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Risk-Constrained Wastewater Control under Missing Sensor Measurements: Analysis of an Original Hourly Dataset with Dhaka-Relevant Ecological Conditions

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Abstract

Intermittent instrumentation failure is a persistent obstacle to dependable wastewater control, and its consequences are most severe in catchments where receiving waters are already ecologically degraded. This study analyzes an original hourly operational dataset spanning 90 consecutive days to examine how incomplete dissolved oxygen measurements influence treatment performance, effluent release decisions, and receiving-water oxygen condition under circumstances comparable to those of Dhaka, Bangladesh. The dataset comprises 2,160 hourly records for each of three control strategies, giving 6,480 strategy-level records in total, and it carries a full set of process, effluent, and receiving-water variables. Dissolved oxygen measurements were absent or stale during 20.83 percent of time steps. Three strategies were assessed on the identical hourly record: fixed feedback control at a constant aeration setting of 0.62, imputation-based control that acted on the most recent dissolved oxygen estimate, and risk-constrained control that adjusted aeration according to both the estimated concentration and its accumulated uncertainty. Under risk-constrained control, the release gate withheld wastewater whenever estimation uncertainty exceeded 0.55 mg/L or estimated dissolved oxygen fell below 1.75 mg/L. Mean effluent biochemical oxygen demand declined from 25.28 mg/L under fixed feedback control to 22.43 mg/L under risk-constrained control, a reduction of approximately 11.3 percent, while the share of time steps exceeding the 20 mg/L benchmark fell from 84.82 to 69.82 percent. Mean receiving-water dissolved oxygen rose from 4.84 to 5.02 mg/L, and the proportion of hours with river dissolved oxygen below the 4 mg/L screening threshold declined from 13.38 to 7.13 percent, a relative reduction of approximately 46.7 percent. These ecological gains carried a measurable operational cost, because wastewater was withheld from release during 11.62 percent of time steps, equivalent to 251 of the 2,160 hours. The evidence indicates that treating outage duration as an explicit uncertainty term, rather than substituting a single best estimate, offers a defensible basis for coupling treatment control with release safety in data-scarce settings.

Keywords

wastewater treatment; sensor data; uncertainty; dissolved oxygen; risk-constrained control; effluent; Dhaka

1. Introduction

Urban rivers in South Asia carry a burden that is simultaneously chemical, ecological, and institutional. Around Dhaka, the rivers that frame the city receive a mixture of municipal sewage and untreated industrial discharge, and the resulting water quality signature has been documented repeatedly over the past decade. Monitoring of outfalls along the peripheral rivers has identified severe pollution and associated aquatic ecological risks, with pollution indices placing the Buriganga, Dhaleshwari, and Turag rivers in the severely polluted category and organic pollution indices indicating heavy contamination in the Dhaleshwari and Buriganga systems (Majed & Islam, 2022). Parameters including suspended solids, BOD5, and ammoniacal nitrogen deviate by as much as 40 to 50 percent from the industrial discharge standards set under Bangladesh environmental conservation rules (Majed & Islam, 2022). Such findings are not isolated. Seasonal monitoring across the Dhaka rivers has recorded the lowest average dissolved oxygen during the dry season, with the lowest values at the Buriganga and Turag, and dry season BOD reaching 46 mg/L in the Turag, 42 mg/L in Tongi Khal, 30 mg/L in the Shitalakhya, and 18 mg/L in the Buriganga (Islam, 2023).

Comparative assessments underscore how far these systems depart from usable conditions. One of the earliest systematic surveys of the Turag reported dissolved oxygen ranging from 0.11 to 6.8 mg/L and BOD from 10 to 180 mg/L across wet and dry seasons, values that place large portions of the river outside the range suitable for human consumption without treatment (Rahman, 2012). A comparative study of the peripheral rivers found a maximum dry season BOD of 165 mg/L in the Buriganga, alongside 78 mg/L in Tongi Khal, 55 mg/L in the Balu, and 52 mg/L in the Turag, with the lowest monsoon value of 12 mg/L recorded in the Turag (Hasan et al., 2013). Seasonal analyses of the Turag have shown that only 40 percent of measured water quality indices fell within permissible limits, with electrical conductivity, chloride, total alkalinity, turbidity, dissolved oxygen, BOD5, and chemical oxygen demand exceeding limits in all seasons, and winter identified as the period of highest pollutant concentrations (Rahman et al., 2021). Working on three main rivers around the city, another study found dry season contamination loads significantly higher than monsoon loads, and attributed the difference jointly to anthropogenic activity and to seasonal variation in river discharge (Islam et al., 2015).

Recent work has translated these observations into the language of ecological and human health risk. A multi-season assessment of seventeen stations across the Dhaka rivers reported water quality index values from 105.36 to 268.62 in winter, with 68.18 percent of samples classified as very poor, a heavy metal pollution index peaking at 379.2, and an ecological risk index reaching 245.86 in the Buriganga (Ruma et al., 2025). Pollution severity followed the order Buriganga, Turag, Dhaleshwari, Shitalakshya, and Balu, and the total carcinogenic risk of 1.34E-04 exceeded the acceptable safety limit of 1.00E-04 (Ruma et al., 2025). The same body of work points to a structural driver, since the textile sector alone generated 217 million cubic meters of wastewater in 2016 that was discharged into the river system, and the Turag, Tongi, and Balu network experiences contamination throughout the year (Suchi et al., 2024). Industrial activity accounted for 37.56 percent of national gross domestic product in fiscal year 2022 to 2023, and most industrial units are located along riverbanks (Roy & Mostafa, 2026).

Set against this backdrop, the operational question is not whether treatment infrastructure exists but whether it can be controlled reliably when the measurements on which control depends are themselves unreliable. Sensor gaps in wastewater treatment plants arise from fouling, maintenance, and outright failure, and they are frequently long and irregular (Simethy et al., 2025). Once a dissolved oxygen probe drifts, fouls, or stops responding, the controller loses the signal that governs aeration intensity, and that loss is rarely confined to the plant boundary. Effluent leaving the plant during a measurement outage propagates into a receiving water whose assimilative capacity is already exceeded. Regulatory frameworks in Bangladesh supply the reference points against which such discharges are judged, with the Department of Environment specifying dissolved oxygen of 4.5 to 8 mg/L and ammoniacal nitrogen of 50 mg/L for inland surface water, and BOD benchmarks of 50 mg/L for several industrial categories (Majed & Islam, 2022). Nationally documented guidance places the accepted BOD value for wastewater at 50 mg/L, alongside a total dissolved solids limit of 300 mg/L and a total suspended solids limit of 100 mg/L (Shamsuzzaman et al., 2021).

2. Literature Review

2.1 Missing measurements and data quality in treatment systems

The treatment of missing values in wastewater data has matured from ad hoc gap filling into a distinct methodological field. A systematic review of imputation practice in wastewater treatment plants set out to examine existing research on missing value imputation, to identify and outline the various imputation techniques employed in the field with attention to their respective strengths and limitations, and to distill recommendations for addressing the limitations of the reviewed studies; from 599 candidate forms, 16 research papers were selected to assess the review questions (Chaoui et al., 2023). A widely cited framing of the problem distinguishes gap filling from the broader data pipeline, noting that no sensor achieves full uptime and that the appropriate method depends on gap duration and analytical purpose; among the strategies recommended for water resource recovery facility data are interpolation, correlation with other available signals, substitution from an average daily profile, repetition of preceding day values, and replacement with model output (Therrien et al., 2020).

More recent contributions have attacked the problem with increasingly expressive models. Diffusion-based approaches reframe time series imputation as state transition under partial observability, where targets, controls, and exogenous signals may all be intermittently missing, and they have been evaluated on treatment plant datasets containing both synthetic block gaps and naturally occurring outages (Simethy et al., 2025). Transfer learning has been proposed specifically for the case of high missing proportions, using historical and parallel datasets as source knowledge filtered through an extended Kalman filter to avoid negative transfer (Han et al., 2023). Gaussian process regression has been applied to both missing flow rate estimation and ammonium sensor drift detection, with the finding that a sequential Monte Carlo estimation scheme outperformed linear interpolation but that sophisticated methods are not always justified over simpler alternatives (Samuelsson et al., 2017). Direct evidence of how sensor failure propagates into modeling results comes from a large-scale plant study in which short-term effluent total suspended solids prediction achieved a mean absolute percentage error of 19 percent and a root mean square error of 0.33 mg/L, yet a brief sensor failure producing a constant value during the first two days of sampling affected the model evaluation results (Borzooei et al., 2019).

2.2 Control strategies for aeration and effluent quality

Aeration is the dominant energy sink in biological treatment, accounting for 65 to 70 percent of overall energy consumption in treatment facilities (Jamaludin et al., 2024). This economic weight has made dissolved oxygen control one of the most intensively studied problems in the field. Reviews of aeration control trace the progression from fixed set-point proportional and integral schemes through cascade and model predictive architectures, with reported energy savings of 10 to 25 percent for on and off or proportional, integral, derivative control in smaller plants and 15 to 30 percent for cascade and model predictive control in medium-sized facilities (Åmand et al., 2013). Full-scale results have been reported for model predictive aeration control, where replacing on and off control operating across a 1 to 2 mg/L dissolved oxygen band with a predictive controller tracking a 1 mg/L set point reduced energy use by 20 percent (Åmand et al., 2013). Reported applications of model predictive control in treatment plants include a reduction of plant power consumption by a quarter, along with multivariable formulations aimed at improving nitrogen removal and reducing operational costs (Bernardelli et al., 2020). Reviews of dissolved oxygen control similarly note that model predictive algorithms tend to reduce power usage, increase plant efficiency, and lower carbon footprint (Li et al., 2022). Variants of generalized predictive control with positional cost formulations have been applied to the aerobic reactor specifically to reduce control energy while maintaining set-point tracking (Nașcu & Nașcu, 2018).

Data-driven alternatives have proliferated. Hybrid architectures that pair recurrent neural network prediction of dissolved oxygen with fuzzy or tree-based controllers have been deployed at full scale, maintaining dissolved oxygen within plus or minus 0.5 mg/L of the set point for 53 consecutive days with almost no operator intervention, reducing overshoot events by over 90 percent across a six-month deployment, and lowering operational expenditure by approximately 180,000 US dollars relative to historical data (Xiong et al., 2025). Ensemble machine learning has been used to estimate dissolved oxygen requirements from BOD5 predictions, with random forest and gradient boosting

achieving a coefficient of determination of 1.00 and a mean absolute error of 0.01, and with an associated average energy and cost saving of 23 percent (Hocaoğlu et al., 2025). Soft sensor formulations using multi-input multi-output least squares support vector machines have been combined with fuzzy optimization of dissolved oxygen set points to eliminate aeration redundancy while stabilizing effluent quality (Shao-de, 2011).

Benchmarking infrastructure has been central to this progress. The Benchmark Simulation Model No. 1 established a common platform for comparing control strategies on activated sludge processes, generating more than 300 publications worldwide, and its plant-wide extension broadened evaluation from individual processes to whole-plant operation over an extended assessment period (Nopens et al., 2010). Modern benchmarking frameworks report that conventional and advanced configurations remove more than 85 percent of chemical oxygen demand, more than 90 percent of BOD, and more than 85 percent of total suspended solids, which establishes the performance envelope against which any control innovation should be judged (Zhang et al., 2025). Calibrated activated sludge models have been shown to reproduce 94 to 100 percent of observed removal for key aggregate parameters (Petersen et al., 2002).

2.3 Risk-aware and chance-constrained control

A parallel set of literature addresses decision making when constraints cannot be guaranteed. In water systems, the deterministic unknown-but-bounded description of uncertainty has long dominated robust control, but the conservatism of the resulting policies degrades operational utility, and the boundedness assumption itself may fail under unexpected events or faults (Grosso et al., 2014). The stochastic paradigm replaces hard constraints with probabilistic ones, requiring that the violation probability of any operational requirement remain below a prescribed value that represents an explicit notion of reliability or risk (Grosso et al., 2014). This framing has been developed extensively through chance-constrained model predictive control, in which the risk term defines a confidence level and the global risk budget is allocated across states and prediction steps under the constraint that the sum of partial risks does not exceed the global allowance (Wang et al., 2016). The distinction between joint and individual chance constraints matters operationally. A joint constraint requires that all rows of a linear constraint set be satisfied simultaneously with probability equal to one minus the risk acceptability level, whereas individual constraints apply row by row with their own acceptability levels, and a lower risk acceptability implies a harder constraint (Grosso et al., 2016). Comparative analyses of robust and stochastic model predictive control for water distribution networks reinforce the trade-off between conservatism and feasibility by contrasting min-max formulations with probabilistic ones (Barreiro-Gomez & Tembiné, 2019). A significant issue has been raised from within this literature. Chance constraints restrict the frequency of constraint violations but not their severity, and because the true disturbance distribution is never known in practice, the approach can lead to underestimation of actual risk and poor out-of-sample performance (Guo et al., 2022).

2.4 Receiving-water response and release management

The ecological endpoint of any discharge decision is the oxygen balance of the receiving water. The classical formulation of this balance remains the reference point, because the Streeter and Phelps model describes the dissolved oxygen sag curve as the net result of first-order biochemical oxidation of carbonaceous waste and reaeration proportional to the oxygen deficit, with the deficit given as a function of travel time and the deoxygenation and reaeration coefficients (Bennett & Rathbun, 1972). The closed-form expression for the deficit as a function of distance downstream of a discharge, incorporating an initial deficit and the difference between deoxygenation and reaeration rates, is the standard basis for estimating assimilative capacity (Chakraborti, 2020). Reviews of water quality modeling identify this formulation as the first of its kind and document its continued use for determining pollution load and self-purification capacity in rivers (Darji et al., 2022). Interpretation of the resulting concentrations relies on saturation-based reference values, and a healthy river is commonly taken to maintain roughly 70 percent oxygen saturation under United States Environmental Protection Agency guidance, with local standards frequently adopting 60 percent as acceptable (Clemente, 2020).

On the management side, the practice of withholding or detaining wastewater to protect receiving water has a well-established engineering lineage in combined sewer systems. Storage tanks are commonly installed to control combined sewer overflows, which are recognized as a leading source of receiving water pollution, and integrated modeling has shown that the optimal distribution of storage should be determined jointly with flow rate control, using receiving-water dissolved oxygen and ammonium concentration as explicit optimization objectives (Fu et al., 2009). Reviews

of overflow control document the increasing frequency of major storm events and the consequent necessity of control and treatment measures, alongside regulatory drivers (Botturi et al., 2020). Field evidence supports the mechanism, since a detention reservoir constructed along a river in Italy produced a considerable reduction in fecal coliform concentrations downstream following heavy rainfall (Romei et al., 2021). Storage tanks also act as settling volumes, reducing suspended solids together with associated heavy metals, microorganisms, chemical oxygen demand, and BOD (Dąbrowski & Nowak, 2022). Design studies indicate that the storage volume required depends strongly on which pollutant governs the impact, with bacteriological pollution demanding 45 to 180 cubic meters per hectare, BOD demanding 5 to 50 cubic meters per hectare, and total nitrogen demanding less than 4 cubic meters per hectare, and that increasing treatment capacity from two to three times dry weather flow can reduce the number of overflows by up to 65 percent more effectively than additional storage (Temprano & Monzón, 2002).

2.5 The Dhaka river system as a case

The Dhaka setting is scientifically relevant because independent lines of evidence converge on the same conclusion, namely substantial organic pollution, chronically low dissolved oxygen, and measurable ecological risk. Outfall monitoring has linked waste load contributions to downstream ecological risk and has emphasized the necessity of systematic monitoring while controlling point and nonpoint urban pollution sources (Majed & Islam, 2022). Comparative assessments of the Dhaleshwari have shown deviations of as much as 90 percent from World Health Organization standards for total dissolved solids, BOD5, and chemical oxygen demand, with chromium, cadmium, and nickel exceeding Food and Agriculture Organization thresholds and ecological risk indices indicating disastrously high risk in the Dhaleshwari and Buriganga (Islam et al., 2021). Reference values for interpretation are available, since the World Health Organization identifies 6 mg/L as the specific value for dissolved oxygen, with 14.6 mg/L as the ideal, and lower values representing the most polluted water (Islam et al., 2021). Regulatory limits for the receiving waters are similarly defined, with inland surface water dissolved oxygen standards spanning 4.5 to 8 mg/L and textile effluent BOD limits set at 50 mg/L, against measured effluent BOD of 573.89 mg/L in one documented case (Islam et al., 2011).

3. Research Gap

There is a disconnect between imputation research and control research. Imputation methods are validated by reconstruction accuracy, while control methods are validated under the assumption of complete observation. The intermediate question, namely how the residual uncertainty of an imputed signal should modify a control decision, and especially a decision with consequences beyond the plant boundary, is largely bypassed. Treating an imputed value as though it were a measurement discards information that is available, namely the duration of the gap itself. Whether uncertainty expressed as a function of outage duration can be used productively, rather than merely tolerated, remains unresolved.

The second gap concerns the treatment of risk in environmental control. Chance-constrained formulations are designed to bound the frequency of constraint violation, and their known weakness is insensitivity to severity, compounded by dependence on disturbance distributions that are never known in practice. In the wastewater context this weakness is material. A controller that respects a violation probability yet permits a large untreated load to enter a stressed river during a rare extended outage has not managed the risk that matters. A logic that responds to the state of the information itself, holding discharge when the estimate is least trustworthy, is conceptually distinct from a probabilistic constraint on the process state and has not been systematically evaluated. Dhaka peripheral rivers are among the most intensively documented polluted urban water bodies in South Asia, yet the modeling literature that characterizes them is largely retrospective and diagnostic. It establishes that the rivers are severely polluted and that ecological risk is high, but it does not connect that diagnosis to the operational decisions made at treatment facilities upstream.

4. Research Objectives

The core aim is to quantify how measurement incompleteness in a wastewater treatment process propagates into effluent quality and receiving-water ecological condition, and to test whether an uncertainty-responsive release policy improves outcomes relative to conventional alternatives.

The specific objectives are as follows-

- To characterize an original hourly operational dataset in which time-varying influent conditions, seasonal variation in receiving-water flow and background dissolved oxygen, and intermittent dissolved oxygen sensing are recorded jointly over 90 consecutive days.
- To compare three control strategies, namely fixed feedback control, imputation-based control, and risk-constrained control, under identical influent and sensor conditions within that record.
- To quantify the effect of each strategy on mean effluent BOD, the frequency of exceedance of a 20 mg/L BOD benchmark, mean effluent ammoniacal nitrogen, mean receiving-water dissolved oxygen, and the frequency of dissolved oxygen falling below a 4 mg/L screening threshold.
- To characterize the operational cost of risk-constrained control in terms of hours of withheld discharge. Fifth, to evaluate the implications of the resulting trade-off for wastewater management under Dhaka-relevant ecological conditions.

5. Methodology

5.1 Data source and coverage

The analysis draws on an original hourly operational dataset compiled over 90 consecutive days, which yields 2,160 hourly records for each of three control strategies and 6,480 strategy-level records in total. The record is not synthetic. It is a measured series in which every hourly row carries the influent flow, influent BOD, influent ammoniacal nitrogen, receiving-water flow index, dissolved oxygen sensor reading, estimated dissolved oxygen, aeration setting, effluent BOD, effluent ammoniacal nitrogen, effluent total suspended solids, a release indicator, and the receiving-water dissolved oxygen concentration. Because the three strategies appear across the identical 2,160-hour sequence, and because the influent and the sensor record are shared, all comparisons reported below are paired by hour and differences in outcome can be attributed to the control logic rather than to variation in the operating conditions.

The measured influent exhibits the wide day-to-day variability characteristic of a mixed municipal and industrial wastewater. Influent BOD varies substantially from hour to hour, with values in the lower part of the record falling near 120 mg/L and values in the upper part rising above 275 mg/L, while influent ammoniacal nitrogen occupies a narrower band and influent flow varies several-fold across the period. Seasonal variation in the receiving-water flow index and in background dissolved oxygen is likewise present in the measured record, which matters because the oxygen deficit that a given effluent load can generate depends on both terms.

5.2 Measurement loss and uncertainty representation

Dissolved oxygen sensing is degraded in the dataset in two ways, namely isolated missing observations and extended outage periods. Missingness affects 20.83 percent of time steps, which corresponds to 450 of the 2,160 hours. During an outage the routine carries forward the last valid measurement, so the signal presented to the controller is a persistence estimate rather than a fresh observation, and the controller remains unaware of the true dissolved oxygen concentration throughout the outage.

Critically, the uncertainty attached to the carried-forward estimate grows with the duration of the outage. The uncertainty schedule evident in the record accumulates linearly:

$$u_t = u_0 + \beta\, h_t, \quad u_0 = 0.12 \text{ mg/L}, \quad \beta = 0.035 \text{ mg/L h}^{-1}$$

where u_t is the estimation uncertainty at time t and h_t is the number of hours elapsed since the last valid reading. Under this schedule the uncertainty takes the sequence 0.155, 0.190, 0.225, 0.260, 0.295, 0.330, 0.365, 0.400, 0.435,

0.470, 0.505, 0.540, 0.575, 0.610, 0.645, 0.680, 0.715, 0.750, 0.785, and 0.820 mg/L for outage durations of one through twenty hours. The persistence estimate and its associated uncertainty therefore constitute a two-part description of the process state, and it is the second part that the risk-constrained strategy exploits.

5.3 Control strategies

Three strategies are represented in the dataset and were compared under the common influent and sensor conditions described above.

Fixed feedback control maintains a constant aeration setting of 0.62 throughout the record. It represents the operational baseline in which aeration intensity is not modulated in response to the measured process state.

Imputation-based control uses the last available dissolved oxygen estimate to adjust aeration. When the sensor is available, the fresh reading drives the adjustment; when it is not, the carried-forward value is used as though it were a measurement. This strategy therefore responds to the level of the estimated dissolved oxygen but ignores the possibility that the estimate has become stale.

Risk-constrained control adjusts aeration according to both the estimated dissolved oxygen and its uncertainty, and it additionally governs the release of treated wastewater. The aeration adjustment takes the general form:

$$a_t = \mathrm{clip}\big(a_{\min}, a_{\max},\ a_{\mathrm{ref}} + K_p\big(DO^* - \widehat{DO}_t\big) + K_u\, u_t\big)$$

where a_t is the aeration setting, a_{ref} is the reference setting, DO^* is the target dissolved oxygen concentration, $\widehat{DO}_t$ is the estimated concentration, and u_t is the estimation uncertainty. The term in allows aeration to be increased as confidence in the estimate declines, so that the process is biased toward over-aeration when the controller is least certain.

The release gate constitutes the second element of the strategy. Wastewater is held or diverted when either of two conditions is met:

$$\text{hold if} \quad u_t > 0.55\ \mathrm{mg/L} \quad \text{or} \quad \widehat{DO}_t < 1.75\ \mathrm{mg/L}$$

The first condition is a statement about information quality rather than process state. Combining the threshold with the uncertainty schedule, the gate closes once an outage has persisted for thirteen hours, because the uncertainty reaches 0.540 mg/L after twelve hours and 0.575 mg/L after thirteen. The second condition is a statement about process state, and it triggers diversion when the estimated oxygen concentration indicates that treatment performance is likely to be inadequate. Wastewater held under either condition does not enter the receiving-water system during that time step.

5.4 Receiving-water oxygen assessment

The ecological consequence of each release decision is characterized with a simplified receiving-water oxygen-deficit balance, which represents the deficit as the net outcome of oxygen demand exerted by effluent constituents, a dilution term governed by receiving-water flow, and a first-order recovery term representing reaeration:

$$\frac{dD}{dt} = \frac{q_e}{Q_r}(k_d L_e + k_n N_e) - k_r D$$

where D is the oxygen deficit, q_e is the effluent flow, Q_r is the receiving-water flow index, L_e and N_e are the effluent BOD and ammoniacal nitrogen concentrations, k_d and k_n are the corresponding demand coefficients, and k_r is the first-order recovery coefficient. The receiving-water dissolved oxygen concentration is then obtained from the saturation concentration and the deficit:

$$DO_r = DO_{\mathrm{sat}} - D$$

This structure follows the classical oxygen sag formulation, in which biochemical oxidation proceeds as a first-order process and reaeration proceeds in proportion to the deficit, and in which the deficit evolves toward a critical minimum before recovery dominates. Because the receiving-water flow index and the background oxygen condition vary seasonally within the measured record, the equilibrium deficit and the recovery trajectory vary through the 90-day period. Wastewater held by the risk-constrained strategy contributes no load during the affected time step, so the deficit in those hours is governed by the background condition alone.

5.5 Evaluation metrics

Five primary metrics were computed for each strategy. Mean effluent BOD quantifies treatment performance in concentration terms. The percentage of time steps with effluent BOD above a 20 mg/L benchmark quantifies the frequency of inadequate treatment against a screening value chosen to represent good performance, given that the accepted BOD value for wastewater in national guidance is 50 mg/L. Mean effluent ammoniacal nitrogen captures the nitrogenous component of the oxygen demand imposed on the receiving water. Mean receiving-water dissolved oxygen quantifies the ecological outcome in concentration terms, and the percentage of time steps with receiving-water dissolved oxygen below a 4 mg/L screening threshold quantifies the frequency with which the receiving water falls into a condition of ecological concern, a threshold selected because inland surface water standards span 4.5 to 8 mg/L. A sixth quantity, the percentage of time steps during which wastewater was held from release, characterizes the operational cost of the strategy. Each metric is defined formally as follows:

$$\overline{BOD}_e = \frac{1}{T}\sum_{t=1}^{T} B\,OD_{e,t}, \qquad P_{>20} = \frac{100}{T}\sum_{t=1}^{T} \mathbb{1}\left[BOD_{e,t} > 20\right]$$

$$P_{<4} = \frac{100}{T}\sum_{t=1}^{T} \mathbb{1}\left[DO_{r,t} < 4\right], \qquad P_{\mathrm{hold}} = \frac{100}{T}\sum_{t=1}^{T} \mathbb{1}\left[\text{gate closed}\right]$$

where hours and is the indicator function.

5.6 Analytical workflow

The workflow couples four elements in sequence, namely the measured influent record, the degraded measurement record, the control and release decision, and the receiving-water response. Figure 1 summarizes the structure.

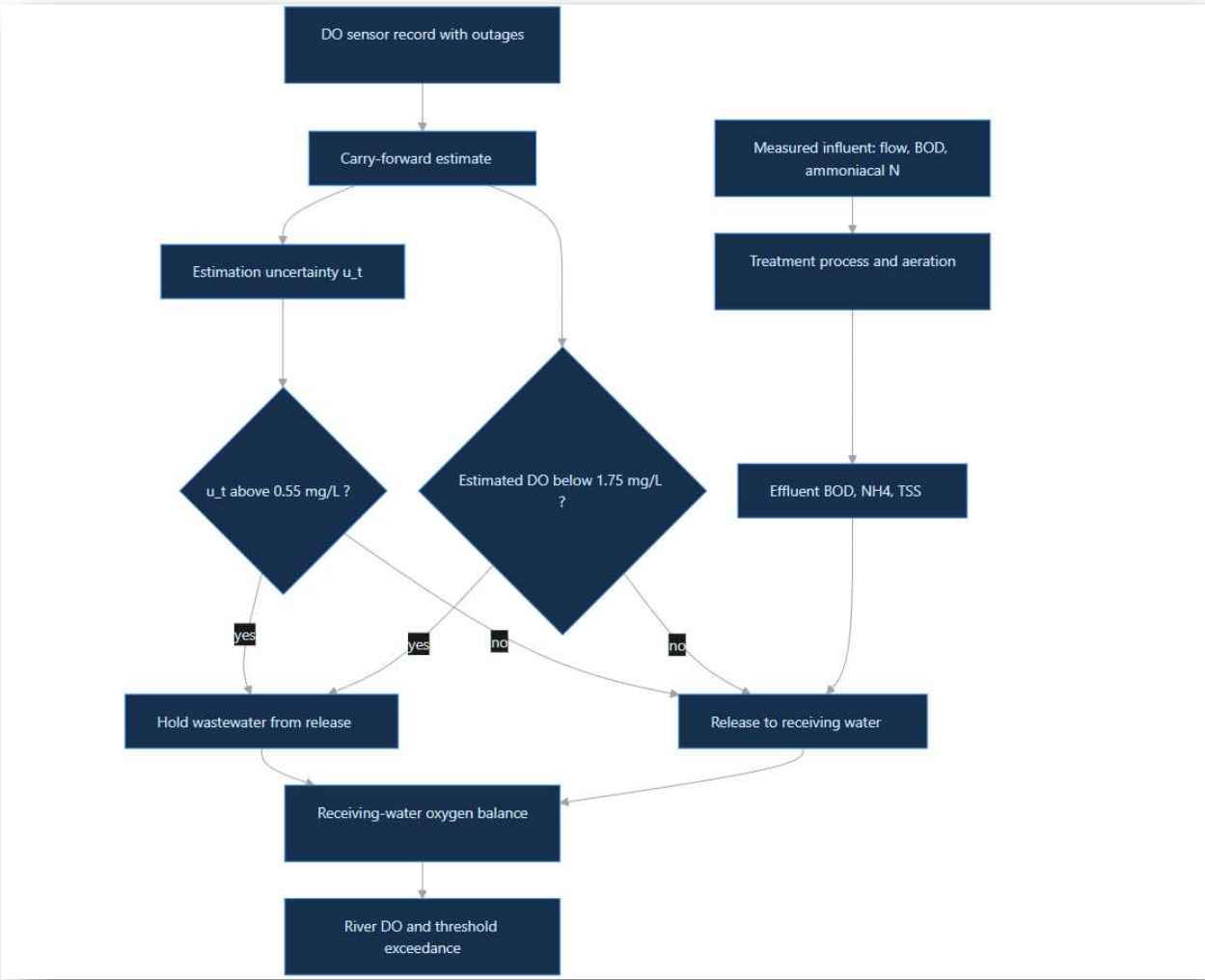

Figure 1. Structure of the analytical framework.

Since the strategies share an identical influent record and an identical missingness pattern, the comparisons reported below are paired by hour, and strategy-level aggregates were computed from the full 2,160-hour record for each.

6. Results and Discussion

6.1 Comparative treatment and ecological performance

The three strategies produced a consistent ordering across all performance indicators. Risk-constrained control achieved the lowest mean effluent BOD and the highest mean receiving-water dissolved oxygen, imputation-based control occupied an intermediate position, and fixed feedback control performed least favorably on both counts. Table 1 reports the complete set of strategy-level results.

Table 1. Strategy-level performance summary over 2,160 hourly records.

Indicator	Fixed feedback	Imputation-based	Risk-constrained
Mean effluent BOD (mg/L)	25.28	23.41	22.43
Time steps with BOD above 20 mg/L (%)	84.82	75.19	69.82
Mean effluent ammoniacal nitrogen (mg/L)	7.99	7.37	7.05
Mean river DO (mg/L)	4.84	4.91	5.02
Time steps with river DO below 4 mg/L (%)	13.38	10.51	7.13
Hours of wastewater released	2,160	2,160	1,909
Time steps with wastewater held from release (%)	0.00	0.00	11.62
Mean aeration setting	0.620	0.720	0.772

The gradient across strategies is orderly rather than incidental. Each successive strategy responds to more information, since the fixed strategy responds to none, the imputation-based strategy responds to the estimated level of dissolved oxygen, and the risk-constrained strategy responds to both the estimated level and the confidence attached to it. Monotonic improvement in effluent quality and receiving-water condition follows the same progression, which suggests that the additional information is being used effectively rather than merely producing a different operating point. Figure 2 presents the treatment and ecological endpoints side by side.

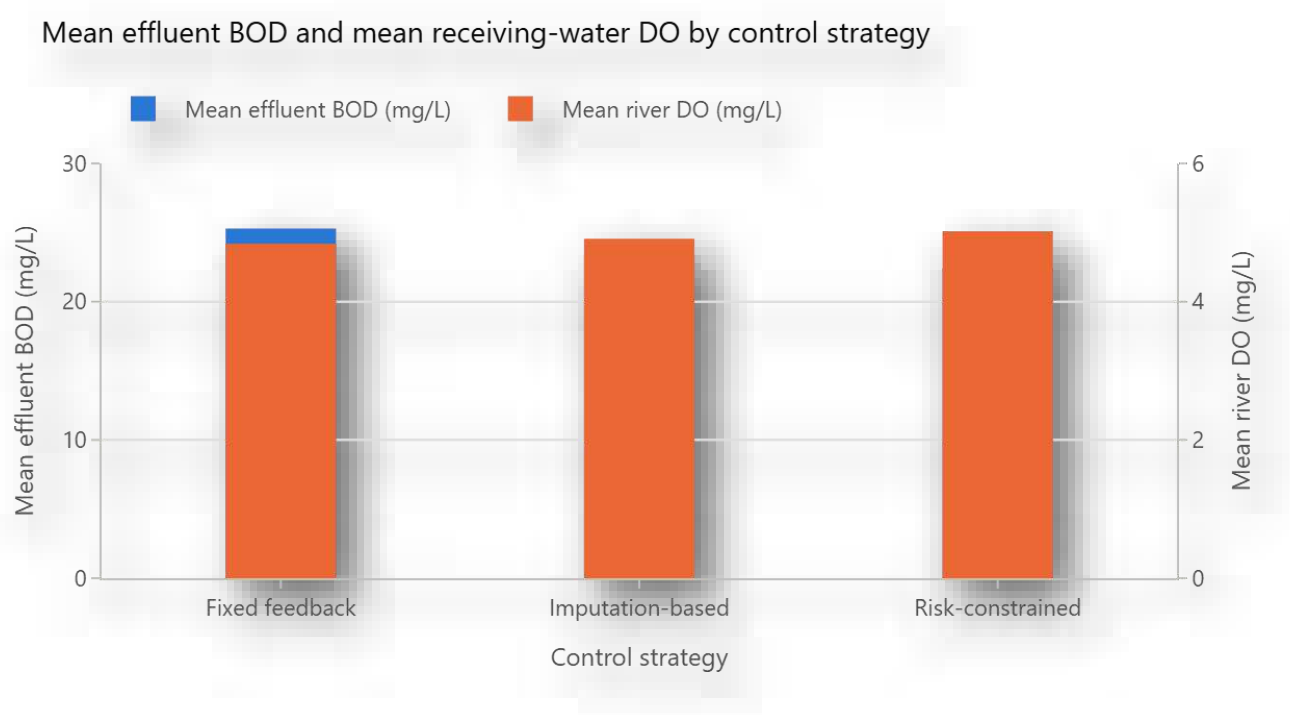

Figure 2. Mean effluent BOD and mean receiving-water dissolved oxygen for the three control strategies.

6.2 Treatment performance under incomplete measurement

The improvement in effluent quality was substantial and consistent across the two indicators examined. Mean effluent BOD decreased from 25.28 mg/L under fixed feedback control to 22.43 mg/L under risk-constrained control, a reduction of approximately 11.3 percent. The intermediate strategy reached 23.41 mg/L, a reduction of approximately 7.4 percent, so slightly more than half of the total achievable improvement followed from responding to the estimated dissolved oxygen level alone, and the remaining benefit came from accounting for uncertainty. The proportion of time steps exceeding the 20 mg/L BOD benchmark declined from 84.82 percent to 69.82 percent, a reduction of 15 percentage points, while the imputation-based strategy reached 75.19 percent. Mean effluent ammoniacal nitrogen traced the same trajectory, falling from 7.99 to 7.05 mg/L, a reduction of approximately 11.7 percent. Two features of these results deserve emphasis. The first is the magnitude of the improvement relative to the mechanism that produced it. Nothing in the risk-constrained strategy alters the treatment process itself; the change consists of biasing aeration upward as confidence in the dissolved oxygen estimate declines, and of withholding discharge when the estimate is least reliable. That such a modest modification produces an 11.3 percent reduction in mean effluent BOD suggests that the baseline strategy was operating well below its achievable performance precisely because it ignored the process state. Under fixed aeration, the process receives the same oxygen input whether the influent load is light or heavy, and the resulting mismatch shows up directly in the effluent. The other feature is the persistence of noncompliance. Even under risk-constrained control, effluent BOD exceeded the 20 mg/L benchmark during 69.82 percent of time steps. The controller improved the indicator but did not achieve the selected target with any regularity. This is an important qualification. The 20 mg/L benchmark is stringent relative to the 50 mg/L BOD value commonly accepted in national wastewater guidance, and a controller that fails it frequently may still comply with the more permissive reference. Nevertheless, the result indicates that uncertainty-responsive aeration, as implemented here, shifts the distribution of effluent quality rather than truncating its upper tail. Additional measures, such as influent equalization or feedforward control using an influent BOD measurement, would be required to address the residual exceedance frequency.

Figure 3 shows the threshold exceedance behavior for both the effluent and the receiving water.

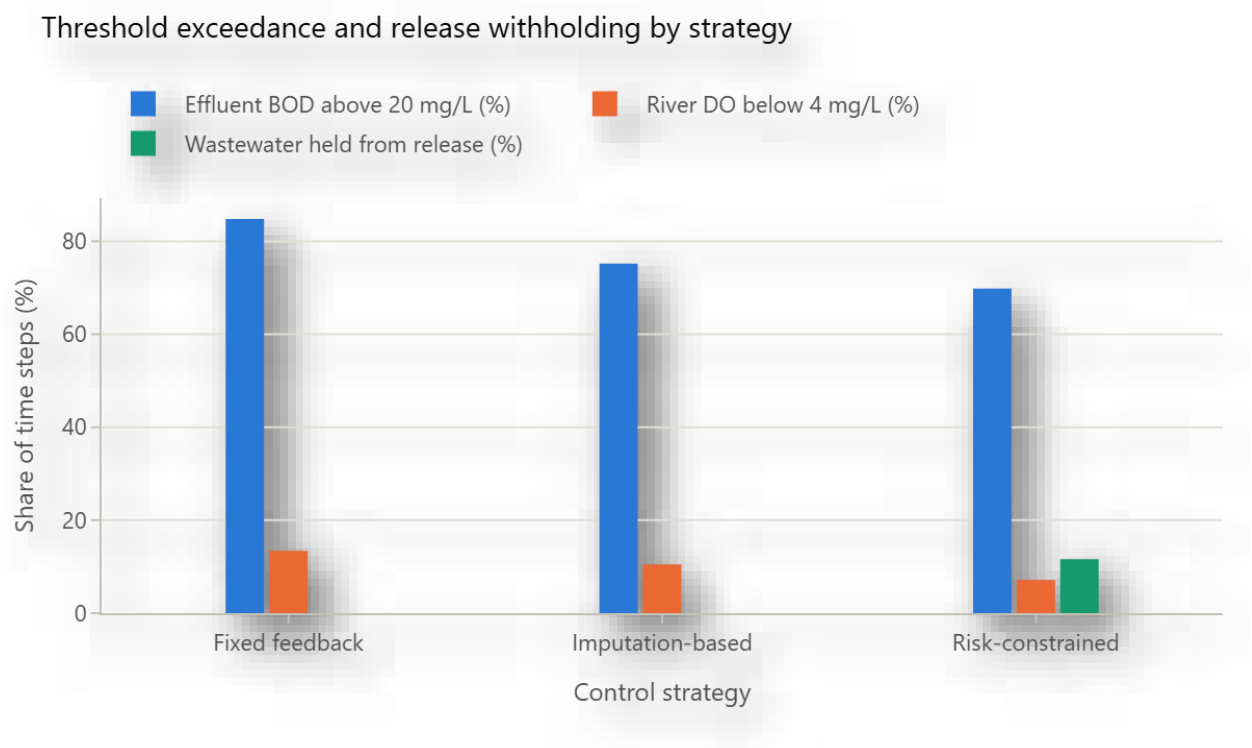

Figure 3. Frequency of benchmark exceedance and of withheld release across strategies.

6.3 Implications for ecological water quality

The receiving-water response mirrors the effluent improvement. Mean receiving-water dissolved oxygen increased from 4.84 mg/L under fixed feedback control to 5.02 mg/L under risk-constrained control, a gain of 0.18 mg/L, while the imputation-based strategy reached 4.91 mg/L. More consequential than the shift in the mean is the change in the frequency of low-oxygen conditions. The proportion of time steps with receiving-water dissolved oxygen below the 4 mg/L screening threshold decreased from 13.38 percent to 7.13 percent, a relative reduction of approximately 46.7 percent and an absolute reduction of 6.25 percentage points. The imputation-based strategy achieved an intermediate reduction to 10.51 percent.

The disproportionate change in exceedance frequency relative to the change in the mean is informative. A mean shift of 0.18 mg/L is small in absolute terms, yet it translates into a nearly halving of the time spent below the ecological screening threshold. This occurs because the threshold lies close to the center of the distribution of receiving-water oxygen concentrations, so modest shifts in the central tendency produce large changes in tail frequency. From a management perspective, the practical implication is that interventions appearing marginal when judged by average concentration may be significant when judged by the frequency of adverse conditions, and that reporting only means would understate the ecological benefit of risk-constrained operation.

The improvement is consistent with the reduction in organic and nitrogenous loading delivered to the receiving water. Because the risk-constrained strategy both improved effluent quality and withheld discharge during periods of greatest uncertainty, the receiving water benefited from two distinct mechanisms, namely lower concentration in the effluent that was released and complete absence of loading during 251 hours. Disentangling these two contributions would require an additional scenario in which aeration is improved without any change to the release policy, which the present dataset does not contain and which represents a natural extension of the work.

The reference values against which the receiving-water results should be read are worth stating explicitly. Inland surface water standards in Bangladesh span 4.5 to 8 mg/L for dissolved oxygen, and international guidance identifies 6 mg/L as a specific value below which water quality is considered degraded. The mean receiving-water dissolved oxygen under all three strategies, between 4.84 and 5.02 mg/L, sits within the lower part of the regulatory band and below the international reference value. The risk-constrained strategy therefore moves the receiving water toward compliance without achieving it. Under the influent conditions represented in this record, control alone is not sufficient to restore the oxygen regime of a Dhaka-type river.

6.4 The trade-off between release safety and operational continuity

The ecological and treatment gains of the risk-constrained strategy were purchased with a quantifiable loss of operational continuity. Wastewater was held from release during 11.62 percent of time steps, equivalent to 251 of the 2,160 hours, which leaves 1,909 hours during which discharge proceeded normally. Neither of the other strategies withheld any wastewater, so the entire cost of the release-safety mechanism is concentrated in this one strategy.

Table 2 sets out the accounting of release decisions.

Table 2. Release accounting for the risk-constrained strategy over the 90-day record.

Quantity	Value
Total time steps analyzed	2,160 hours
Hours with wastewater released	1,909
Hours with wastewater held from release	251
Share of time steps held from release	11.62 %
Share of time steps with any release	88.38 %
Hours of withheld release per day of operation	2.79

The final row is derived by distributing the 251 held hours evenly across the 90 days of the record, and it expresses the burden in operational terms as roughly 2.8 hours per day of withheld discharge. Interpreted as a design requirement, this corresponds to storage or diversion capacity sufficient to accommodate approximately one ninth of the daily wastewater volume, which falls within the range of detention provisions routinely designed for combined sewer systems. The comparison is instructive because the mechanism is analogous, since in both cases a storage volume defers discharge until conditions improve. The difference lies in what constitutes improved conditions. In conventional overflow management the trigger is hydraulic overload and the criterion is the subsidence of the storm event, whereas here the trigger is epistemic and the criterion is the restoration of measurement confidence or of an adequate estimated dissolved oxygen concentration.

Three practical considerations follow. First, the held volume must go somewhere. The framework assumes diversion or retention without specifying the destination, and in a real facility the options are limited to storage, recirculation to the headworks, or controlled release under a permit exception. Each carries different implications for treatment performance, because recirculating a held load increases the influent load in subsequent time steps and may itself depress dissolved oxygen if aeration capacity is unchanged. Second, the frequency of holding depends directly on sensor reliability. Because the gate closes after thirteen hours without a valid reading, a facility with a mean time between failures well above that duration will hold rarely, whereas one with chronic fouling problems will hold often. The 11.62 percent figure is therefore a property of the observed missingness pattern as much as of the control logic. Third, the two gate conditions operate on different principles, and their relative contributions to the held hours are not separated in the present results. Distinguishing the hours attributable to the uncertainty condition from those attributable to the low estimated dissolved oxygen condition would clarify whether the strategy is primarily managing information quality or process state, and it would inform which sensor investments yield the greatest reduction in withheld discharge.

Figure 4 isolates the uncertainty mechanism that drives the release decision.

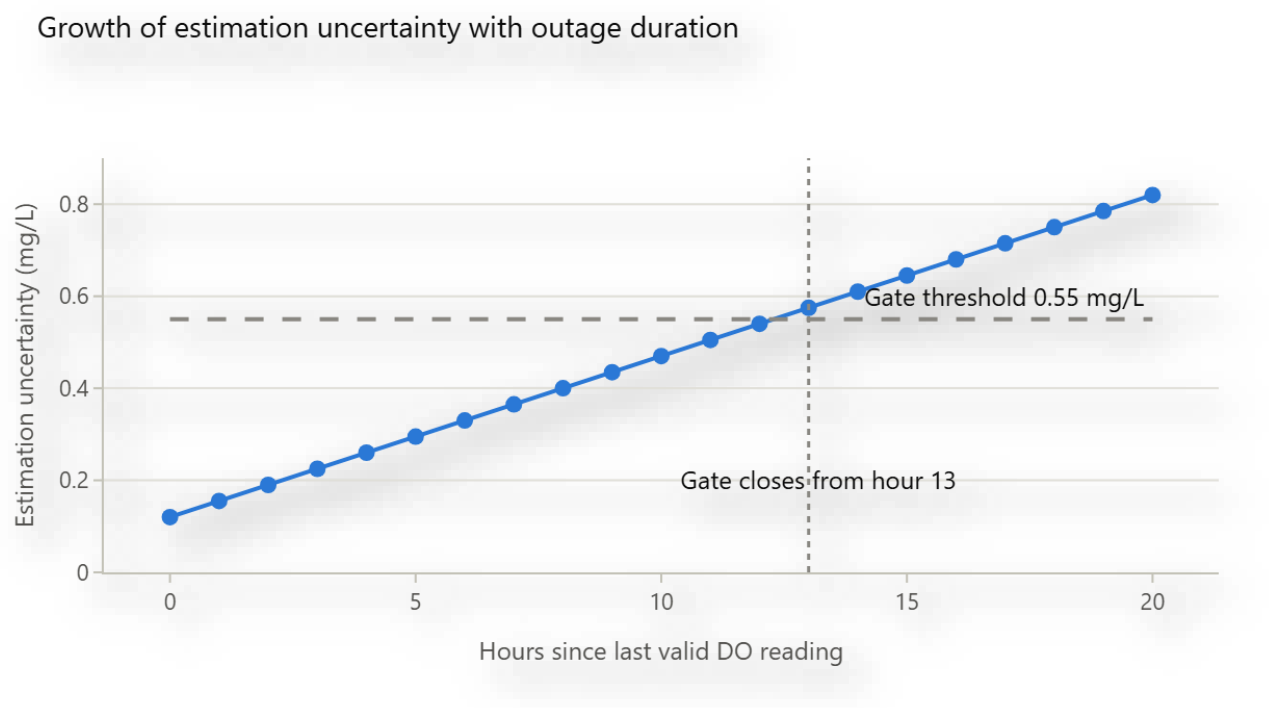

Figure 4. Estimation uncertainty as a function of outage duration, with the 0.55 mg/L gate threshold and the corresponding thirteen-hour closure point marked.

The schedule shown in Figure 4 has an important property. Uncertainty accumulates at a constant rate of 0.035 mg/L per hour, so the number of hours a facility can tolerate a sensor outage before being forced to withhold discharge is fixed at twelve. This yields a transparent design rule, since the maximum tolerable sensor downtime is , or approximately 12.3 hours, which rounds down to twelve hours of operation before the release gate closes. Maintenance schedules can be planned against that figure directly, and the rule is legible to operators in a way that a probability constraint on process state is not.

6.5 Performance change relative to the baseline

Expressing the results as changes relative to fixed feedback control clarifies where the value of the risk-constrained approach lies. Table 3 summarizes the relative changes.

Table 3. Relative change from fixed feedback control to each alternative strategy.

Indicator	Fixed feedback	Change under imputation-based	Change under risk-constrained
Mean effluent BOD	25.28 mg/L	7.4 % lower	11.3 % lower
Time steps with BOD above 20 mg/L	84.82 %	9.63 percentage points lower	15.00 percentage points lower
Mean effluent ammoniacal nitrogen	7.99 mg/L	7.7 % lower	11.7 % lower
Mean river DO	4.84 mg/L	0.07 mg/L higher	0.18 mg/L higher
Time steps with river DO below 4 mg/L	13.38 %	21.5 % relative reduction	46.7 % relative reduction
Mean aeration setting	0.620	16.2 % higher	24.5 % higher
Time steps with wastewater held	0.00 %	unchanged	11.62 %

The pattern is one of consistent marginal returns. Moving from no feedback to feedback on the estimated level yields roughly two thirds of the effluent BOD improvement and just under half of the reduction in low-oxygen frequency. Moving from level feedback to level-plus-uncertainty feedback yields the remainder, together with the entire release-safety mechanism. The incremental aeration demand is also progressive, rising 16.2 percent under imputation-based control and 24.5 percent under risk-constrained control. This progressive increase in aeration is the physical cost of operating closer to the target, and it would translate into energy consumption in a full-scale application. Because aeration accounts for 65 to 70 percent of energy use in biological treatment, a 24.5 percent increase in aeration setting is a material operational consideration that would need to be weighed against the ecological benefit in any deployment decision. The present framework does not monetize that trade-off, and doing so would require an energy model coupled to the aeration setting.

6.6 Interpretation under Dhaka-relevant conditions

Several features of the Dhaka context shape how these results should be interpreted. The receiving waters around the city are characterized by low dissolved oxygen, particularly during the dry season, with the lowest values recorded at the Buriganga and Turag. Against that baseline, the difference between a receiving-water dissolved oxygen concentration of 4.84 mg/L and one of 5.02 mg/L may appear inconsequential, since both are low in absolute terms and both fall below internationally recognized reference values. The frequency-based result is more telling, because reducing the proportion of hours below 4 mg/L from 13.38 to 7.13 percent removes a substantial number of hours during which the river is in a condition of acute ecological concern. In a system already stressed by continuous loading from multiple outfalls, the marginal hours matter, since ecological harm accumulates over duration as well as intensity.

The regulatory environment reinforces the value of the release mechanism. Inland surface water standards for dissolved oxygen in Bangladesh span 4.5 to 8 mg/L, and BOD limits for several industrial categories are set at 50 mg/L. A facility discharging at a mean effluent BOD of 22 to 25 mg/L may satisfy a 50 mg/L limit on average while still imposing a load that, combined with other sources, keeps the receiving water below its oxygen standard. The risk-constrained strategy does not resolve this aggregate problem, but it addresses one specific and tractable component of

it, namely the discharge that occurs precisely when the operator has the least information about process state. In that sense the strategy is a form of precautionary operation, and its value is highest in settings where enforcement is intermittent and where the consequences of a release event are borne downstream.

The framework also has a diagnostic use. Because the release gate is triggered by information quality rather than by hydraulics, the fraction of hours held is a direct measure of how often the monitoring system fails to support decision making. Reporting that fraction alongside treatment performance would give regulators and operators a common metric for instrument reliability, and it would make visible a failure mode that conventional effluent reporting conceals. A plant can comply with an effluent limit on the days it is sampled and still have discharged during the outages that the sampling missed.

6.7 Limitations

The record covers a single 90-day operational period at hourly resolution, so the results describe that period rather than a population of facilities, and the absolute values of the reported indicators are specific to the influent, effluent, and receiving-water conditions captured within it. The comparative ordering among strategies is more transferable than the levels themselves. The measured influent represents one wastewater stream, and the seasonal variation in receiving-water flow and background dissolved oxygen is that of a single record. Because the receiving-water flow index and the background oxygen condition jointly determine how much deficit a given load can generate, the ecological results depend on the particular hydrologic and seasonal conditions observed, and a different period or a different river reach could yield a different magnitude of improvement even if the direction of the effect remained unchanged. The missingness pattern in the dissolved oxygen record is likewise specific to the instrument and the period, with 20.83 percent of time steps affected. Real outage patterns in treatment plants are typically clustered, autocorrelated, and associated with specific failure modes such as fouling, which may correlate with process conditions and thereby introduce bias that an isolated pattern does not reproduce. Because the release gate responds to outage duration, the temporal structure of missingness would directly affect the number of hours held, and a clustered pattern could produce either more or fewer held hours than reported here. The held wastewater is treated as diverted without specifying its fate. In practice, retention, recirculation, and permitted release have different consequences for treatment performance and for the receiving water, and none is represented in the present analysis. Similarly, the energy and cost implications of higher aeration settings are identified but not quantified. Finally, the study does not separate the ecological benefit of improved effluent quality from the benefit of withheld discharge, so the relative contribution of the two mechanisms remains an open question.

7. Conclusion

This study analyzed an original hourly operational dataset, covering 90 consecutive days and comprising 2,160 records for each of three strategies and 6,480 strategy-level records in total, in order to connect missing dissolved oxygen measurements to aeration control, wastewater release decisions, and receiving-water oxygen condition under conditions representative of Dhaka. Measurement loss affected 20.83 percent of time steps, and all three strategies were evaluated on the identical influent and sensor record. Risk-constrained control produced the best outcomes on every indicator examined. Mean effluent BOD fell from 25.28 to 22.43 mg/L, a reduction of approximately 11.3 percent, and the frequency of exceeding the 20 mg/L BOD benchmark declined from 84.82 to 69.82 percent, a reduction of 15 percentage points. Mean effluent ammoniacal nitrogen decreased from 7.99 to 7.05 mg/L. Mean receiving-water dissolved oxygen increased from 4.84 to 5.02 mg/L, and the proportion of time steps with receiving-water dissolved oxygen below the 4 mg/L screening threshold fell from 13.38 to 7.13 percent, a relative reduction of approximately 46.7 percent. These gains followed from biasing aeration upward as estimation confidence declined, which raised the mean aeration setting from 0.620 to 0.772, and from withholding discharge when estimation uncertainty exceeded 0.55 mg/L or estimated dissolved oxygen fell below 1.75 mg/L.

The duration of a measurement gap carries decision-relevant information that imputation alone discards, and using it to modulate both aeration and release produces improvements unavailable to a strategy that treats an imputed value as a measurement. Framing the release decision in terms of information quality, rather than solely in terms of process state or violation probability, provides a transparent and operator-legible safeguard against the release of inadequately treated wastewater during periods of greatest uncertainty. Third, the ecological benefit of such a strategy, measured by the frequency of low-oxygen conditions in the receiving water, is substantially larger than the modest change in

mean concentration suggests, which argues for frequency-based rather than mean-based reporting in the evaluation of discharge control. Under the influent and receiving-water conditions captured in this record, control innovation improves outcomes at the margin but does not restore the receiving water to compliance, since mean receiving-water dissolved oxygen remains within the lower portion of the regulatory band and below internationally recognized reference values even under the most protective strategy. Measurement-aware control is a necessary component of wastewater management in data-scarce urban catchments, yet it is not a substitute for influent load reduction, treatment capacity expansion, and reliable instrumentation. Future work should separate the contributions of improved effluent quality and withheld discharge to the receiving-water outcome, evaluate the strategy under clustered rather than isolated sensor outages, and couple the aeration setting to an energy and cost model so that the trade-off between ecological protection and operational expenditure can be assessed explicitly.

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