

# STRENGTHENING DO-BASED AERATION CONTROL IN BNR SYSTEMS

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## 1. ABSTRACT

Aeration control is one of the most complex and energy-intensive aspects of Biological Nutrient Removal (BNR) wastewater treatment, with dissolved oxygen (DO) directly influencing effluent compliance, process stability, operating cost, and greenhouse gas (GHG) outcomes. This paper evaluates control philosophies applicable to plants like the Ballarat South Wastewater Treatment Plant (WWTP), a multiple aeration tank BNR facility operated by Central Highlands Water. Fixed DO setpoint control, Most Open Valve Pressure (MOVP), ammonia-based aeration control (ABAC), and advanced approaches such as Model Predictive Control (MPC) and Artificial Neural Networks (ANN) are compared using experienced practitioner input into a qualitative framework. The framework considers effluent stability, energy efficiency, resilience, operator usability, scalability, and GHG mitigation.

Simulations using recent plant data and a simplified oxygen transfer and blower power model are then used to compare a fixed DO baseline control configuration with a hybrid ABAC–MOVP. Results indicate that no single control philosophy is universally optimal; instead, well-designed hybrid approaches with robust fallback logic and strong operator engagement provide the most practical and reliable solution. At the Ballarat South WWTP, the hybrid strategy may achieve approximately 12% average daily aeration energy savings and an estimated annual reduction of 1,300 tonnes CO<sub>2</sub>-equivalent. These findings reinforce that strengthening DO-based aeration control requires not only optimisation capability, but also reliability and operational resilience.

## 2. INTRODUCTION

Aeration is the dominant controllable energy demand in activated sludge and Biological Nutrient Removal (BNR) systems and plays a central role in maintaining biological stability. By regulating the dissolved oxygen concentration (DO), operators directly influence nitrification performance, process resilience, and overall treatment reliability.

Maintaining DO within an effective operating range is inherently dynamic. Oxygen demand varies with diurnal loading, seasonal temperature changes, and operational disturbances. Insufficient aeration risks ammonia breakthrough, while excessive aeration increases energy use and reduces efficiency. DO control is therefore a balance between compliance assurance, energy performance, and operational robustness.

At the Ballarat South WWTP, operated by Central Highlands Water, the importance of resilient aeration control was highlighted by an operational incident involving effluent ammonia concentrations exceeding operational targets. Although not solely caused by aeration control issues, the event highlighted the sensitivity of nitrification performance to instrumentation reliability, supervisory response, and control logic response transparency under abnormal conditions. It underscored the need for stronger fallback logic and clearer oversight within the aeration control architecture. The plant comprises three parallel aeration tanks with independently controlled aeration zones supplied by fine-bubble diffusers and high-speed turbo blowers operating pressurising a common aeration header/manifold. This layered control structure provides flexibility but introduces interaction between DO control logic and whole of system supervisory strategies, increasing the importance of coordination and resilience.

Across the industry, utilities face similar constraints: sensor fouling and drift, communication interruptions, variable influent characteristics, tightening effluent standards, and increasing pressure to reduce energy consumption and greenhouse gas emissions. While advanced and model-based

control approaches promise improved responsiveness, their practical success depends on data integrity, system transparency, operator trust, and robust behaviour during sensor or actuator failure.

This paper evaluates fixed DO, MOVP, ABAC, and advanced model-based aeration control philosophies (as outlined in Table 1) at Ballarat South WWTP using a structured framework calibrated to CHW’s context. The framework is built from a synthesis of practical challenges, input from industry practitioners, and site-specific considerations, and uses a pairwise comparison method to weight performance parameters. The paper then applies high-frequency plant data and a simplified oxygen transfer and blower power model to compare a fixed-DO baseline against a hybrid ABAC–MOVP architecture. The overall aim is to identify control approaches that strengthen DO-based aeration control by balancing effluent performance, resilience, energy efficiency, operator usability, scalability, and GHG mitigation in a practical, implementable manner.

Group	Control Philosophy	How it works ?or expected to in BS	Key Data/ Instrumentation required	Operational Constraint	Fallbacks Applied /Expected
DO Setpoint - Driven Control	Fixed DO Setpoint	Zone DO held at constant setpoints via PID	DO analysers	Over-aeration at low load, Analyser reliability	Manual DO increase/decrease
	Time-of-Day DO	Scheduled DO setpoints layered on PID	DO analysers, clock logic	Poor wet-weather adaptability, Analyser reliability	Revert to fixed DO
	Low-DO Operation	Intentional operation near minimum DO	High-quality DO, Ammonia & Nitrate analysers	Narrow control margin	Lift to conservative DO
	MOVP (Efficiency Overlay)	Blower pressure trimmed based on most open valve while DO PID remains active	Header pressure, Do analysers, Valve position feedback	Valve feedback reliability, Analyser reliability	Fixed pressure mode
Process-Responsive Control	ABAC	Ammonia signal adjusts common DO setpoints across lanes	Ammonia & DO Analyser	Ammonia & DO analyser fouling/drift	Automatic reversion to DO control
	Fuzzy Logic	Rule-based multi-signal control emulating operator judgement	DO, Ammonia, P, flow & Other as may be required	Rule tuning and validation effort	Default rule set or DO-only control
Predictive / AI Control	MPC	Predictive model optimises aeration over future horizon	DO, NH <sub>4</sub> , flow, MLSS	Model accuracy	PID / DO fallback
	ANN	Data-driven prediction of optimal aeration	Large multi-sensor dataset	Data quality, transparency	ABAC / DO fallback

Table 1. Control Philosophies considered in this paper.

### 3. DISCUSSION

#### Evaluation framework and pairwise weighting

To systematically compare aeration control philosophies against Central Highlands Water's (CHW) operational priorities, six key performance parameters were defined and weighed through pairwise comparison. These factors were derived by applying a risk lens to CHW’s regulatory obligations and sustainability objectives.

Parameter	Relative Weight (%)	Key Driver
Effluent Compliance & Stability	32%	Highest regulatory and environmental risk
Resilience / Fallback Capability	23%	Frequent instrumentation and asset challenges
Energy Efficiency	13%	Major operational cost contributor
Scalability / Future Readiness	12%	Long-term planning and digital maturity
Operator Usability / Training Needs	11%	Human factors influencing reliability
GHG Mitigation	10%	Sustainability and emissions

Table 2. Key process control factors weighed through pairwise comparison

## Scoring Rubrics for Semi-Quantitative /Qualitative Assessment

For each parameter, semi-quantitative rubrics defined 1–5 scores in terms of measurable bands (for example, exceedance frequency, energy saving, number of fallback modes, training hours), and the same 1–5 structure was used for separate Capex and Opex ratings. Several experienced practitioners independently scored each philosophy using these rubrics, and scores were averaged to obtain representative “benefit ratings” and cost indices for Ballarat South WWTP.

Parameter	What the 1–5 score represents
Compliance & stability	% of ammonia exceedances and DO safety margin
Resilience / fallback	Number and quality of fallback modes and FDI
Energy efficiency	% change in aeration energy vs fixed DO
Operator usability	Training hours and number of parameters to monitor
Scalability	Ease of adding sensors/analytics
GHG mitigation	Change in Scope 1+2 emissions
Capex cost	Order-of-magnitude implementation cost
Opex	Net change in annual operating cost (energy, GHG, maintenance)

Table 3. Simplified Rubric matrix (1–5 ratings)

Average weighted Score	Benefit Ratings (Expert)	Cost(capex+opex)	Benefit/cost ratio
ANN	3.5	11.7	30%
ABAC	3.3	8.0	41%
MPC	3.4	11.0	31%
Fuzzy Logic	3.8	10.0	38%
MOVP	3.0	7.3	41%
Time of Day DO	3.1	5.7	55%
Low-DO	2.3	6.7	35%
Fixed DO	2.9	6.7	44%
Hybrid			
ABAC+MOVP+FixedAir	4.3	7.3	59%
Hybrid ANN+ABAC+MOVP	4.0	11.7	35%

Table 4. Averaged benefit ratings, combined cost (Capital +Operational) and benefit–cost ratios for aeration control philosophies (expert and author assessment)

Applying the weighted rubric scores produced average benefit ratings ranging from approximately 2.3 to 4.3. Advanced data-driven approaches such as Artificial Neural Networks (ANN), Model Predictive Control (MPC), and fuzzy logic achieved relatively high technical benefit scores (3.4–3.8). These systems performed strongly across energy efficiency, scalability and theoretical GHG mitigation potential. However, their dependence on high-quality datasets, model maintenance and communication reliability reduced their resilience scores. Lower transparency and interpretability also reduced operator usability ratings, particularly under abnormal operating conditions where manual override confidence is essential.

Among single-layer strategies, Ammonia-Based Aeration Control (ABAC) and Most Open Valve Pressure (MOVP) optimisation performed strongly because they directly target ammonia-driven compliance and blower efficiency while maintaining relatively transparent and well-understood logic structures. These philosophies retained established fallback modes and therefore scored higher in resilience compared to ANN or MPC-based approaches.

### Hybrid performance and resilience

The three-layer Hybrid ABAC + MOVP + Fixed Air configuration achieved the highest average weighted benefit score (4.3). Its strength lies not only in optimisation potential but in architectural robustness.

The structure distributes optimisation across independent layers: “Layer 1 – ABAC: Ammonia-responsive DO setpoint control, Layer 2 – MOVP: Blower pressure optimisation, Layer 3 – Fixed Air / Fixed DO: Deterministic fallback mode”.

This layered approach enables graceful degradation. If ammonia analysers drift, valves fail, or communications are interrupted, the system transitions to simpler deterministic control rather than experiencing abrupt optimisation collapse. This significantly improved resilience scoring under CHW’s risk-weighted framework.

In contrast, the Hybrid ANN + ABAC + MOVP strategy, while achieving a high benefit rating (4.0), remained constrained by ANN’s dependency on dense multi-sensor inputs and specialist model oversight. Under abnormal events, reduced interpretability lowered operator trust, impacting both resilience and usability metrics.

### Capex, Opex and Value Assessment

Cost indices were derived using the same 1–5 rubric approach applied to Capex and Opex categories and averaged across experienced practitioners.

ANN and MPC strategies attracted the highest cost indices (11.7 and 11.0 respectively), driven by:

- Additional instrumentation
- Data infrastructure requirements
- Model development and commissioning effort
- Ongoing specialist maintenance

The Hybrid ANN + ABAC + MOVP configuration also recorded a high-cost index (11.7) because it layers ANN capability rather than replacing lower-cost optimisation methods.

By comparison, the Hybrid ABAC + MOVP + Fixed Air approach achieved a moderate cost index of 7.3. Capital investment is primarily associated with ammonia analysers and supervisory logic modifications, without requiring full machine-learning infrastructure.

Lower complexity strategies such as Time-of-Day DO, Low DO and Fixed DO recorded the lowest cost indices (5.7–6.7), reflecting reliance on existing instrumentation.

To evaluate value per unit cost, a normalised benefit–cost ratio was calculated as:

$$\text{Benefit–Cost Ratio} = \frac{\text{Average Weighted Benefit Score}}{\text{Cost Index}}$$

The Hybrid ABAC + MOVP + Fixed Air configuration achieved the highest ratio (59%), indicating the strongest performance return for investment under CHW’s weighted risk profile.

Time-of-Day DO achieved a relatively high ratio (55%) due to very low implementation cost.

However, its absolute benefit rating (3.1) was substantially lower, limiting its suitability as a primary optimisation architecture. It is better positioned as a supplementary or fallback layer.

Although Hybrid ANN + ABAC + MOVP achieved a strong benefit score (4.0), its high combined cost reduced its benefit–cost ratio to 35%, making it unsuitable for near-term deployment under current capital constraints.

### Quantitative Performance Analysis

A 24-hour model was created, populated with the diurnal flow profile and ammonia concentration for the plant. Power consumption and GHG emissions were modelled for Fixed DO control and ABAC+MOVP control. Results are charted in Figures 1, 2 and 3 below. The daily ammonia load was 1,037.3 kg (56 mg/L average, 28-90 mg/L range, double-peak pattern).

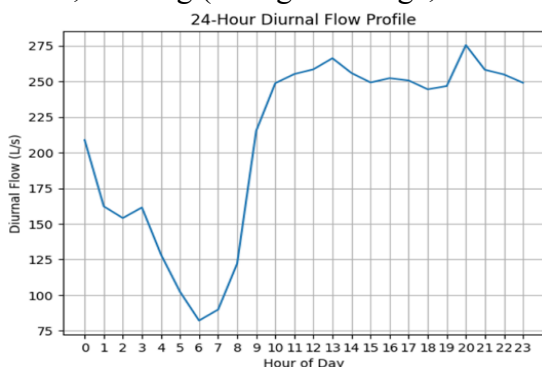


Figure 1 Diurnal flow profile

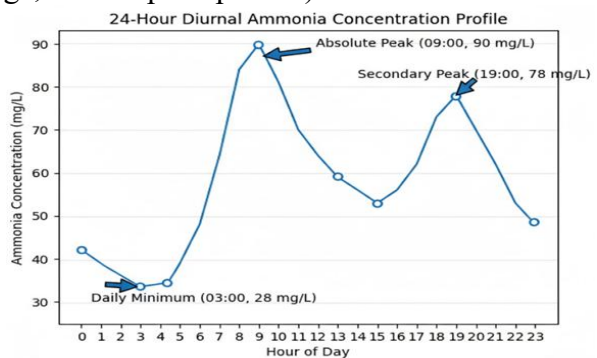


Figure 2 Diurnal Ammonia concentration

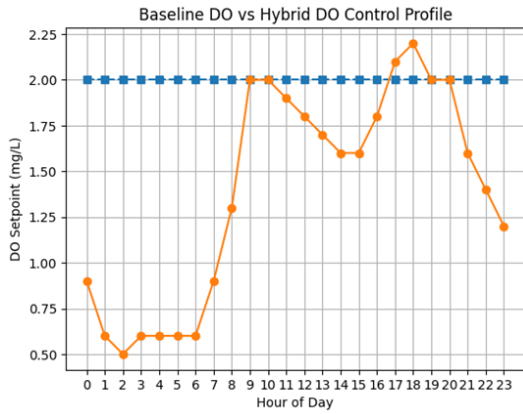


Figure 3 DO concentration, FIXED DO and ABAC+MOV P

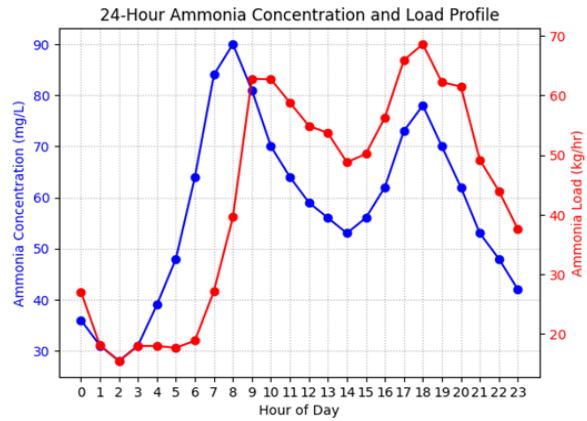


Figure 4 Diurnal Ammonia concentration and load profile

Normalised blower power results in Figure 4 show a peak hourly reduction of 24.24% (Hour 2), a minimum reduction of 5.29% (Hour 18), and an average daily reduction of 12.27% under the hybrid/combined configuration. Scaled to actual aeration energy consumption of 9,072.41 kWh/day, this would be a significant electricity saving.

Analysing greenhouse gas emissions, using the Victorian grid emission factor of 0.85 kg CO<sub>2</sub>/kWh, Scope 2 reductions were calculated directly from energy savings. Scope 1 N<sub>2</sub>O emissions were estimated using a baseline emission factor of 1.2% (IPCC 2019 range up to 1.6%) and a hybrid factor of 0.6% (representative lower-range value for stable nitrification conditions, with a GWP of 273 (IPCC AR6)). The emissions are shown in Figure 5.

The combined mitigation equates to approximately 3,616.5 kg CO<sub>2</sub>e per day, or ~1,320 tonnes CO<sub>2</sub>e annually.

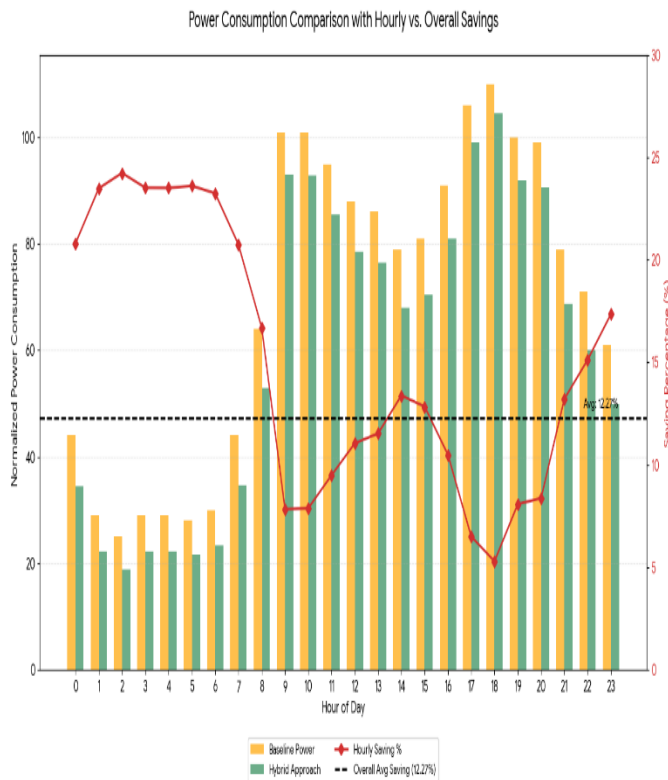


Figure 5 Power consumption comparison /Saving percentage in KWh

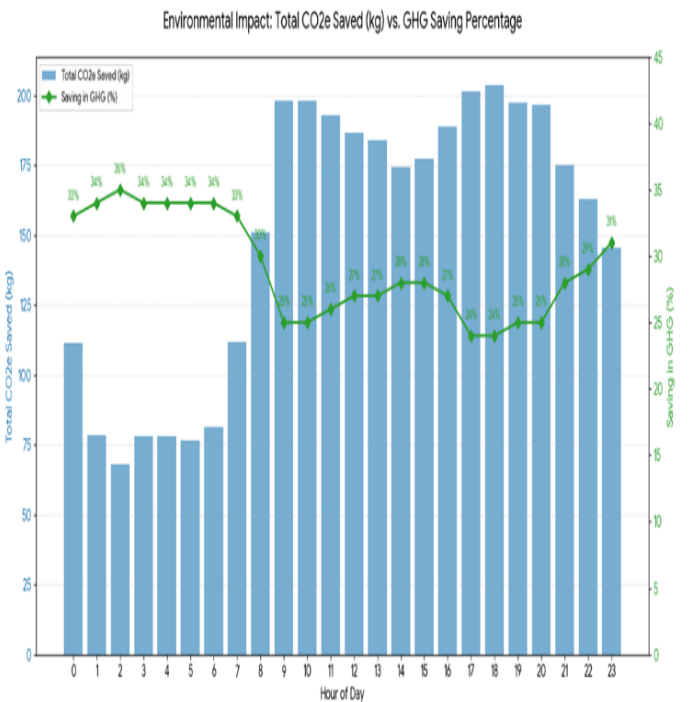


Figure 6 GHG emission comparison/Saving percentage in kgCO<sub>2</sub>e/hr

## Fault & Resilience framework

In reviewing the reliability of various control philosophies, it is important to consider the failure modes and control response for the key instrumentation and equipment. Table 6 summarises these for the Ballarat South WWTP. These have been considered in the analysis to date.

Failure Mode	Detection Logic	Automated Response	Resilience Benefit
<b>NH<sub>3</sub> Analyzer Fault</b>	Loop validation: signal freeze detection or lack of variance during measurable influent flow fluctuations	ABAC bypass; revert to fixed 2.0 mg/L DO baseline	Ensures effluent compliance and prevents ammonia breakthrough
<b>DO Probe Drift / False-Low</b>	Blower-to-DO correlation: Increase in blower frequency (Sdf\$) does not produce expected \$dC/dt\$ response	VFD clamping; switch to flow-paced volumetric air delivery (open-loop control)	Prevents ammonia spike, energy waste, or biomass stress
<b>Actuator Failure (MOVVP Valve Jam)</b>	PLC command vs valve position feedback mismatch	Isolate affected zone; redistribute air to maintain header pressure	Prevents blower surge and mechanical fatigue
<b>Blower Mechanical Failure</b>	Header pressure instability or loss of VFD feedback	Load redistribution; temporary DO relaxation	Maintains minimum nitrification capacity
<b>Process Shock Load (Hydraulic or Nitrite Spike)</b>	Rapid influent flow change or NH <sub>3</sub> -NOx imbalance	Temporary DO elevation or flow-paced override	Reduces N <sub>2</sub> O escalation risk and protects compliance
<b>Control System / PLC Communication Loss</b>	Device heartbeat timeout or signal loss	Revert to conservative fixed DO operation	Maintains safe aeration envelope under degraded control

**Table 6 Failure modes and response**

## 4. CONCLUSION

This study applied a structured, risk-weighted framework to evaluate aeration control strategies for BNR wastewater treatment at Ballarat South WWTP. No single control philosophy is universally optimal. Advanced strategies such as ANN and MPC offer strong theoretical potential but carry disproportionate implementation risk at CHW's current stage of operational capability and capital availability. The three-layer Hybrid ABAC + MOVVP + Fixed Air architecture achieved the highest weighted benefit score (4.3/5.0), the strongest benefit–cost ratio (59%), and the most robust resilience profile. Quantitative simulation confirmed a 12.27% average daily reduction in aeration energy — equivalent to approximately 1,113 kWh/day and 1,320 tonnes CO<sub>2</sub>e per annum. Its layered design is its core strength: ABAC delivers ammonia-responsive compliance protection, MOVVP optimises blower efficiency, and a fixed airflow fallback provides unconditional process protection under fault conditions.

CHW is recommended to adopt a staged implementation pathway — beginning with MOVVP (no additional instrumentation required), followed by ABAC integration as analyser performance and operator capability are confirmed. Future work should include site-specific N<sub>2</sub>O monitoring to validate GHG reduction estimates.

## 5. ACKNOWLEDGEMENT

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