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Effluent phosphorus in 149 wastewater treatment plants from the French Seine-Normandie basin: Associations with documented treatment categories and whole-plant electricity intensity

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ABSTRACT

Whole-plant electricity intensity is often available for wastewater treatment facilities, but its interpretation against nutrient quality is complicated by differences in plant scale, hydraulic loading, influent conditions, and treatment configuration. This study evaluated whether whole-plant specific electricity distinguished total phosphorus in treated effluent after accounting for those factors and for the phosphorus-treatment category documented in the annual French Urban Waste Water registry. Raw parameter-level self-monitoring measurements from January 2024 were reconstructed by exact plant code and date for the Seine-Normandie basin. The strict phosphorus set contained 655 plant-day occasions from 149 plants; one median per plant was analyzed by ordinary least squares with HC3 uncertainty. Relative to no entry in the annual registry phosphorus-treatment field, a standard documented entry was associated with an adjusted effluent-phosphorus ratio of 0.343, equivalent to 65.7% lower phosphorus (95% confidence interval: 39.4% to 80.5% lower; $p < 0.001$). The advanced entry estimate was 43.0% lower but imprecise (95% confidence interval: 76.1% lower to 35.9% higher). A doubling of whole-plant specific electricity was associated with an estimated 8.0% lower effluent phosphorus, with an interval spanning 18.4% lower to 3.8% higher ($p = 0.177$). The standard entry was also associated with a 0.238 higher apparent daily phosphorus-load reduction fraction (95% confidence interval: 0.122 to 0.354). In a contextual nitrogen analysis of 647 occasions from 142 plants, the electricity estimate was 1.0% lower (95% confidence interval: 9.5% lower to 8.2% higher), whereas documented denitrification was associated with 71.0% lower effluent nitrogen. The standard documented phosphorus-treatment entry showed a precise cross-plant association with January effluent phosphorus, while the whole-plant electricity estimate was smaller and imprecise. Comparisons of nutrient outcomes across heterogeneous plants therefore require explicit treatment-category, influent, hydraulic, and scale context.

Keywords: wastewater treatment; total phosphorus; electricity intensity; effluent quality; treatment registry; plant-level analysis.

INTRODUCTION

Phosphorus control in municipal wastewater treatment is important for limiting nutrient discharge to receiving waters, while electricity use remains a substantial operational input. These two dimensions are related within treatment systems, yet a single facility-level electricity ratio does not isolate the energy used for phosphorus removal. Whole-plant consumption includes pumping, aeration, solids processing, recirculation, auxiliary equipment, and site-specific loads. Consequently, an observed value expressed as kilowatt-hours per cubic metre can reflect both treatment requirements and structural differences among plants.

Large multi-plant studies have shown that electricity indicators vary with scale, loading, process configuration, utilization, and the

denominator used. Surveys in Italy and China identified strong structural influences on plant energy intensity, and methodological reviews have emphasized that the choice of comparison metric must follow the analytical purpose and available data (Niu et al., 2019; Vaccari et al., 2018). Studies based on energy per unit of pollutant removed, machine-learning prediction, or efficiency frontiers address related but distinct questions and require annual mass, process, or economic information that a date-specific observational cross-section does not provide (Li et al., 2023; Zhu et al., 2024). A recent analysis of 2,576 Chinese plants jointly considered electricity, influent and effluent quality, nutrients, scale, and process attributes, but electricity consumption was the main outcome and the information was annual (Li et al., 2025).

French evidence already covers important parts of the nutrient and energy context. Starck et al. (2024) quantified long-term phosphorus flows and removal across French wastewater systems at plant, basin, and national scales. Joannis et al. (2024a) analyzed self-monitoring flow and quality records under dry- and wet-weather conditions in the Seine-Normandie basin, and the companion study evaluated pollutant loads and treatment performance for 25 plants, including nitrogen and phosphorus (Joannis et al., 2024b). An official French synthesis also documented energy consumption patterns by plant size and process (Irstea & Agence de l'eau Rhône Méditerranée Corse, 2018). These studies preclude claims based merely on using French self-monitoring data, comparing several plants, or combining concentrations and loads.

The remaining operational question is narrower. Across plants observed on exact dates, does whole-plant specific electricity distinguish treated-effluent phosphorus after differences in influent phosphorus, hydraulic loading, plant scale, and the annually documented phosphorus-treatment category are considered? This focus is compatible with recent Journal of Ecological Engineering work on full-scale energy-quality tradeoffs, while differing from three-configuration longitudinal comparisons and from studies centered on phosphorus recovery from solids streams (Ribarova et al., 2026; Sbai et al., 2026).

This study therefore examined a January 2024 cross-section of wastewater treatment plants in the Seine-Normandie basin. The primary outcome was total phosphorus in treated effluent. The terms of operational interest were the nominal standard and advanced phosphorus-treatment entries documented in the annual French Urban Waste Water registry and whole-plant electricity divided by influent flow. We hypothesized that a documented phosphorus-treatment entry would be associated with lower treated-effluent phosphorus after adjustment. For electricity, the analysis estimated whether it provided additional differentiation without imposing a causal or directional interpretation. Apparent daily phosphorus-load reduction was secondary, and a parallel global-nitrogen model was included only as contextual evidence.

MATERIALS AND METHODS

Study design and data sources

This was an observational cross-sectional analysis of raw regulatory self-monitoring measurements from January 2024. The measurements were obtained from the Agence de l'eau Seine-Normandie (AESN) open-data resource for wastewater treatment plant monitoring (Agence de l'eau Seine-Normandie, 2026). The exact source file, *autosurveillance-donnees-2024-01.csv*, contained 326,021 parameter-level rows from 1,481 station codes. It was a measurement file rather than a table of published annual results. The source catalogue identifies the Licence Ouverte / Open Licence 2.0.

Annual plant attributes were obtained from the 2024 export of the French Urban Waste Water database, referred to here by its French abbreviation ERU (Eaux résiduaires urbaines) (Ministère de la Transition écologique et al., n.d.). The export contained 22,901 unique treatment-station records. It supplied documented capacity, main water-treatment process, nutrient-treatment entries, treatment requirements, and sensitive-zone context. ERU fields were interpreted as annual registry attributes, not as certification of the process operating on each measurement date. All dates of last registry modification for the analytical plants were after January 2024, reinforcing this restricted interpretation.

Record reconstruction and quality rules

The initial reconstruction unit was the treatment plant on an exact calendar date. AESN

records were joined only when the station code, date, parameter, sampling point, unit, support, and fraction matched the predefined semantic key. Influent and treated-effluent points were A3 and A4, respectively. Total phosphorus used SANDRE parameter 1350 in mg P/L, global nitrogen used parameter 1551 in mg N/L, mean daily volume used parameter 1552 in m3/d, and whole-station electricity used parameter 2521 in kWh. The electricity record is conventionally associated with A3 in the source and was treated as a whole-plant quantity.

One duplicate key containing exactly identical values was collapsed. Fifteen station-date-variable keys with conflicting values were excluded rather than averaged. Values reported at or below a stated quantification limit were retained as reported in the primary analysis and removed in a sensitivity analysis. No date tolerance, interpolation, or nearest-date pairing was used.

A phosphorus plant-day occasion required same-date influent and treated-effluent phosphorus, influent and treated-effluent flow, and electricity. Influent phosphorus and influent flow had to be strictly positive; treated-effluent phosphorus and treated-effluent flow had to be non-negative; electricity had to be strictly positive. The nitrogen set was reconstructed analogously. Plant attributes were linked by exact equality between the AESN SANDRE station code and the ERU treatment-station code.

Because repeated January coverage was unequal, eligible occasions were summarized by their median within each plant. Ninety-five of 149 phosphorus plants contributed only one eligible occasion. The plant-level median was therefore used as the primary inference unit so that plants, rather than measurement frequency, received equal weight. Plant-day analyses with station-clustered uncertainty were retained as sensitivity analyses.

The official names and SANDRE codes of all 149 plants included in the primary phosphorus analysis are listed in Supplementary Table S20.

Outcomes, exposures, and covariates

The primary outcome was the plant-level median total phosphorus concentration in treated effluent, expressed as mg P/L. The secondary outcome was apparent daily phosphorus-load reduction:

$$1 - [(P_A4 \times Q_A4) / (P_A3 \times Q_A3)] \quad (1)$$

This quantity compares same-date concentration-flow products and is not a complete mass balance. Same-date influent and effluent measurements do not establish that the same hydraulic parcel was sampled.

Whole-plant specific electricity was electricity divided by influent daily flow, expressed as kWh/m3. It represents total station consumption and was not attributed to aeration, phosphorus removal, or any individual treatment step. Hydraulic intensity was influent daily flow divided by nominal capacity in population equivalents. The primary capacity value came from the AESN station attribute; ERU capacity was examined in sensitivity analysis.

The annual ERU phosphorus-treatment field was classified as standard (*Déphosphatation*), advanced (*Déphosphatation plus poussée*), or empty. These were nominal categories. The empty ERU field means that the annual registry contained no phosphorus-treatment entry; it does not mean that the plant had no treatment or that treatment was inactive. The standard and advanced categories were represented by separate indicator variables and were not assumed to form an ordinal gradient.

The contextual global-nitrogen analysis used the same structure, with annual ERU nitrogen entries classified as nitrification, denitrification, advanced denitrification, or empty. The phosphorus and nitrogen models adjusted for the corresponding influent nutrient concentration, whole-plant specific electricity, hydraulic intensity, and nominal capacity.

Statistical analysis

Plant characteristics were summarized by phosphorus-treatment field using medians and interquartile ranges. Unadjusted group contrasts used 20,000 plant-level bootstrap resamples with a fixed seed of 20260914. These descriptive contrasts were not used to infer treatment effects.

The primary model was ordinary least squares with the natural logarithm of plant-level treated-effluent phosphorus as the outcome. Predictors were the natural logarithm of influent phosphorus, base-2 logarithms of whole-plant specific electricity, hydraulic intensity, and nominal capacity, plus separate indicators for the standard and advanced ERU entries. HC3 heteroskedasticity-consistent uncertainty was used. Results were exponentiated and reported

as adjusted ratios and percentage differences. The influent coefficient was rescaled to a doubling for presentation. Ratios for treatment entries used the empty ERU phosphorus-treatment field as the reference. The secondary apparent-load model used the same predictors and HC3 uncertainty but retained the outcome on its fraction scale. The contextual global-nitrogen model used a natural-log effluent outcome and analogous nutrient-treatment indicators. Variance inflation factors were examined for the primary phosphorus model.

Predefined diagnostic sensitivities added influent biochemical oxygen demand, broad process class, or both; excluded the upper 1% of electricity intensity; excluded plants with any nutrient value at or below the quantification limit; replaced AESN capacity with ERU capacity; restricted the sample by the number of eligible occasions; and fitted all plant-day occasions with station-clustered uncertainty. Cook's distance was calculated for every plant. Twelve plants exceeded 4/n in the primary model; they were retained in the main analysis and removed only in the corresponding influence sensitivity.

Additional analyses performed during independent review evaluated the standard-entry contrast under restrictions to capacity of at least 2,000 population equivalents, extended-aeration activated sludge, the standard and empty-field groups, observed common capacity support, common 5th-95th percentile capacity support, process adjustment, and documented treatment-requirement compliance by 31 January 2024. These analyses were post hoc and are labelled as such. A single post hoc restricted cubic spline was also fitted for base-2 log electricity. Three knots were fixed at its 10th, 50th, and 90th percentiles before fitting that one model, yielding one linear and one nonlinear degree of freedom. No alternative knots, cut points, or functional forms were searched. Robust Wald tests assessed the joint electricity terms and nonlinearity; model fit was compared with the linear model by Akaike information criterion.

Analyses were performed in Python 3.13.5 with NumPy 2.3.5, SciPy 1.17.0, and statsmodels 0.14.6. Model-ready files, code, derived outputs, and source identities were independently reconstructed from the original official files. The complete scripts and validation checks are described in the accompanying repository and Supplementary Material.

RESULTS

Analytical cohort and availability of electricity

Exact-date reconstruction identified 1,247 phosphorus occasions in 479 plants with influent and treated-effluent phosphorus. Adding both flows left 1,244 occasions in 477 plants. Concurrent electricity was present for 671 occasions in 150 plants, and 655 occasions in 149 plants met the strict positive-value rules. The excluded plant had electricity equal to zero on its eligible phosphorus dates. The contextual nitrogen set contained 647 occasions from 142 plants.

The electricity cohort was selected by data availability. Among the 477 plants with phosphorus and flows, plants with at least one concurrent electricity record had a median capacity of 12,250 population equivalents, compared with 4,200 among plants without electricity. Median influent flow was 1,548 versus 618 m3/d. The advanced phosphorus-treatment entry accounted for 16.0% of plants with electricity and 5.8% without it, while the empty ERU field accounted for 24.0% and 35.5%, respectively. The 149-plant analytical cohort was therefore not treated as representative of all 477 plants.

Plant-level characteristics

The 149 phosphorus plants comprised 36 with an empty ERU phosphorus-treatment field, 90 with a standard entry, and 23 with an advanced entry (Table 1). Median treated-effluent phosphorus was 2.15 mg P/L in the empty-field group, 0.42 mg P/L in the standard group, and 0.637 mg P/L in the advanced group. Capacity differed substantially across the same groups, with medians of 2,500, 15,000, and 150,000 population equivalents. Whole-plant specific electricity medians were 0.651, 0.775, and 0.719 kWh/m3, respectively. Figure 1 displays the unadjusted phosphorus and capacity distributions.

Primary adjusted phosphorus model

In the simultaneously adjusted plant-level model, the standard ERU phosphorus-treatment entry had a ratio of 0.343 relative to an empty ERU field, equivalent to 65.7% lower treated-effluent phosphorus (95% CI: 80.5% to 39.4% lower; $p<0.001$) (Table 2). The advanced entry

Table 1. Plant-level characteristics by the phosphorus-treatment field in the 2024 French Urban Waste Water registry (ERU)

ERU 2024 phosphorus-treatment field	n	Plant-days, n	Capacity, PE	Influent total P, mg P/L	Treated-effluent total P, mg P/L	Apparent daily P load reduction	Whole-plant electricity, kWh/m3
Empty ERU phosphorus-treatment field	36	38	2,500 [1,150, 6,000]	7.26 [4.1, 9.78]	2.15 [1.2, 3.36]	0.676 [0.358, 0.828]	0.651 [0.335, 1.38]
Standard phosphorus-treatment entry	90	203	15,000 [5,500, 33,725]	5.72 [4.11, 7.68]	0.42 [0.209, 0.867]	0.913 [0.847, 0.962]	0.775 [0.565, 1.24]
Advanced phosphorus-treatment entry	23	414	150,000 [78,334, 445,816]	5.7 [4.98, 7.38]	0.637 [0.467, 0.748]	0.896 [0.849, 0.92]	0.719 [0.527, 0.868]

Note: values are medians [interquartile range] unless indicated otherwise. PE – population equivalents; P – phosphorus. An empty registry field does not prove absence of phosphorus treatment. Plant-day occasions were reconstructed by exact plant and date; models use one median per plant.

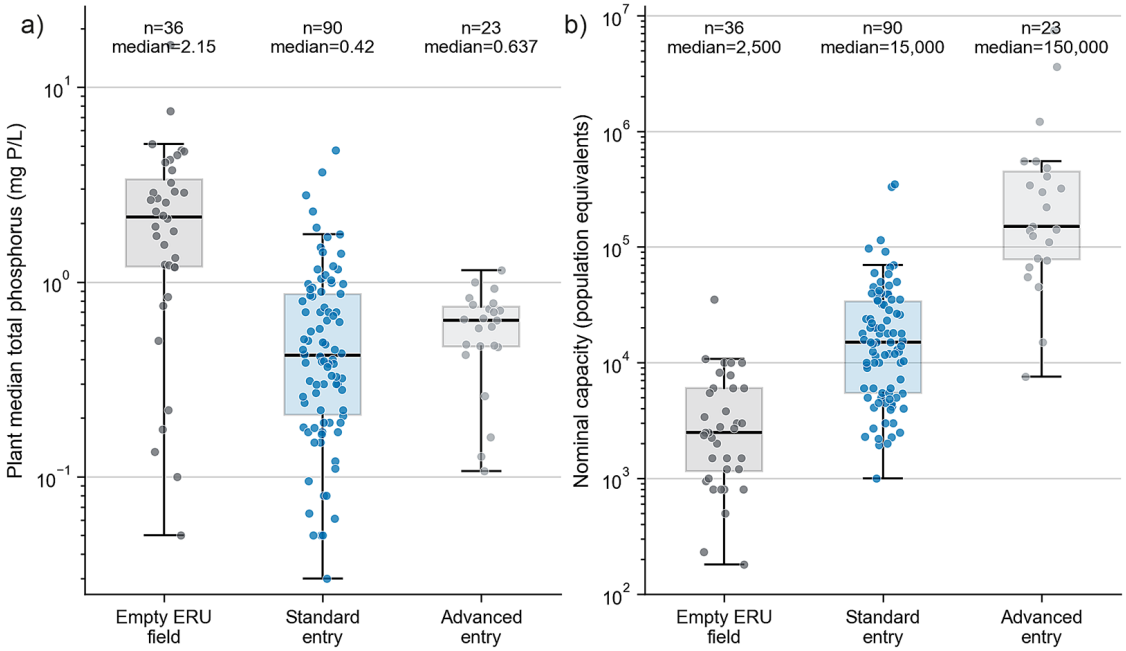

Figure 1. Descriptive plant-level distributions of (a) median total phosphorus concentration in treated effluent and (b) nominal treatment capacity across the phosphorus-treatment fields recorded in the 2024 French Urban Waste Water registry (ERU). Each point represents one wastewater treatment plant. Panel a uses the median of that plant's eligible January 2024 occasions; panel b uses the nominal capacity attribute reported for that plant in the AESN source. Boxes show the interquartile range and median; whiskers extend to 1.5 times the interquartile range. Both vertical axes are logarithmic; the plotted contrasts are unadjusted and do not represent treatment effects. "Empty ERU field" means that the annual registry contained no phosphorus-treatment entry; it does not prove that a plant operated without phosphorus treatment. PE, population equivalents; P, phosphorus

ratio was 0.570, corresponding to an estimated 43.0% lower phosphorus, but its 95% CI ranged from 76.1% lower to 35.9% higher (p = 0.205).

A doubling of whole-plant specific electricity had an adjusted ratio of 0.920, equivalent to an estimated 8.0% lower phosphorus (95% CI: 18.4% lower to 3.8% higher; p=0.177). The capacity estimate was 7.7% lower per doubling (95% CI: 15.8% lower to 1.3% higher; p=0.090). The model R^2 was 0.266, and variance inflation factors ranged from 1.43 to 3.27.

Secondary phosphorus and sensitivity analyses

For apparent daily phosphorus-load reduction, the standard entry was associated with an adjusted difference of +0.238 (95% CI: +0.122 to +0.354). The advanced entry difference was +0.175 (95% CI: +0.019 to +0.331). The electricity coefficient was +0.012 per doubling (95% CI: -0.008 to +0.032). These estimates describe the defined same-date apparent-load metric rather

Table 2. Adjusted associations with plant-level total phosphorus concentration in treated effluent

Term	Adjusted ratio (95% CI)	Adjusted difference, % (95% CI)	p value
Influent total P, per doubling	1.190 (0.810, 1.749)	19.0 (-19.0, 74.9)	0.376
Whole-plant specific electricity, per doubling	0.920 (0.816, 1.038)	-8.0 (-18.4, 3.8)	0.177
Hydraulic intensity, per doubling	0.919 (0.670, 1.262)	-8.1 (-33.0, 26.2)	0.602
Nominal capacity, per doubling	0.923 (0.842, 1.013)	-7.7 (-15.8, 1.3)	0.090
Standard ERU entry vs empty field	0.343 (0.195, 0.606)	-65.7 (-80.5, -39.4)	<0.001
Advanced ERU entry vs empty field	0.570 (0.239, 1.359)	-43.0 (-76.1, 35.9)	0.205

Note: the outcome was natural-log transformed. Ordinary least-squares estimates used HC3 heteroskedasticity-consistent uncertainty (n=149) and simultaneous adjustment for all listed terms. Ratios below 1 indicate lower treated-effluent phosphorus. ERU – French Urban Waste Water registry; CI – confidence interval.

than a complete phosphorus balance. The standard-entry association remained negative in all additional restrictions (Table 3; Figure 2a). It was 58.1% lower among plants with capacity of at least 2,000 population equivalents, 67.4% lower within extended-aeration activated sludge, and 54.8% lower in the observed common capacity range. In the narrower common 5th-95th percentile capacity subset, the estimate remained negative at 50.7% lower, while the interval widened from 78.1% lower to 10.6% higher. Excluding the 12 plants above the Cook threshold produced a 75.3% lower estimate for the standard entry and a 5.6% lower, still imprecise, electricity estimate. Complete sensitivity coefficients are reported in the Supplementary Material. The fixed restricted cubic spline had a slightly higher Akaike information criterion than the linear electricity specification (438.21 versus 437.22) and yielded no precise evidence for either the joint electricity terms (robust Wald p=0.336) or nonlinearity (p = 0.313). All fixed electricity-percentile contrasts relative to the median had intervals spanning zero.

All 149 phosphorus plants were marked as phosphorus-sensitive in ERU, so that field had no within-cohort contrast. A phosphorus-treatment requirement was populated for 81 plants and empty for 68. No plant-specific numeric phosphorus discharge limit was identified in the available ERU fields.

Table 3. Sensitivity of the adjusted standard phosphorus-treatment entry contrast relative to an empty ERU phosphorus-treatment field.

Analysis	Role	n	Adjusted ratio (95% CI)	Adjusted difference, % (95% CI)
Primary model	Primary	149	0.343 (0.195, 0.606)	-65.7 (-80.5, -39.4)
Capacity at least 2,000 PE	Additional sensitivity analysis	133	0.419 (0.215, 0.816)	-58.1 (-78.5, -18.4)
Extended-aeration activated sludge	Additional sensitivity analysis	107	0.326 (0.172, 0.619)	-67.4 (-82.8, -38.1)
Standard-entry and empty-field groups only	Additional sensitivity analysis	126	0.400 (0.224, 0.715)	-60.0 (-77.6, -28.5)
Observed common capacity range	Additional sensitivity analysis	99	0.452 (0.245, 0.836)	-54.8 (-75.5, -16.4)
Common 5th-95th percentile capacity	Additional sensitivity analysis	47	0.493 (0.219, 1.106)	-50.7 (-78.1, 10.6)
Capacity at least 2,000 PE plus process class	Additional sensitivity analysis	133	0.429 (0.220, 0.838)	-57.1 (-78.0, -16.2)
Treated entries with documented compliance date by January 2024, plus empty fields	Additional sensitivity analysis	108	0.308 (0.147, 0.645)	-69.2 (-85.3, -35.5)

Note: each model adjusted for influent total phosphorus, whole-plant specific electricity, hydraulic intensity and nominal capacity; the process-restricted model also adjusted for broad process class. The temporal restriction retained all empty-field records and restricted treatment-entry groups to plants whose documented compliance date for required phosphorus treatment was no later than 31 January 2024. These additional analyses were defined after the main analysis during independent review and were not preregistered.

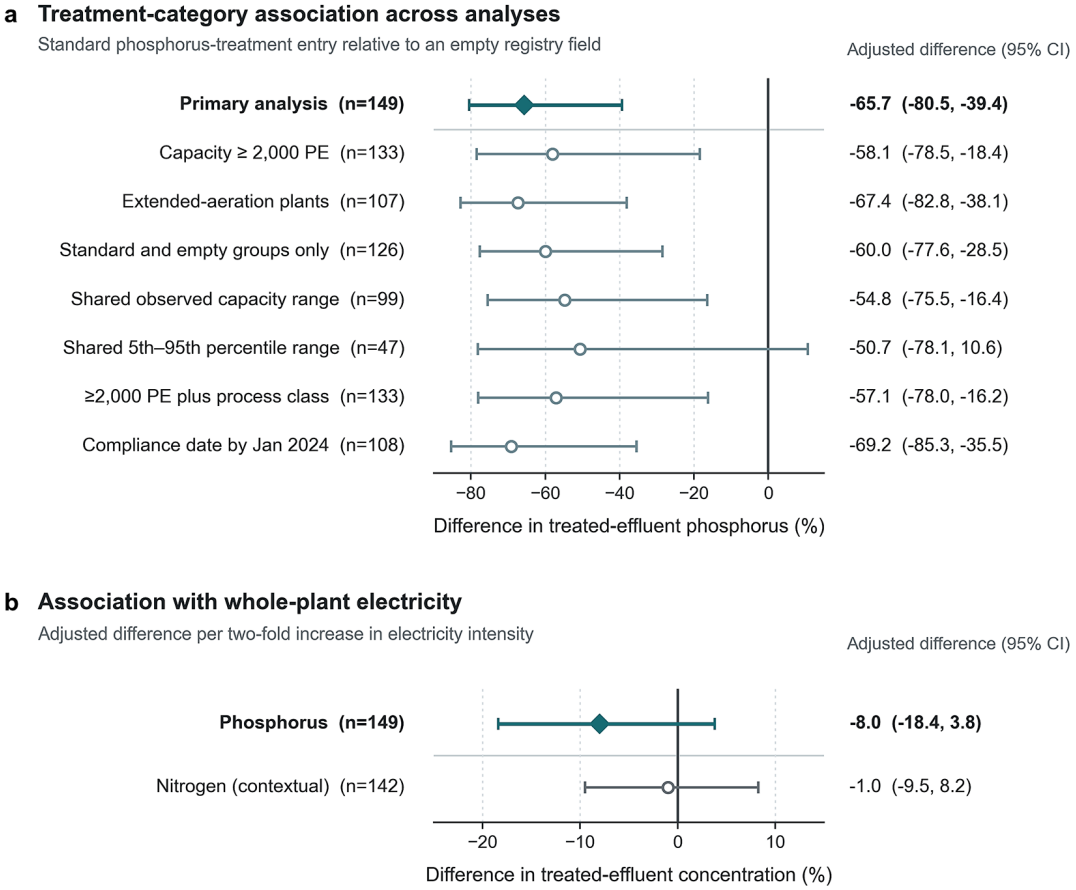

Figure 2. Adjusted percentage differences in plant-level treated-effluent nutrient concentrations. (a) Primary and post hoc sensitivity estimates for a standard phosphorus-treatment entry relative to an empty ERU phosphorus-treatment field. An empty field indicates that the annual registry contained no entry and does not establish absence or inactivity of phosphorus treatment. All models adjusted for influent total phosphorus, whole-plant specific electricity, hydraulic intensity and nominal capacity; the process-class sensitivity additionally included broad process class. The compliance-date sensitivity retained all empty-field records and restricted treatment-entry records to plants with a documented compliance date no later than 31 January 2024. (b) Adjusted associations of a doubling in whole-plant specific electricity with phosphorus and contextual global-nitrogen concentrations. Each estimate came from the corresponding nutrient model and adjusted for documented treatment categories, influent concentration, hydraulic intensity and nominal capacity. Filled diamonds show primary estimates, open circles show sensitivity or contextual estimates, horizontal bars show 95% HC3 confidence intervals, and the vertical line indicates no adjusted difference. Negative values indicate lower treated-effluent concentrations. Values were back-transformed as 100[exp(β) – 1]; n denotes plants

Contextual nitrogen model

The contextual global-nitrogen model contained 647 plant-day occasions summarized across 142 plants. A doubling of whole-plant specific electricity was associated with an estimated 1.0% lower treated-effluent nitrogen (95% CI: 9.5% lower to 8.2% higher; p = 0.824) (Figure 2b). Documented denitrification was associated with 71.0% lower nitrogen relative to an empty ERU nitrogen-treatment field (95% CI: 83.4% to 49.4% lower). This analysis was treated as contextual and not as a second primary contribution.

DISCUSSION

Main findings

This cross-sectional analysis separated two kinds of information that can otherwise be conflated in plant comparisons. The annual standard phosphorus-treatment entry showed a precise adjusted association with lower January treated-effluent phosphorus, while the coefficient for whole-plant specific electricity was smaller and imprecisely estimated. The same standard entry was associated with a higher apparent daily

phosphorus-load reduction fraction. In the contextual nitrogen model, whole-plant electricity was likewise imprecise, whereas a documented denitrification entry was associated with markedly lower treated-effluent nitrogen.

The standard-entry association was not confined to the large unadjusted capacity differences visible in Figure 1. Its direction persisted after adjustment for nominal capacity and hydraulic intensity and under restrictions to common capacity ranges, plants of at least 2,000 population equivalents, and extended-aeration activated sludge. Precision was lost in the narrowest common-support subset, which contained only 47 plants. The advanced category remained secondary because it included 23 plants and its main interval was wide. Its point estimate did not support an ordinal claim that the advanced entry outperformed the standard entry.

Relation to previous evidence

The present question complements rather than duplicates earlier French work. Starck et al. (2024) quantified long-term phosphorus flows, removal, and recycling potential across French wastewater systems. Joannis et al. (2024a) demonstrated the analytical value of SANDRE-formatted self-monitoring flow and quality data in Seine-Normandie, and their companion study examined pollutant loads and treatment performance under dry- and wet-weather conditions (Joannis et al., 2024b). The current estimand is different: the plant-level cross-sectional association of January 2024 effluent phosphorus with whole-plant electricity intensity and annually documented phosphorus-treatment entries after adjustment for influent, hydraulic, and scale conditions.

The electricity result should also be interpreted against international studies in which energy use was itself the main outcome. Niu et al. (2019) and Vaccari et al. (2018) showed that plant scale, process, loading, and hydraulic conditions shape observed electricity intensity. Li et al. (2025) extended this type of assessment to 2,576 Chinese plants using annual information and machine-learning methods. In contrast, the present study did not construct a ranking, efficiency frontier, or annual energy model. It asked whether a readily observed whole-plant ratio distinguished residual phosphorus quality within a restricted cross-section.

The imprecise electricity coefficient is compatible with the composite nature of the exposure. A facility with a high kWh/m3 value may differ in pumping lift, aeration demand, solids handling, inflow dilution, equipment condition, utilization, or treatment objectives. The available measure cannot assign consumption to phosphorus treatment. Methodological work has consequently emphasized matching the energy indicator to the comparison purpose rather than assuming that a single denominator identifies operational causes (Longo et al., 2023). Studies of energy per mass of pollutant removed or plant-level energy neutrality address more process-specific questions, but they require information not present here (Li et al., 2023; Zaborowska et al., 2017).

Recent Journal of Ecological Engineering studies confirm the relevance of linking treatment performance and resource use while also illustrating the importance of study scale. Sbai et al. (2026) compared energy use, conventional effluent indicators, and temporal variability across three full-scale configurations over three years. Ribarova et al. (2026) evaluated phosphorus recovery potential from conventional plants with attention to solids-related streams. The present analysis instead used effluent total phosphorus as the primary outcome across 149 plants and treated global electricity as an operational exposure. It therefore adds an incremental cross-plant perspective without claiming uniqueness for energy-quality analysis or phosphorus assessment.

Applied interpretation

For cross-plant interpretation, the findings indicate that documented nutrient-treatment context should be considered explicitly before a whole-plant electricity ratio is related to residual nutrient quality. The median phosphorus difference between treatment-entry groups was large, but the same groups also differed strongly in capacity. Simultaneous adjustment and common-support restrictions reduced, but could not eliminate, those structural differences. Reporting treatment entry, influent nutrient level, hydraulic intensity, and plant scale alongside kWh/m3 provides a more defensible description of heterogeneous facilities than using the electricity ratio alone.

The secondary apparent-load result points in the same direction as the concentration model, but it must remain a supporting outcome. Multiplying same-date concentrations by same-date flows produces an interpretable daily comparison, yet does not track the same water parcel through the

plant. It also omits storage, recycles, solids pathways, and other mass-balance terms. The result therefore cannot be substituted for hydraulically aligned removal performance.

The nitrogen analysis adds context rather than a separate claim. The electricity interval was centered near zero and remained compatible with modest differences in either direction, while documented denitrification showed a much clearer association with effluent nitrogen. This parallel pattern is consistent with the broader interpretation that annual treatment-category information and whole-plant energy describe different aspects of plant operation.

Strengths and limitations

A principal strength was the reconstruction of raw parameter-level records by exact station and date rather than reliance on published annual result tables. The analysis preserved source units and sampling points, excluded conflicting keys without averaging, and gave each plant equal weight through plant-level medians. Exact linkage to ERU provided documented process context, while HC3 uncertainty, influence diagnostics, plant-clustered analyses, common-support restrictions, quantification-limit sensitivity, and one fixed-knot spline alternative tested the stability of the main interpretation. Independent reproduction recovered the source hashes, denominators, model coefficients, selection comparisons, and functional-form results.

Several limitations define the scope of inference. Electricity availability selected larger and more frequently monitored plants and changed the treatment-category composition; the 149-plant cohort is not representative of all 477 plants with phosphorus and flow records. The design describes between-plant associations in January 2024 and supports no annual, seasonal, longitudinal, meteorological, or trend inference. Most plants had sparse temporal coverage, and 95 contributed one eligible occasion. Same-date influent and effluent measurements did not identify the same hydraulic parcel. ERU categories were annual documented attributes whose last-modification dates postdated January 2024; they did not verify daily operation. No individual numeric phosphorus limit was available, and residual confounding may remain from permit objectives, chemical dosing, operating conditions, equipment, and unmeasured process details. Finally, global electricity combined multiple plant loads, so its coefficient should not be interpreted as the association of nutrient-removal energy.

CONCLUSIONS

In this January 2024 cross-section of 149 Seine-Normandie wastewater treatment plants, a standard phosphorus-treatment entry documented in the annual ERU registry was associated with 65.7% lower plant-level treated-effluent total phosphorus relative to no entry in that field after adjustment for influent phosphorus, hydraulic intensity, nominal capacity, and whole-plant specific electricity. The corresponding estimate for a doubling of electricity was 8.0% lower phosphorus, with a 95% interval from 18.4% lower to 3.8% higher. The standard entry was also associated with a 0.238 higher apparent daily phosphorus-load reduction fraction. In the contextual nitrogen model, electricity was associated with an estimated 1.0% lower effluent nitrogen, whereas documented denitrification was associated with 71.0% lower nitrogen. The results distinguish the cross-plant information carried by documented treatment categories from that carried by a global electricity ratio.

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