



Sunstone Institute

Seasonal Nutrient Loading from

Norwegian Aquaculture

*An Assessment of Environmental Impact Using
Monthly Population Equivalents*

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Introduction

The aquaculture industry in Norway is a large source of anthropogenic pollution in coastal waters (Sample, 2025). In 2024, over 70,000 tonnes of nitrogen (N), 12,000 tonnes of phosphorus (P), and 334,000 tonnes of organic carbon (OC) were recorded in Norwegian coastal waters, which can be directly attributed to aquaculture (Pires Duro & Brown, 2026). To demonstrate the ecological impact of nutrient pollution, Pires Duro and Brown (2026) converted the values into Population Equivalents (PE). PE is a standardised, widely accepted figure used in wastewater regulation and assessment calculations that converts pollution values into the number of people required to generate an equivalent amount of pollution.

In 2025, the waste from aquaculture pollution was estimated to be equivalent to a population of over 17,000,000 for N, 19,900,000 for P, and 29,500,000 for OC. After converting pollution figures to PE, it becomes much clearer how much pollution aquaculture generates, as the values range from 3 to 5 times the Norwegian population, excluding pollution from industrial, agricultural, or other anthropogenic sources.

Still, annual PE values assume a constant discharge rate, yet Norwegian aquaculture exhibits significant seasonal variability. Because nutrient loading is directly proportional to feed consumption, annual averages underestimate the localised ecological stress experienced during summer growth peaks. Data from the Norwegian Directorate of Fisheries (Fiskeridirktoratet, 2025) illustrates this seasonal disparity; in 2025, feed consumption rose from 130,218 tonnes in February to a peak of 244,739 tonnes in September. This 87.9% increase is driven by the fact that most fish, including Atlantic salmon, are ectothermic (cold-blooded) organisms whose metabolic rates are dictated by environmental water temperatures (Volkoff, 2020). Elevated summer water temperatures, combined with concentrated nutrient pulses from intensified feeding, create a prime environment for opportunistic filamentous algae (Gundersen et al., 2012; Moy & Christie, 2012; Filbee-Dexter et al., 2020).

Consequently, evaluating the impact of pollution on a monthly scale is essential to capture these acute loading events. By adapting the population-equivalence metric to a monthly model, we quantified the specific anthropogenic pressure exerted by seasonal feeding patterns on the localised marine environment.

Methodology

To evaluate seasonal environmental pressures on aquaculture, a time-weighted approach was used to calculate monthly population equivalents.

The following steps were used to calculate monthly PE:

1. Calculating annual net waste discharge: Before determining monthly nutrient loading, it was necessary to measure actual nutrient levels in the environment rather than relying on total feed input. The annual net waste for nitrogen, phosphorus, and organic carbon was calculated by subtracting the changes in biomass, slaughter, and mortality from annual feed usage. This method ensures the resulting PE values reflect the true pollution load entering the ecosystem.
2. Determining the monthly distribution (waste coefficient): To find the specific monthly impact of feed consumption, a monthly feed coefficient was developed. This method was calculated by dividing the specific feed usage of a given month by the annual total feed usage. This coefficient was then applied to the annual net waste to estimate the monthly pollution figures.
3. Calculating monthly Population Equivalence (PE_m): The estimated monthly waste (converted from tonnes to kilograms) was divided by a monthly PE loading benchmark. This benchmark was calculated from the daily loading factors established by Norway's Statistisk Sentralbyrå (SSB) for N and P (Statistics Norway, 2025) and the EU Urban Wastewater Treatment Directive for OC (European Union, 1991). To ensure temporal accuracy, the daily benchmark (e.g., 12g N/day, Table 1) was multiplied by the exact number of days in each month to account for varying month lengths.

It is important to note that, when calculating the PE_m for organic carbon, pollution values are converted from Total Organic Carbon (TOC) to Five-day Biochemical Oxygen Demand (BOD5) using a factor of 1.8 (Siwiec et al., 2018) to align with the EU Urban Wastewater Directive.

Table 1. Daily loading benchmarks

Nutrient	Nitrogen	Phosphorus	Organic Carbon
Loading Value	12g	1.8g	60g ₂

Note: The loading values for Nitrogen and Phosphorus are from the SSB, and the value for Organic Carbon BOD5 is from the EU Urban Wastewater Directive.

Monthly PE formula

$$PE_m = \text{Pollution}_m / \text{Load}_m$$

Data Acquisition

The feed data used to calculate annual pollution figures and the monthly population equivalence were retrieved from the Norwegian Directorate of Fisheries databases.

Seasonal Loading Dynamics

The calculated monthly metrics reveal a stark disparity in the impacts of summer and winter population equivalence. In 2024, the nitrogen (PE) surged from a low of 9.5 million people in March to a peak of 22.6 million people during the peak feeding season in August (see Table 2), a 138% increase over 5 months. The annual average for nitrogen stands at approximately 16 million PE, significantly lower than the summer values. This contrast highlights how pollution loads are temporally concentrated during periods of intensified feeding activity rather than evenly distributed throughout the year.

This trend is mirrored across the other measured pollutants. During the same period, phosphorus and organic carbon PE values rose from 9.5 million and 16.3 million, respectively, to 26.2 million and 38.7 million, respectively, in the summer months. Although pollutant levels vary, the consistent seasonal increase across all indicators indicates a possible ecosystem-wide impact of seasonal feeding.

These values are particularly significant compared with Norway's population. In 2024, Norway's population was approximately 5.5 million, meaning that the peak monthly PE values in August correspond to pollution loads about four times the country's monthly wastewater flow.

It is important to note a key distinction between annual and monthly population equivalent values. Annual PE is the amount of pollution that an equivalent population would generate over a year, which is substantially greater than the pollution released in any single month (such as August). Monthly PE, by contrast, indicates that the pollution released during a given month is comparable to the amount of wastewater a population of that size would produce over the same month-long period.

Table 2. 2025 Monthly Population Equivalence Values (number of people)

Month	Nitrogen	Phosphorus	Organic Carbon
January	13,707,251	15,894,240	23,561,220
February	12,766,968	14,803,935	21,944,979
March	12,452,338	14,439,106	21,404,166
April	13,092,980	15,181,963	22,505,358
May	15,008,744	17,403,386	25,798,340
June	18,054,572	20,935,175	31,033,776
July	20,571,326	23,853,477	35,359,792
August	21,488,224	24,916,666	36,935,837
September	22,395,290	25,968,454	38,494,981
October	21,100,531	24,467,116	36,269,435
November	19,377,029	22,468,630	33,306,930
December	16,212,649	18,799,374	27,867,717

To validate the robustness of the monthly PE framework, annual PE values were compared with their monthly counterparts (see Table 3). As shown in the accompanying table, the difference between these two calculations remains within approximately 50,000 people across all pollutants. Given that total annual PE values are on the order of tens of millions, this deviation is negligible (<0.5%) and primarily attributable to rounding and month-length variation. This close alignment confirms that the monthly breakdown preserves the integrity of the annual load while redistributing it across months in line with feeding patterns.

Table 3. 2024 Annual vs Monthly Average PE Values (number of people)

Type	Nitrogen	Phosphorus	Organic Carbon
Average of Monthly Values	17,185,658	19,927,627	29,540,211
Annual Values	17,210,532	19,956,469	29,582,966

Ecological Context

Temperate and polar marine ecosystems rely on pronounced seasonal nutrient cycling to sustain annual patterns of growth, productivity, and reproduction. During the winter months, surface waters are mixed or replaced by deeper, nutrient-rich waters through physical processes such as vertical mixing and upwelling, replenishing nutrients depleted during the preceding growing season (Ryther, 1969). Over evolutionary timescales, these marine ecosystems have adapted to this cyclical exchange, with biological communities structured around the predictable seasonal availability of nutrients (Schaffelcke & Luning, 1994; Sjøtun et al., 1995).

During colder months, nutrients are effectively retained within the system, either remaining dissolved in the water column or incorporated into sediments and microbial biomass. As light availability and temperatures increase in spring and summer, these stored nutrients are assimilated by primary producers, often approaching the ecosystem's natural assimilative capacity (Marcus & Boero, 1998). This seasonal synchronisation between nutrient availability and biological demand is critical for maintaining ecological stability (Griffiths et al., 2017).

When large quantities of additional nutrients are introduced during the summer months, this balance can be disrupted. In periods of peak biological activity, native flora often have limited capacity to assimilate additional nutrient inputs (Abdullah & Fredriksen, 2014). Excess nutrients, therefore, become available to fast-growing, opportunistic algae, which thrive under warm temperatures and high light conditions. These species can rapidly outcompete slower-growing perennial seaweeds by reducing light penetration, smothering them, and impairing ecosystem structure and function (Andersen et al., 2019; Christie et al., 2019).

Such events are characteristics of eutrophication and are well documented in marine and coastal systems (Valiela et al., 1997). Seasonal nutrient enrichment from agriculture provides a widely recognised parallel. Fertilisers, applied during the summer months to enhance crop production, are transported to local waterways via surface runoff, triggering algal blooms and oxygen depletion (Akinnowo, 2023). Similarly, concentrated nutrient releases from aquaculture during the summer months risk overwhelming natural assimilative processes, amplifying ecological stress at a time when ecosystems are least resilient to additional nutrient loading (Smith et al., 2021).

Implications

Kelp forests provide a well-documented example of how seasonal nutrient enrichment and increased algal competition can alter coastal ecosystem structure. Long-lived, light-dependent foundation species, such as Sugar kelp (*Saccharina latissima*), are particularly sensitive to conditions that favour

fast-growing filamentous algae, which can proliferate under elevated nutrient availability during summer months (Filbee-Dexter et al., 2020).

Along the Norwegian coast, substantial declines in *Saccharina latissima* kelp forest extent have been observed, with losses of up to 80% reported between 2002 and 2012 along parts of the west coast and Skagerrak region (Moy & Christie, 2012). While this decline has been attributed to multiple interacting stressors, including elevated summer temperatures, coastal eutrophication, increased sedimentation, and the expansion of turf-forming algae, the timing and nature of these impacts highlight the vulnerability of kelp ecosystems to seasonal imbalances in nutrient and light availability.

Importantly, these changes occurred during periods of anomalously warm summers, reinforcing the role of seasonal conditions in mediating ecosystem responses to nutrient enrichment rather than to nutrient inputs alone.

Andersen et al. (2019) found that sugar kelp growth was highly dependent on light absorption, with kelp at shallower depths growing more than in deeper waters in spring and summer. The study also found that epibionts, such as turf algae, significantly affect kelp growth by shading their hosts. By fall, the kelp individuals at 1–9m were heavily covered with algal growth, resulting in much slower growth and higher mortality than those at 15m. Additionally, the study found that algal growth likely restricts nutrient uptake from the water, preventing the uptake of carbon and other nutrients necessary for kelp growth.

Limitations

A primary limitation of this study is the assumption of a temporally constant annual waste-to-feed ratio. An alternative approach would estimate monthly waste directly from biomass change, slaughter, and mortality data; however, substantial variability in the monthly biomass data complicates its use for resolving seasonal patterns in waste generation. As a result, monthly estimates derived from this approach were highly sensitive to short-term fluctuations and did not consistently reflect the temporal distribution of pollution inputs. Consequently, the methodology applies a linearised distribution of annual net waste based on monthly feed intensity.

However, empirical research indicates that nutrient retention efficiency is not static. Wang and Olsen. (2023) demonstrated that nutrient discharge is highly sensitive to seasonal water temperatures and regional environmental variability. Specifically, metabolic costs—such as the Standard Metabolic Rate (SMR)—increase during warmer summer months, leading to decreased feed conversion efficiency. This suggests that the current model likely underestimates nutrient load during peak summer temperatures (when metabolic waste is highest) and overestimates it during colder periods, when biological efficiency is higher.

Furthermore, the model assumes spatial uniformity in waste-to-feed ratios across all production areas. As regional water temperatures and local climates vary significantly across the Norwegian coast, the actual Population Equivalent loading may fluctuate between sites, even when feed inputs are identical.

Conclusion

This study demonstrates that evaluating aquaculture-derived nutrient pollution using annual averages underestimates the ecological pressure exerted on Norwegian coastal ecosystems. By adapting the population equivalence framework to a monthly scale, this analysis reveals pronounced seasonal concentration of nutrient loading that coincides with periods of heightened biological activity and reduced ecosystem resilience.

Monthly PE values for nitrogen, phosphorus, and organic carbon peak during the summer feeding season, reaching levels several times greater than the monthly wastewater output of Norway's entire population. These results highlight that the ecological relevance of aquaculture pollution is governed not only by total annual load but also, critically, by its timing. Concentrated nutrient inputs during summer months may amplify pressure on coastal ecosystems precisely when assimilative capacity is most constrained and ecological impacts are most likely to occur.

Framing nutrient pollution in terms of monthly population equivalents provides an intuitive, policy-relevant metric that captures both the magnitude and the temporal distribution of anthropogenic pressure. This approach bridges the gap between conventional annual accounting and the seasonal processes that govern ecosystem response, offering a clearer basis for understanding ecological risk than annual PE values alone.

This study does not attempt to attribute specific ecological outcomes to individual species. However, the observed seasonal loading patterns are consistent with documented vulnerabilities in Norwegian coastal ecosystems, including those affecting the stability of sugar kelp forests.

Future work should refine monthly estimates by integrating higher-resolution biomass data, site-specific hydrodynamics, and ecological response indicators for N, P, and C, individually and in combination. Nevertheless, the monthly PE framework presented here improves upon annual metrics and provides a robust foundation for evaluating the seasonal ecological implications of aquaculture-derived nutrient pollution in Norway.

All analysis code, data processing scripts, and intermediate outputs are publicly available on Sunstone Institute's GitHub, allowing any researcher with access to the same input datasets to reproduce all results by executing the documented analysis pipeline.

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Figures

Figure 1. Monthly PE 2020

Month	Nitrogen	Phosphorus	Organic Carbon
January	11,238,159	13,006,183	19,022,602
February	10,422,960	12,062,734	17,642,731
March	9,777,309	11,315,507	16,549,851
April	9,838,759	11,386,624	16,653,865
May	11,276,737	13,050,830	19,087,903
June	14,188,887	16,421,129	24,017,240
July	17,850,877	20,659,235	30,215,815
August	20,650,638	23,899,463	34,954,912
September	21,821,638	25,254,689	36,937,040
October	21,389,201	24,754,219	36,205,064
November	18,551,375	21,469,937	31,401,533
December	15,262,533	17,663,685	25,834,578

Figure 2. Monthly PE 2021

Month	Nitrogen	Phosphorus	Organic Carbon
January	12,423,887	14,384,256	21,097,917
February	10,219,233	11,831,728	17,354,030
March	9,961,070	11,532,831	16,915,626
April	10,476,592	12,129,697	17,791,072
May	12,554,844	14,535,877	21,320,304
June	15,617,912	18,082,267	26,521,925
July	18,847,146	21,821,043	32,005,724

August	21,440,830	24,823,985	36,410,250
September	22,739,883	26,328,016	38,616,268
October	21,019,455	24,336,121	35,694,682
November	17,772,139	20,576,410	30,180,176
December	13,503,543	15,634,271	22,931,360

Figure 3. Monthly PE 2022

Month	Nitrogen	Phosphorus	Organic Carbon
January	10,884,547	12,619,320	18,687,422
February	10,093,873	11,702,628	17,329,931
March	9,468,933	10,978,086	16,256,987
April	9,923,451	11,505,045	17,037,338
May	11,556,137	13,397,948	19,840,459
June	14,628,657	16,960,164	25,115,595
July	18,681,819	21,659,317	32,074,374
August	21,740,901	25,205,954	37,326,439
September	21,406,173	24,817,877	36,751,752
October	20,436,731	23,693,925	35,087,340
November	17,845,135	20,689,282	30,637,890
December	13,746,629	15,937,559	23,601,263

Figure 4. Monthly PE 2023

Month	Nitrogen	Phosphorus	Organic Carbon
January	11,393,056	13,203,467	19,496,755
February	10,819,360	12,538,609	18,514,999
March	10,227,119	11,852,257	17,501,506

April	10,694,496	12,393,903	18,301,320
May	12,926,795	14,980,924	22,121,418
June	15,262,042	17,687,254	26,117,690
July	19,775,739	22,918,199	33,841,907
August	22,402,655	25,962,544	38,337,306
September	22,708,226	26,316,671	38,860,224
October	20,339,050	23,571,022	34,805,892
November	17,083,307	19,797,926	29,234,391
December	12,819,078	14,856,091	21,937,084

Figure 5. Monthly PE 2024

Month	Nitrogen	Phosphorus	Organic Carbon
January	10,511,935	12,183,655	18,004,580
February	9,765,250	11,318,224	16,725,676
March	9,550,884	11,069,767	16,358,515
April	10,237,039	11,865,042	17,533,745
May	13,168,291	15,262,453	22,554,320
June	16,452,876	19,069,388	28,180,076
July	21,154,600	24,518,830	36,233,070
August	22,641,768	26,242,503	38,780,255
September	22,566,962	26,155,801	38,652,130
October	21,505,285	24,925,285	36,833,715
November	18,727,039	21,705,213	32,075,206
December	15,750,884	18,255,758	26,977,721