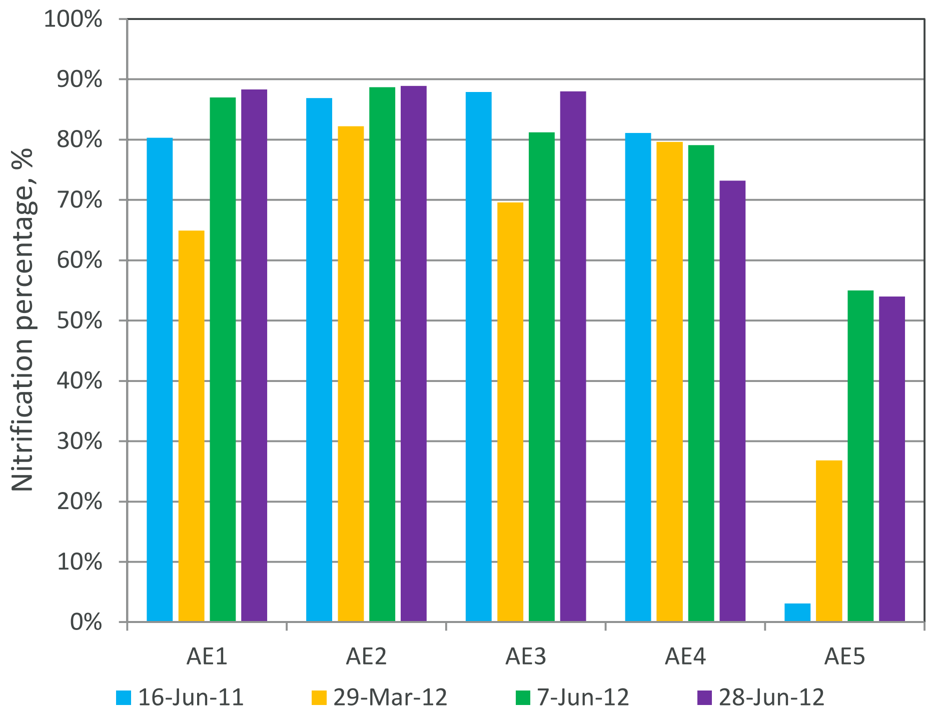
- **Ammonium removal in both aerobic and anoxic zones**
  氨氮去除在好氧区和缺氧区中都有发生
- **Robust nitrite shunt with an average 61.2% of NAR at aerobic zones**
  好氧区的短程硝化活跃. 高效的短程硝化!

Cao, 2016

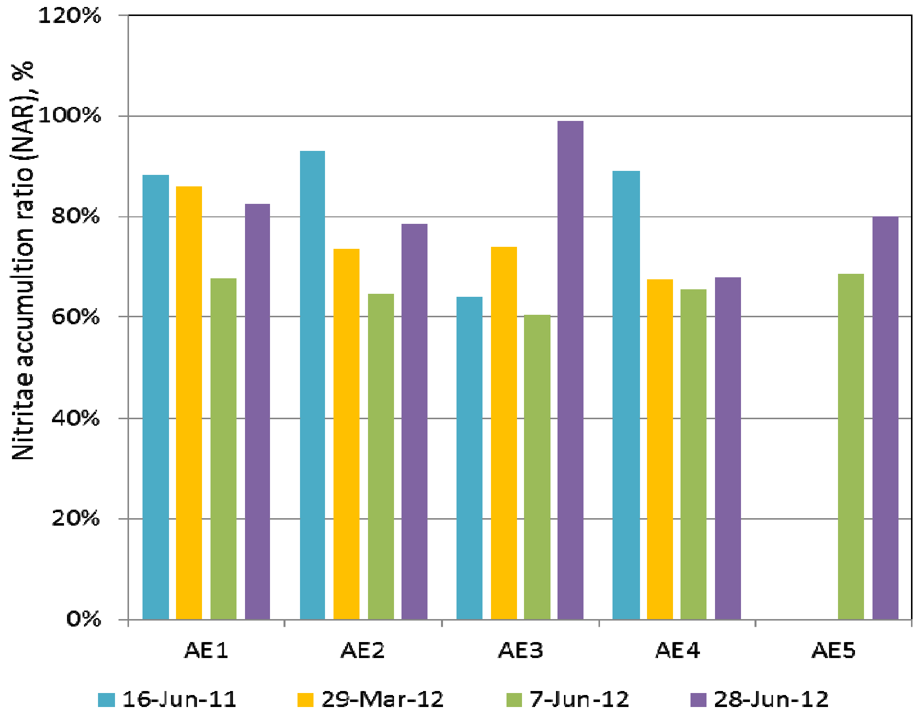
Partial nitritation in aerobic zones: 2011-2012

好氧区部分短程硝化: 2011-2012

NH_4 oxidation: 72.2%



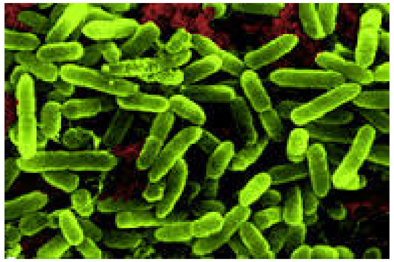
NO_2 ratio (NAR): 76.0%

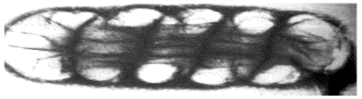


很高的亚硝酸盐积累率 (76.0%)

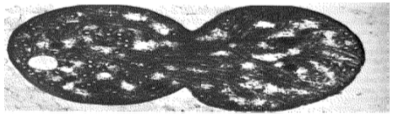
氨需氧化菌占支配地位, 亚硝化氧化菌生长被严重地抑制

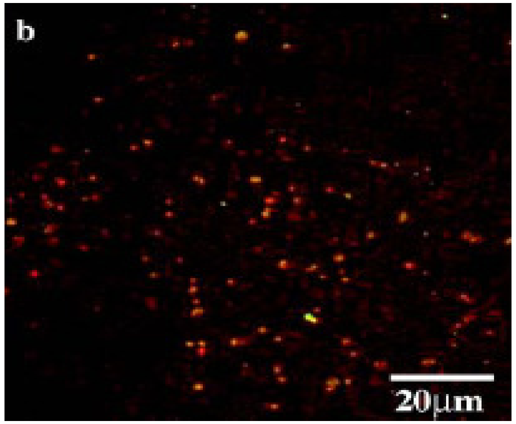
Nitrogen conversion microbial community
氮转化微生物分子学研究





Stanier et al., 1986





Isaka et al. (2006)

Nitrosomonas: **5.3E+7** copies/ml

Nitrobacter sp. **3.0E+7** copies/ml

Nitrospira sp: **0.4 E+7** copies/ml

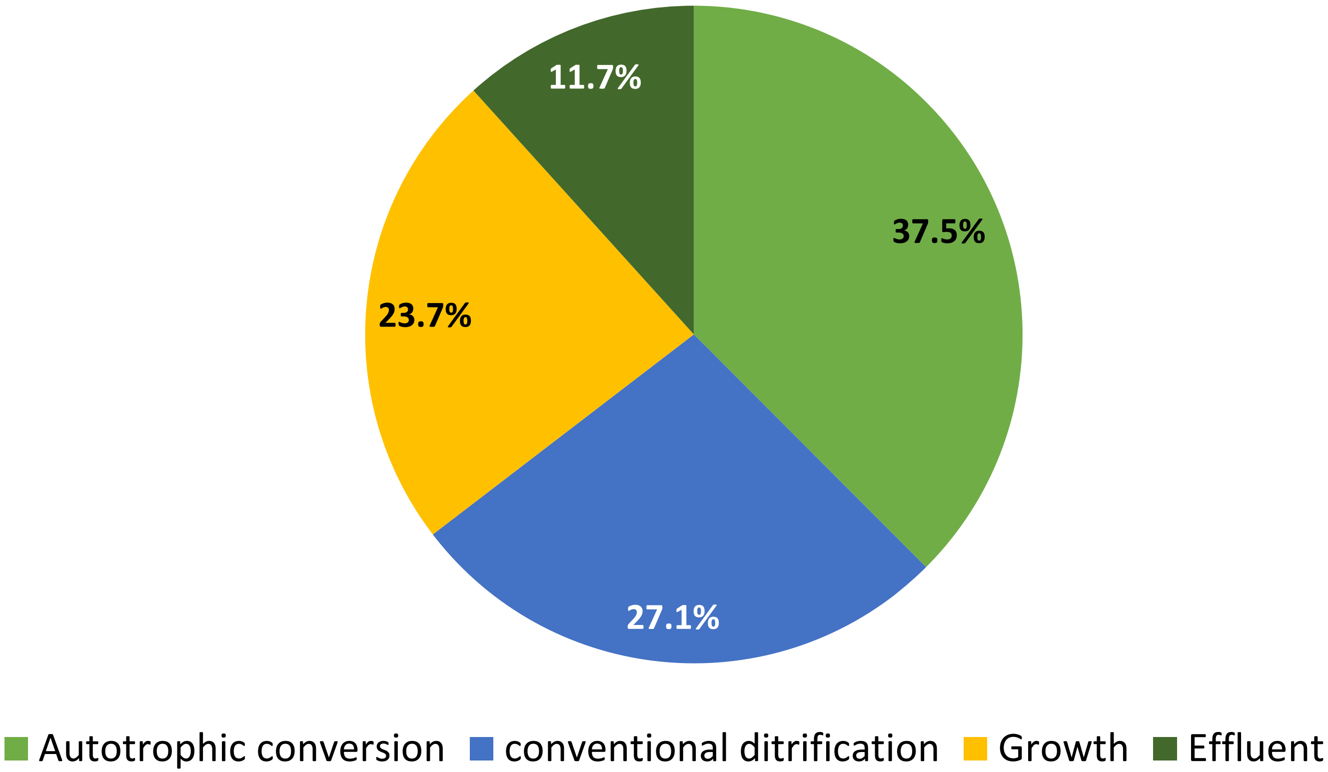
Lee et al., 2014

Dominant Anammox bacteria: ***Ca Brocadia* sp. 40** in morphology of free cells
μ_{max}: 0.35 day-1: the fastest growth Anammox bacteria (Lotti et al. 2015)

Population (16S rRNA gene): **2.37 (±2.6) x 10^{8} copies/g.ds**
Abundance (16 S rRNA gene): **0.83 ±0.18 %** (He, 2015)

Cao et al., 2014

Nitrogen fate and balance (2011-2013)
氮的分配和平衡 (2011 – 2013)



Nitrogen removal contribution through autotrophic pathways (37.5%) was higher than that of heterotrophic denitrification (27.1%).

通过自养通路的脱氮(37.5%)高于异养反硝化脱氮 (27.1%).

What are the advantages/benefits ?

先进性/效益在哪里？

The primary and final effluent: 2012
初级出水和最终出水水质: 2012

	unit	COD	SCOD	TSS	TN	NH4-N	NO2-N	NO3-N	TP	PO4-P	ALK (CaCO3)	pH
Primary effluent	g/m3	306	175	87	41	30.0	~ 0	~ 0	5.9	5.0	166	7.2
Effluent	g/m3	33	23	5.6	4.8	1.7	1.1	0.8	1.9	1.6	59	6.8
Removal efficiency	%	89.2	86.9	93.6	88.3	94.3	NA	NA	67.8	68.0	NA	NA

- COD: 306 mg/L, dilute sewage
- COD/N: 7.5
- ALK:166 mg/L (as CaCO3) near the lower boundary

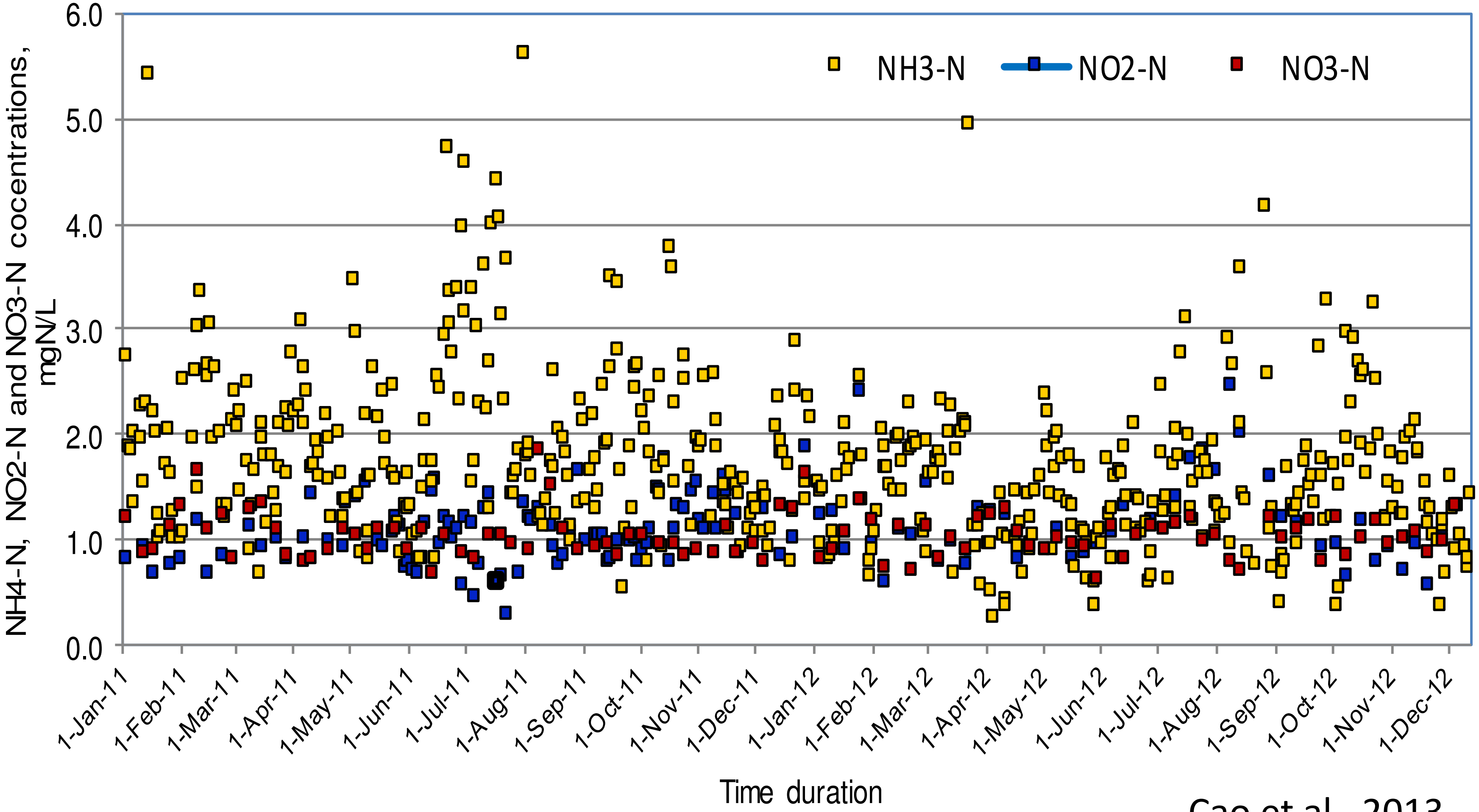
TN < 4 mg N/L with removal efficiency of 88.3%
出水总氮小于 5 毫克升, 去除效率达88.3%
Volumetric nitrogen removal rate (NRR): 0.12 kg N/m^3.d
氮体积去除速率 0.12 kg N/m3.d

Effluent inorganic nitrogen 出水无机氮: 2012年平均值

	NH4-N	NO2-N	NO3-N
Avg	1.7	1.1	1.0

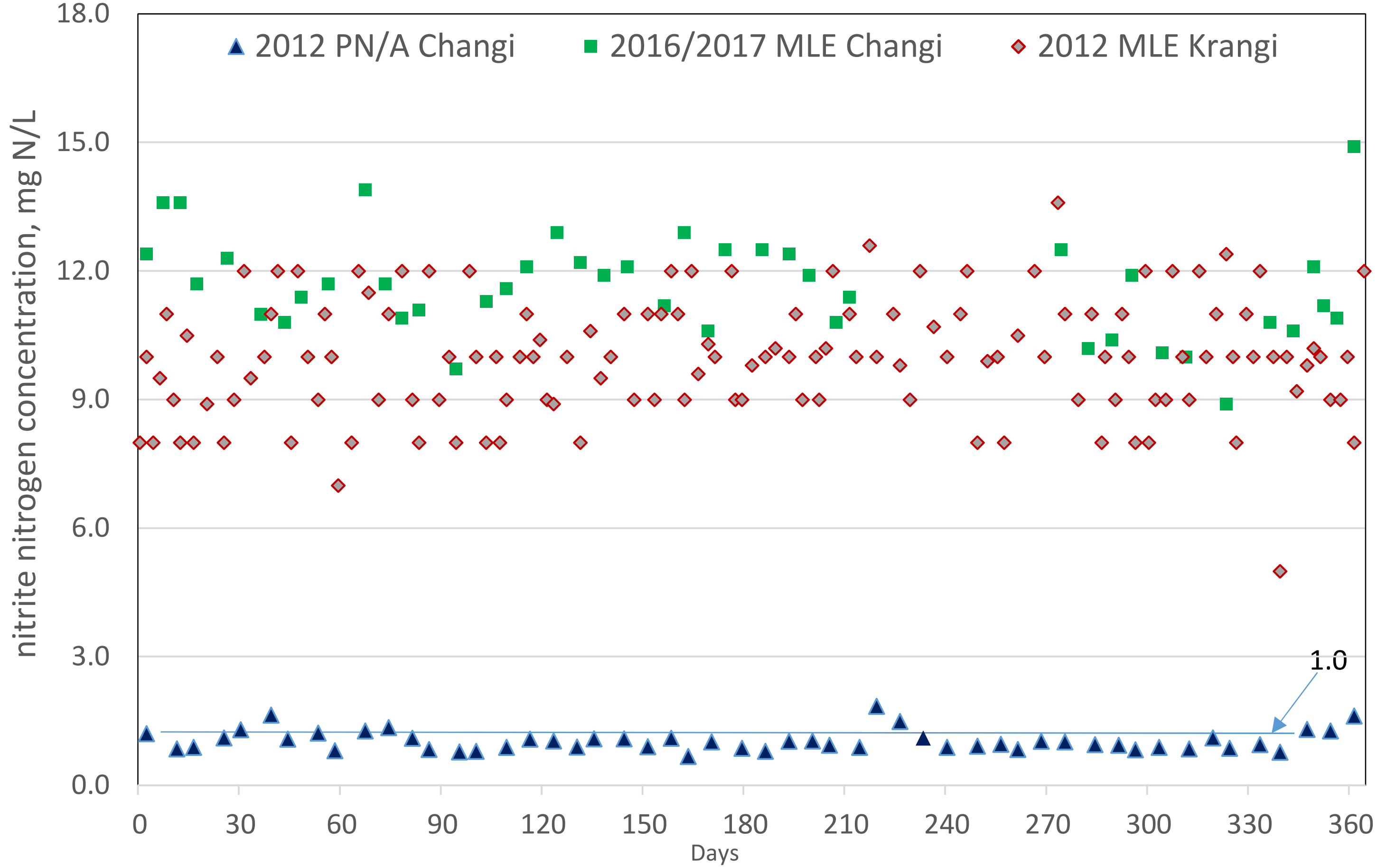
TN < 5 mg/L without chemical addition !

总氮小于 5 毫克升!



Cao et al., 2013

Comparison: nitrate in the final effluent
对比: 出水中硝酸盐氮



Almost 10 mg NO3-N/L less than conventional BNR process!

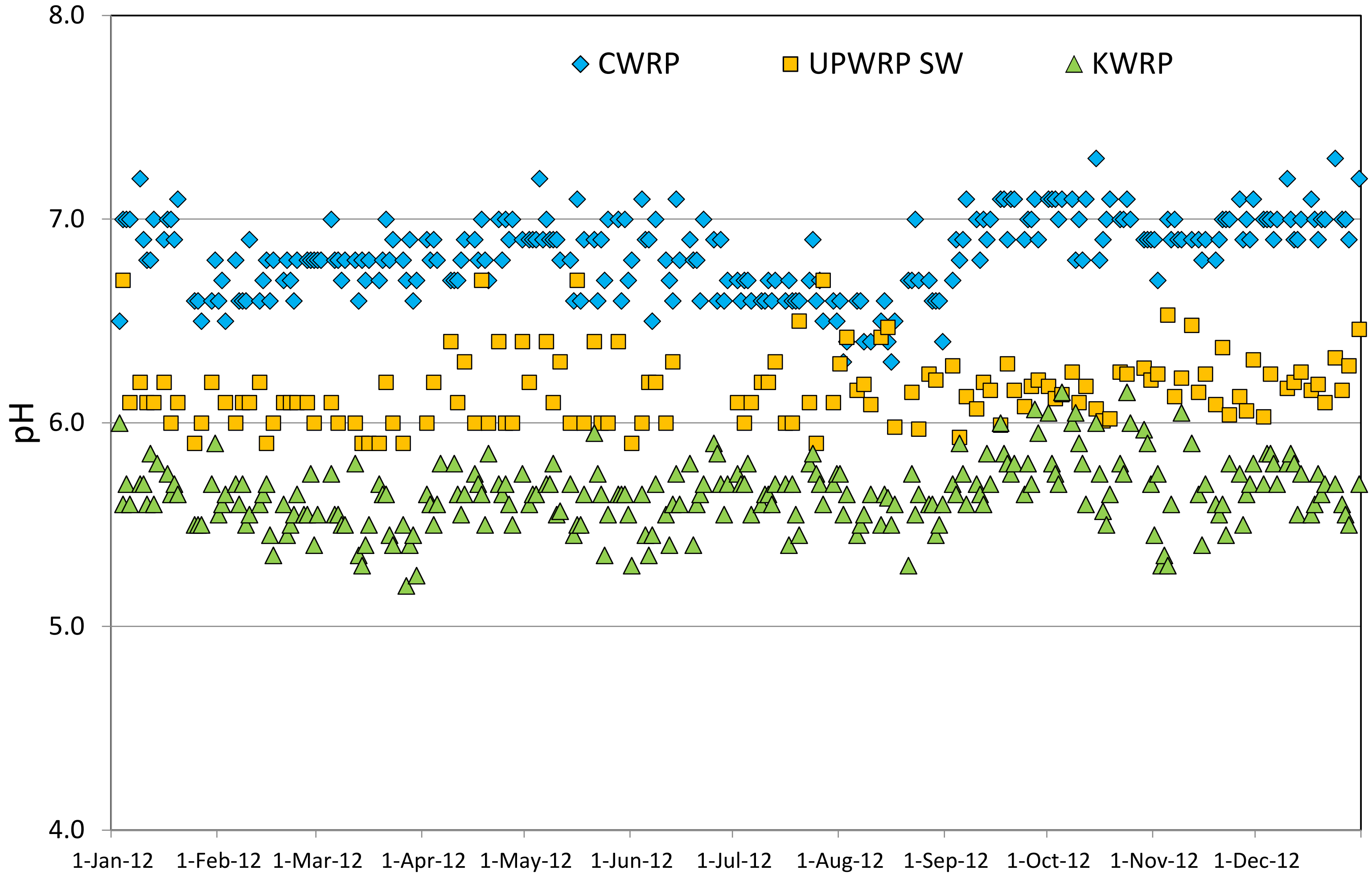
出水硝态氮比传统生物脱氮少大约10 毫克升!

Comparisons: final effluent nitrogen
对比: 出水中氮的各项值 (2012)

	NH_4-N mg N/L	NO_2-N mg N/L	NO_3-N mg N/L	TSIN mg N/L
CWRP PN/A, Train II	1.7 ± 0.8	1.1 ± 0.3	**0.8 ± 0.2**	**3.7**
UWRP MLE, South Work	1.8 ± 16	0.6 ± 0.5	**10.4 ± 3.1**	**12.8**
KWRP MLE, Phase III	1.6 ± 1.4	0.0 ± 0.1	**9.6 ± 1.3**	**11.2**

Cao et al., 2014

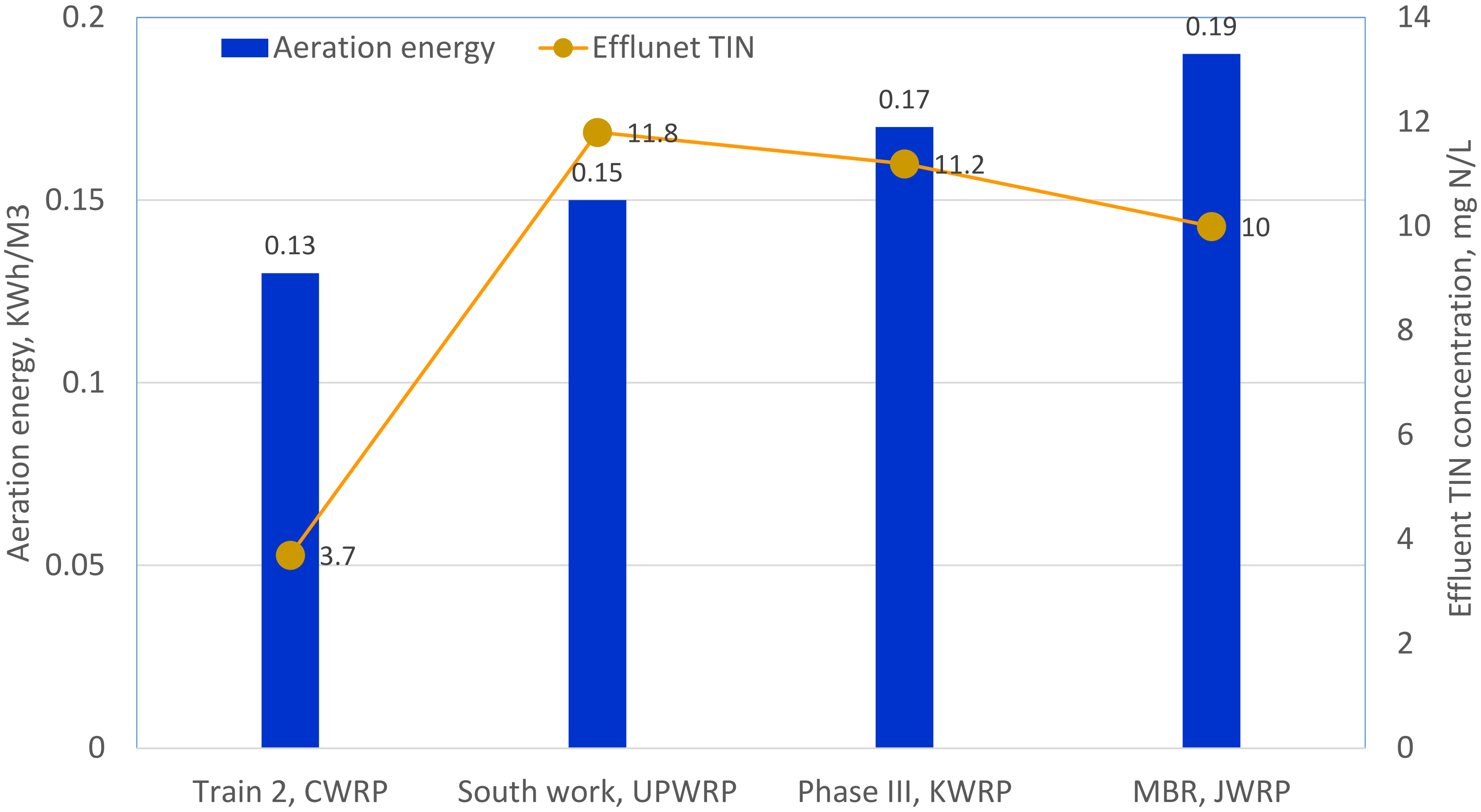
Comparison: effluent pH
对比: 出水 pH 2012



Changi: 6.8±0.2; UPWRP: 6.2±0.3; KWRP: 5.6±0.2

Cao et al., 2014

Comparisons: Aeration energy
对比：曝气能耗



The lowest aeration energy with the highest N removal: saving from PN/N nitrogen removal

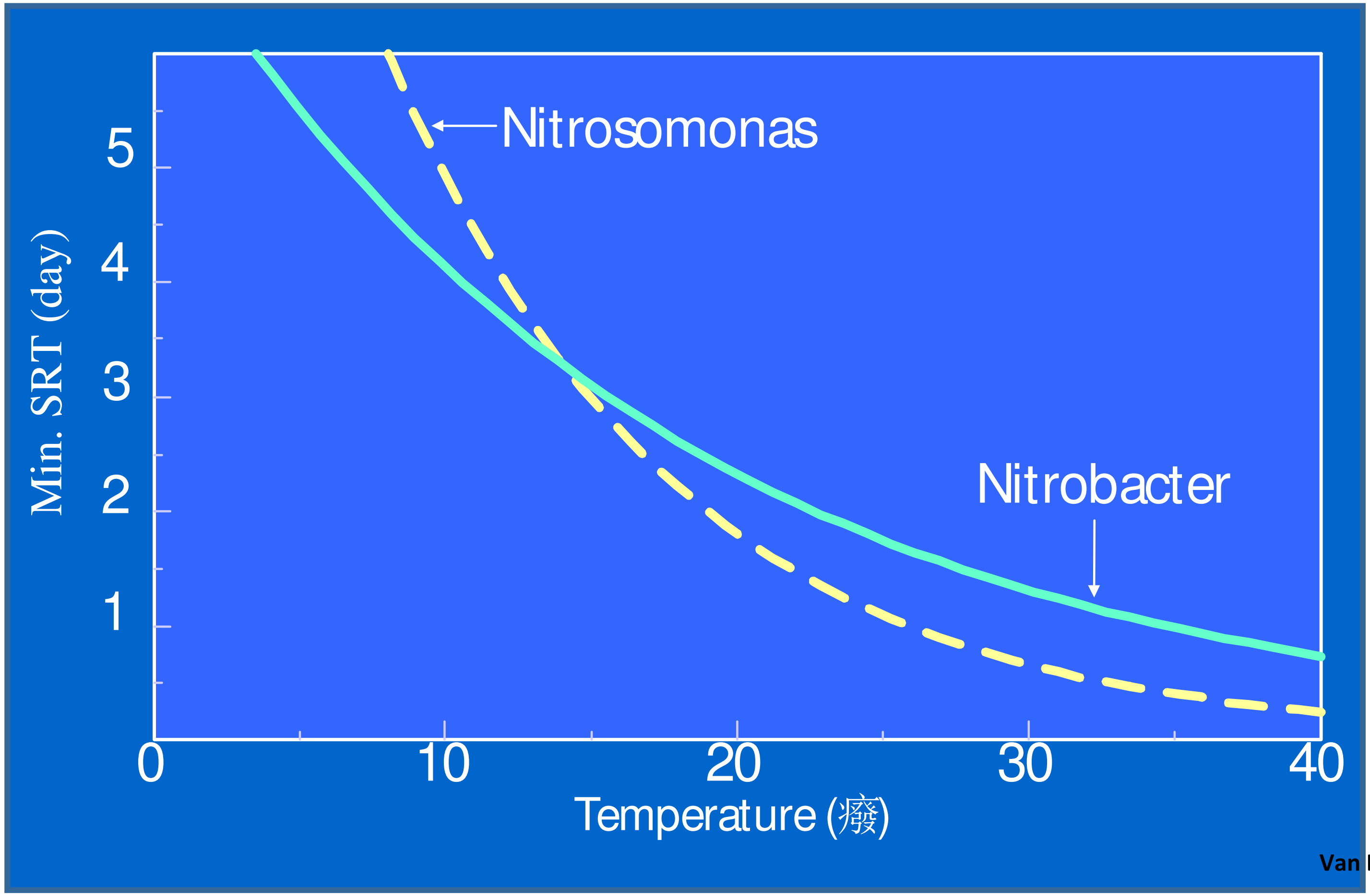
曝气能量减少百分之10到30！

Cao et al., 2014

Factors to make Changi mainstream PN/A story
樟宜主流部分短程硝化和氨氮厌氧氧化的因素

- High temperature,
  高温
- Residual ammonium
  残余氨氮
- transient anoxia
  瞬态缺氧好氧
- Short aerobic SRT
  短泥龄
- On-line control
  在线控制

Key factor of nitrite of shunt: temperature
亚硝酸途径的最关键因素: 温度



Van Dongen et al. (2001)

What is the annual temperature range in Hainan and Guandong?

海南和广东的年度温度范围?

Summary 总结

- Excellent nitrogen shunt due to strong NOB suppression was achieved in the aerobic zones; Anammox reaction occurred in the anoxic zones. Nitrogen mass balance indicated the nitrogen removal through autotrophic pathway was higher than heterotrophic denitrification.
- 在好氧区建立高效的部分短程氮氧化且抑制亚硝化氧化菌生长; 厌氧氨氧化发生在缺氧区. 氮平衡表明通过自养通路的脱氮高于异养反硝化脱氮.
- The annual average effluent TN was less than 5 mg TN/L, almost 10 mg N/L less than that of conventional BNR; while aeration energy was 10-20% less.
- 年平均出水总氮小于 5 毫克升, 比传统生物脱氮少大约10 毫克升. 与此同时, 曝气能量少10~30%.
- It is feasible first to explore application of mainstream PN/A in the South part of China.
- 首先在南方地区开发主流部分短程硝化和氨氮厌氧氧化的工艺应用.

Mainstream PN/A in Changi WRP

Cao, Y.S., Kwok, B. H., Yong, W. H., Chua, S. C., Wah, Y.L. and Yahya ABD GHANI (2013) The Main Stream Autotrophic Nitrogen Removal in the Largest Full Scale Activated Sludge Process in Singapore: Process Analysis. WEF/IWA Nutrient Removal and Recovery 2013: Trends in Resource Recovery and Use, July 28-31, 2013, Vancouver.

Cao Yeshi, Kwok Bee Hong, Yan Zhou, Zarraz Lee, Yu Liu, Jianzhong He, van Loosdrecht, M.C.M, Daigger G. T., Winson Lay, Chua Seng Chye, Wah Yuen Long and Yahya Ghani (2014a) Activated Sludge Nitrogen Removal in Warm Climates: from Conventional to Innovative processes. IWA Global Challenges: Sustainable Wastewater Treatment and Resource Recovery, 2014, Kathmandu, Nepal.

Cao, Y. S., Kwok, B. H., Noraini, A. Z. Lau, C.L., Zulkifli, I., Chua, S.C., Wah, Y. L. and Yahya A. G. (2014b) The Mainstream Partial Nitritation-Anammox Nitrogen Removal in the Largest Activated Sludge Process and Comparisons with Other BNR Activated Sludge Process in Singapore, IWA World Water Congress, 21-26 Sept. 2014, Lisbon.

Cao Yeshi, Kwok Bee Hong, Mark C. M. van Loosdrecht, Glen. T. Daigger, Png Hui Yi, Chua Seng Chye, Yuen Long Wah and Yahya ABD Ghani. (2015) Mainstream Partial Nitritation and Anammox in a 200 000 m3/day Activated Sludge Process in Singapore: scale-down by using laboratory fed-batch reactor. IWA Nutrient Removal and Recovery 2015: moving innovation into practice. May 18-21, 2015, Gdansk, Poland.

Cao Yeshi, Kwok Bee Hong, Mark C.M. van Loosdrecht, Glen. T. Daigger, Chua Sun Chye, Wah Yuen Long, Yahya ABD Ghani (2016) The EPBR coupled Mainstream Partial Nitritation and Anammox in a 200 000 m3/day Activated Sludge Process in Singapore, *WEF/IWA Nutrient Removal and Recovery Conference*. 10-13 July 2016. Denver, USA .

Cao Yeshi, Kwok Bee Hong, van Loosdrecht, M.C.M, Daigger G. T., Wah Yuen Long, Chua Seng Chye and Ooi Kian Eng (2017a) The Influence of Dissolved Oxygen on PN/A Performance and Microbial Community of the 200, 000 M^3/D Activated Sludge Process at the Changi Water Reclamation Plant (2011 to 2016). IWA NRR/LWWTP Conference, 10-13 Nov. 2017, Chongqing, China (accepted).

Cao Yeshi, Mark van Loosdrecht, Glen T. Daigger (2017b) Mainstream Partial Nitritation-Anammox in Municipal Wastewater Treatment: Status, Bottlenecks and Further Studies (Review paper). Appl. Microbial. Biotech . 101(4): 1365-1383 (DOI:10.1007/s00253-016-8058-7).

Acknowledgment

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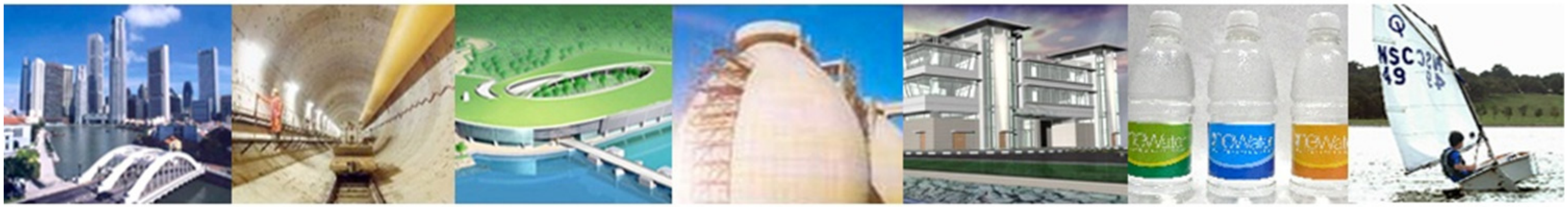

Thank you !

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