# ASSESSING THE ENVIRONMENTAL CONSEQUENCES OF PHOSPHATE EMISSIONS IN CIVIL ENGINEERING PROJECTS AND THEIR INCLUSION IN THE LIFECYCLE COSTS OF BUILDINGS

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**Abstract**

Eutrophication, characterized by rising levels of nitrogen and phosphorus, poses a significant risk to biodiversity. In civil engineering, the contribution of phosphate emissions to this process has been insufficiently addressed and requires detailed examination. This study evaluates both the environmental and economic impacts of phosphate emissions in civil engineering, with a focus on their integration into the lifecycle costs of buildings. Detailed analysis of 17 residential buildings in the South Moravian Region has quantified environmental harm, establishing an economic cost of 5000 €/t for $PO_4^{3-}$. Environmental damage caused by phosphate emissions was monitored throughout the construction and operational phases of the residential buildings. The research reveals that the ratio of annual operating costs to external societal costs varies from 1% to 11%. Furthermore, the research reveals that annual negative externalities per square metre due to phosphate emissions fluctuated between 4.99 €/m² and 0.19 €/m². These higher externalities also correlate with increased annual operating costs per square metre. Variations were primarily attributed to the characteristics of the building envelope, construction materials, and energy sources. These findings underscore the need for incorporating ecological costs into fiscal planning, highlighting the importance of sustainable construction practices in mitigating environmental impacts.

**Keywords**

Phosphate emissions, environmental impact assessment, construction materials, sustainable construction, economic valuation

## 1 INTRODUCTION

In the context of this study, the term "nutrient" primarily signifies phosphorus, as an essential element, crucial for the proliferation of plant life, thereby supporting a diverse ecosystem of grazers and consumers throughout the food chain. Phosphorus, as a vital nutrient, can have natural origins through a series of physical, chemical, geological, and biological processes within the environment. However, it is equally prevalent due to human activities [1]. Anthropogenic sources, including agriculture practices such as animal manure application and the use of synthetic fertilizers, alongside the discharge of municipal and industrial wastewater from facilities like wastewater treatment plants and septic systems, contribute significantly to phosphorus levels in aquatic systems. Additionally, stormwater runoff and emissions from the combustion of fossil fuels are notable sources of phosphorus [2], [3]. Phosphate, commonly generated in civil engineering from emissions from energy sources, emissions during the production and transportation of construction materials, and the discharge of untreated sewage, carries significant yet often overlooked environmental consequences.

This study bridges the gap by meticulously evaluating the environmental damage incurred from phosphate emissions during both construction and operational phases of civil engineering projects. Utilizing data from 17 distinct residential construction projects and the SBToolCZ methodology, phosphate production was systematically quantified. The primary objective of this study is to determine the economic cost of this environmental damage, expressed in euros per tonne of $PO_4^{3-}$. To achieve this, an extensive review of existing research was undertaken to identify an economic valuation model for the adverse environmental impacts of phosphate. This research extends beyond the conventional economic perspective, considering the frequently disregarded environmental implications of construction choices. The findings not only enhance the comprehension

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of the ecological consequences of construction activities but also offer valuable insights for policymakers and industry stakeholders striving to promote sustainable construction practices.

## State of the art

Eutrophication, a complex process that afflicts both freshwater and marine environments, leads to a cascade of environmental issues, including algal blooms, “red tides”, “green tides”, fish kills, inedible shellfish, and public health threats. At its core, eutrophication poses a severe disruption to aquatic ecosystems, endangering both animal and human well-being. This phenomenon primarily arises from the excessive accumulation of plant nutrients, often stemming from agricultural, sewage treatment sources, and emissions from the combustion of fossil fuels [4]. These processes can have far-reaching consequences, affecting not only the ecological balance of aquatic environments but also posing management challenges for sustaining healthy ecosystems. Understanding their triggers and impacts is essential for effective conservation and resource management [5].

The environmental consequences of nutrient pollution, particularly phosphate emissions in civil engineering, have often been overlooked. These emissions occur during multiple phases, from the production, transportation of construction materials to energy source-related emissions. When untreated sewage is discharged into water, it adds to the overall phosphorus load, exacerbating eutrophication issues [6].

Nevertheless, in some situations there is a mismatch between actual environmental impacts and regulatory practices. If industries generate negative externalities that are not taken into account by regulators, they may face regulation in future, leading to sub-optimal production for society. To use environmental resources efficiently for the greater good, it is essential to consider all aspects of an activity, which include both positive and negative aspects [7].

The issue of phosphate emissions during construction and operational phases of civil engineering projects has garnered attention in recent years. Research has been conducted to understand the environmental implications and economic costs associated with these emissions. One notable aspect of this research is the determination of the economic valuation of the adverse environmental impacts of phosphate. Such valuation models are essential for assessing the true cost of phosphate emissions on the environment and society. This analysis, combining literature and a case study, demonstrates the potential of monetary valuation for nutrients and pollution in decision-making processes. It highlights significant economic costs associated with nutrient pollution and removal but underscores the need for a comprehensive view across sectors and the combination of costs and restoration efforts. In the case study, monetary valuation was applied, showing that phosphate recovery can offer substantial benefits. At a conservative value of $8.41 per kg of P, the benefits outweigh the costs over a 20-year period. With a potentially higher P value of $30.41 per kg, the benefits far exceed the capital investment [8].

This study demonstrates that P removal costs in different treatment scenarios range from approximately $93 to $134 per kg of P removed. Among the options, MUCT BNR + tertiary reactive media filtration offers a cost-effective approach at around $99 per kg of P removed, producing effluent with a total P concentration of 0.05 mg/l. Incorporating phosphate precipitation for P recovery yields a slight reduction in effluent P (about 6%) and may not meet stringent total P discharge limits. The study highlights the significant expense associated with chemical additions in the phosphate precipitation process and suggests the need for research into more cost-effective alternatives. Biosolids remain the primary outlet for P in all scenarios, emphasizing the importance of managing them safely. These findings have implications for assessing life cycle costs and environmental impacts of various P removal and recovery processes [9].

The following source discusses excessive nutrient pollution in water that carries significant economic consequences, such as:

1. Tourism and recreation: Algal blooms in Ohio, Florida, Texas, and Washington led to losses in restaurant sales and tourism revenue, notably $37–47 million in Ohio over two years.
2. Commercial fishing: Algal blooms reduce harvests and increase processing costs, e.g., Maine suffered $2.5 million losses in clam harvests and $460,000 in mussel harvests.
3. Property values: Poor water quality depresses waterfront property values; for example , slight differences in water clarity cause property value shifts of up to $85,000 in Minnesota.
4. Human health: Algal blooms can lead to health issues, with Sarasota County facing over $130,000 in emergency room visit costs during bloom years.
5. Drinking water treatment costs: Treating water with excess nutrients cost over $13 million in Ohio due to algal blooms.
6. Mitigation: Algal bloom mitigation measures range from $11,000 for barley straw treatment to over $28 million for long-term dredging and alum treatment.
7. Restoration: Restoring waterbodies incurs substantial costs, for example , a nutrient trading program in Ohio’s Great Miami River Watershed estimated expenses exceeding $2.4 million over three years.

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A case study demonstrates the impact of method variability on decisions, underscoring the need for standardized valuation techniques for nutrient pollution in future decision-making [6].

This study addresses the impact of nutrient pollution from livestock waste on aquatic ecosystems, human health, and local economies through Harmful Algae Blooms (HABs). The research introduces a computational framework to quantify the economic consequences of HABs, demonstrated in a Wisconsin case study. Each excess kilogram of phosphorus runoff leads to $74.5 in total economic losses. This analysis supports the development of a nutrient management market to mitigate phosphorus imbalances in the region and offers guidance for regulatory policies [10].

Despite various articles, calculations, and knowledge about the negative impacts of phosphate, it is very difficult to determine the exact environmental damages. While it is understood that heightened water pollution results in animal mortality, loss of biodiversity, reduced property values, decreased tourism, and even negative health effects. These variables are highly dependent on the specific location and the amount of phosphates in the vicinity. With variables that are so diverse and dependent on various factors, it is challenging to establish a unified and precise figure for the overall environmental damages caused by phosphates. In this context, the present study aims to contribute to the existing body of knowledge by meticulously quantifying emissions of phosphate from energy sources and emissions from the production and transportation of construction materials production, evaluating its environmental damage, and determining its economic cost. A particular focus is placed on evaluating phosphate emissions in the realm of civil engineering, offering insights into sustainable construction practices and addressing the frequently disregarded environmental implications of these activities. The study utilizes a comprehensive review of existing research to identify an economic valuation model for phosphate's adverse environmental impacts.

# 2 METHODOLOGY

The study covered 17 residential buildings located mainly in the South Moravian Region of the Czech Republic. For each of these buildings, energy performance certificates were gradually created. The annual specific energy consumption measured in MJ/m$^2$ of total floor area was calculated. SBToolCZ is capable of evaluating both primary energy consumption, which takes into account the whole process of energy acquisition and delivery to the point of consumption, and bound energy consumption, which takes into account the materials used in the construction of the building and their transport. The assessment includes two distinct phases based on the life cycle of the building. The production phase assesses the bound energy consumption and the energy used for transporting the materials. In contrast, the operational phase analyses the consumption of primary energy from non-renewable sources, considering the energy performance of the building and the energy carriers used.

Due to the challenge of determining the cost of negative environmental impacts, the values were selected for a conservative estimate. Sourcing from the Sustainability Impact Metrics, the cost was set at 5,000 €/t for $PO4^{3-}$,eqv. emissions generated. This methodology employs eco-costs, representing marginal prevention costs of toxic emissions, determined by a prevention curve. The curve prioritizes economically efficient prevention measures for countries or groups. The negligible-risk level is where emissions are significantly below toxicity thresholds or background levels, potentially beneficial. Hence, the 5,000 €/t value provides a conservative estimate for phosphate emissions economic cost, which proves to be a baseline prize to economically sustain and mitigate phosphate risks [11].

Methodology process breakdown:

- Objective identification: The aim was to assess the environmental damage caused by phosphate emissions during the construction and operational phases of residential buildings.
- Building selection: 17 residential buildings within the South Moravian Region were selected for analysis to provide a comprehensive overview of various construction types and energy consumption patterns.
- Data collection. For each selected building, the following data were collected:
    - The annual energy consumption.
    - The construction materials used.
    - The energy required for the production and transportation of these materials.
- Energy and material analysis:
    - The SBToolCZ methodology was utilized to evaluate the energy associated with the consumption and transportation of materials in the building.
    - Energy performance certificates were used to assess the energy consumption during the operational phase.

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- Phosphate emissions for both the construction and operational phases of the buildings were calculated using the SBToolCZ methodology.
- Economic valuation:
  - A cost of 5,000 €/t was attributed to the environmental damage caused by phosphate emissions, based on established valuation models.
- Compilation of results:
  - Data were organized into tables, displaying:
    - The specific energy used for usage of building and materials associated with each building.
    - The calculated phosphate emissions.
    - The cumulative cost of these emissions over the buildings' lifecycle. Calculation was performed according to formula (1).
- Final analysis:
  - The overall costs for constructing and maintaining each building were determined, incorporating both standard expenses and the environmental costs due to phosphate emissions.
  - This analysis provided insights into the true financial impact of various building practices in relation to their environmental footprint.

$$WLC = \sum_{i=0}^{n} \frac{C_i}{(1+r)^i} + \sum_{i=0}^{n} \frac{Ex_i}{(1+r)^i} \tag{1}$$

The equation for Whole Life Costs (WLC) accounts for various components. WLC represents the overall financial expenditure associated with a project. It includes the annual costs (C) incurred in each specific year (i) during the project's assessed period, which typically spans multiple years (n). Additionally, it incorporates the costs of externalities (Ex), which are quantified as the societal cost of producing $PO_4^{3-}{}_{,eqv}$ within the same year (i). To evaluate the present and future value of these costs over the assessed period, a discount rate (r), converted from a percentage to a decimal, is applied to reflect the time value of money.

Tab. 1, found below, provides the fundamental data essential for subsequent economic analysis, encompassing parameters such as the total built-up and floor area in square meters, the built-up space in cubic meters, and the specific annual consumption of bundled, primary, and total energy measured in MJ/m$^2$ of total floor area.

Tab. 1 Input parameters of the residential buildings of the research sample.

| **No.** | **Total floor area** | **Built-up space** | **Built-up area** | **Specific annual consumption of bundled energy** | **Specific annual consumption of primary energy** | **Total specific annual energy consumption** |
|---|---|---|---|---|---|---|
| | **(m$^2$)** | **(m$^3$)** | **(m$^2$)** | **(MJ / m$^2$ · a)** | **(MJ / m$^2$ · a)** | **(MJ / m$^2$ · a)** |
| **1** | *808* | *2,656* | *256* | *177* | *312* | *489* |
| **2** | *831* | *2,850* | *238* | *104* | *277* | *381* |
| **3** | *3,587* | *14,690* | *529* | *77* | *327* | *404* |
| **4** | *878* | *2,751* | *351* | *146* | *914* | *1,061* |
| **5** | *2,151* | *4,484* | *233* | *92* | *214* | *307* |
| **6** | *1,811* | *6,256* | *1,264* | *215* | *458* | *672* |
| **7** | *810* | *2,995* | *187* | *155* | *303* | *458* |
| **8** | *228* | *805* | *111* | *91* | *427* | *517* |
| **9** | *1,155* | *4,930* | *408* | *197* | *469* | *666* |

| | | | | | | |
|---|---|---|---|---|---|---|
| **10** | *647* | *2,010* | *285* | *123* | *539* | *663* |
| **11** | *275* | *1,081* | *163* | *132* | *530* | *662* |
| **12** | *1,427* | *4,017* | *309* | *116* | *534* | *651* |
| **13** | *1,654* | *7,607* | *495* | *125* | *320* | *445* |
| **14** | *1,690* | *5,468* | *468* | *233* | *533* | *766* |
| **15** | *433* | *1,492* | *313* | *139* | *644* | *782* |
| **16** | *965* | *4,922* | *343* | *68* | *470* | *538* |
| **17** | *987* | *3,428* | *328* | *234* | *535* | *769* |

The specific annual $PO_4^{3-}{}_{,eqv.}$ release rates were calculated based on the total energy consumption. These rates were determined during the production phase to assess bounded and transportation $PO_4^{3-}{}_{,eqv.}$ releases, which account the energy required for the entire lifecycle of the building, and during the operational phase to evaluate the $PO_4^{3-}{}_{,eqv.}$ releases resulting from the energy consumption during the building's operational phase. The values are provided in Tab. 2.

Tab. 2 Values for the potential eutrophication of the buildings under study.

| | **Specific annual bundled $PO_4^{3-}{}_{eqv.}$ emission production (kg $PO_4^{3-}{}_{eqv.}$ / ($m^2 \cdot$ a))** | **Specific annual $PO_4^{3-}{}_{eqv.}$ emission production (kg $PO_4^{3-}{}_{eqv.}$ / ($m^2 \cdot$ a))** | **Total specific annual bundled $PO_4^{3-}{}_{eqv.}$ emission production (kg $PO_4^{3-}{}_{eqv.}$ / ($m^2 \cdot$ a))** |
|---|---|---|---|
| **1** | *0.017000* | *0.105034* | *0.122034* |
| **2** | *0.008520* | *0.060771* | *0.069291* |
| **3** | *0.008400* | *0.039704* | *0.048104* |
| **4** | *0.009500* | *0.988371* | *0.997871* |
| **5** | *0.010725* | *0.027526* | *0.038251* |
| **6** | *0.054550* | *0.051550* | *0.106100* |
| **7** | *0.012521* | *0.104965* | *0.117486* |
| **8** | *0.005805* | *0.042984* | *0.048789* |
| **9** | *0.021755* | *0.040901* | *0.062656* |
| **10** | *0.010440* | *0.264302* | *0.274742* |
| **11** | *0.010750* | *0.080147* | *0.090897* |
| **12** | *0.007134* | *0.236338* | *0.243472* |
| **13** | *0.012854* | *0.079357* | *0.092210* |
| **14** | *0.017494* | *0.082756* | *0100250* |
| **15** | *0.004400* | *0.695728* | *0.700128* |
| **16** | *0.055030* | *0.103784* | *0.158814* |
| **17** | *0.025900* | *0.077323* | *0.103223* |

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# 3 RESULTS

To determine the partial lifetime costs of each building, the economic cash flow (CF) was determined. The calculation of the economic CF consists of the following components: initial investment costs, operating costs associated with maintenance and repairs, and societal external costs (attributed to damages) associated with the production of $PO_4^{3-}{}_{,eqv.}$. The calculation of external costs takes into account the rate of 5,000 €/t for the generation of $PO_4^{3-}{}_{,eqv}$. emissions as set out in the Sustainability Impact Metrics [11]. The lifetime costs can be determined according to formula (1).

The lifetime costs, as outlined in Tab. 3, were computed using the previously mentioned formula, considering a 5% discount rate that is being typically applied to public projects in the Czech Republic during the EU program period from 2021 to 2027. The assessment period spans 10 years, where $t_0$ represents the investment costs, and $t_1$ to $t_{10}$ encompass the operational costs of buildings and the operational costs associated with externalities.

Tab. 3 Whole life costs in €.

| **No.** | **Investment costs** | **Annual operating costs of the building** | **Annual externalities** | **WLC** | **WLC/m²** | **The ratio of building costs and externalities** |
|---|---|---|---|---|---|---|
| | **(a)** | **(b)** | **(c)** | **(d)** | **(e)** | **(f) = (c) / ((b) + (c))** |
| **1** | *992,694* | *21,064* | *493* | *1,103,953* | *1,367* | *2%* |
| **2** | *1,065,203* | *21,655* | *288* | *1,175,848* | *1,415* | *1%* |
| **3** | *5,490,466* | *92,893* | *863* | *5,918,497* | *1,650* | *1%* |
| **4** | *1,028,306* | *34,395* | *4,378* | *1,264,477* | *1,441* | *11%* |
| **5** | *1,675,919* | *29,333* | *411* | *1,814,857* | *844* | *1%* |
| **6** | *2,338,288* | *55,628* | *961* | *2,643,094* | *1,459* | *2%* |
| **7** | *1,119,532* | *24,508* | *476* | *1,249,951* | *1,543* | *2%* |
| **8** | *300,761* | *4,513* | *55* | *320,032* | *1,407* | *1%* |
| **9** | *1,842,614* | *32,224* | *362* | *1,994,509* | *1,727* | *1%* |
| **10** | *751,248* | *20,204* | *889* | *870,594* | *1,345* | *4%* |
| **11** | *404,030* | *9,674* | *125* | *456,851* | *1,659* | *1%* |
| **12** | *1,501,375* | *41,129* | *1,737* | *1,745,118* | *1,223* | *4%* |
| **13** | *2,843,157* | *48,223* | *763* | *3,068,015* | *1,855* | *2%* |
| **14** | *2,043,694* | *39,221* | *847* | *2,241,040* | *1,326* | *2%* |
| **15** | *557,456* | *14,943* | *1,514* | *651,938* | *1,507* | *9%* |
| **16** | *1,839,665* | *38,776* | *766* | *2,042,851* | *2,118* | *2%* |
| **17** | *1,281,233* | *32,294* | *509* | *1,461,461* | *1,481* | *2%* |

# 4 DISCUSSION

Our findings indicate a substantial variance in phosphate emissions among the studied buildings, highlighting the influence of construction materials and energy sources. When juxtaposed with the state-of-the-art literature, our study fills a critical gap by providing an economic valuation of phosphate emissions. The novelty of our work lies in the detailed economic assessment, where we correlate specific construction practices with their long-term

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ecological costs. This direct linkage emphasizes the economic feasibility of sustainable construction practices, advancing the conversation beyond environmental impact to also consider economic implications.

In the study, the environmental impact of phosphate emissions was quantified in terms of eutrophication potential. Economically, these emissions were valued at 5,000 €/t . Specific annual $PO_4^{3-}{}_{eqv.}$ release rates were calculated for the buildings, with emissions during production and operational phases varying widely. For instance, Building 5 showed a total specific annual bundled $PO_4^{3-}{}_{eqv.}$ emission production of 0.0382 kg $PO_4^{3-}{}_{eqv.}/(m^2{\cdot}a)$, while Building 4 had 0.9978 kg $PO_4^{3-}{}_{eqv.}/(m^2{\cdot}a)$, demonstrating the economic and environmental variability depending on the construction and operation specifics. Buildings 5 and 15 have all building systems powered by electricity, which is the reason for the large load of phosphate emissions. The other buildings mainly use gas or a municipal natural gas-powered heating plant for heating. Other significant factors affecting phosphate production are the materials used for construction and the building envelope. In terms of materials used, wood comes out as one of best options, while concrete is one of the worst.

Column (e) in Tab. 3 displays the Whole Life Costs (WLC) per square meter of floor area, which in this part of research includes one environmental societal cost component, namely $PO_4^{3-}{}_{,eqv}$, with values ranging from 844 €/$m^2$ (Building 5) to 2,118 €/$m^2$ (Building 16). These variations are primarily attributed to differences in the average heat transfer coefficient of the building envelope, influenced by construction materials, technology and energy carriers.

Column (f) presents the ratio of annual operating costs to external societal costs (negative externalities). The ratios range from 1% (Building 2) to 11% (Building 4). These differences are mainly due to the energy source used for heating, domestic hot water, lighting, and other purposes, as well as its energy conversion factor and environmental impact in terms of $PO_4^{3-}{}_{,eqv.}$ pollution. Building 4 relies on electricity, while Building 2 connects to a municipal natural gas-powered heating plant, leading to these variations.

Incorporating lifecycle costs into economic models makes the environmental impact of phosphate emissions a quantifiable part of financial planning. This encourages more sustainable construction practices by making the long-term ecological costs visible and impactful in decision-making processes.

The evaluation of phosphate emissions during both the construction and operational phases of civil engineering projects has revealed certain environmental damage. Discussions on this topic are limited by the availability of relevant research papers, posing a challenge in formulating a comprehensive conclusion in this area.

# 5 CONCLUSION

The study comprehensively assessed the environmental consequences of phosphate emissions in civil engineering projects and their impact on the lifecycle costs of buildings. Phosphate emissions, often overlooked, pose a significant threat to biodiversity and aquatic ecosystems due to eutrophication. The research aimed to quantify the environmental damage and economic cost of phosphate emissions, innovatively expressed in euros per tonne of $PO_4^{3-}{}_{eqv.}$. Findings revealed the substantial environmental impact of phosphate emissions in construction and operational phases. Whole Life Costs (WLC) were computed for 17 residential buildings, with WLC per square metre ranging from 844 €/m² to 2,118 €/m². Variations were primarily attributed to building envelope characteristics, construction materials, and energy sources. The ratio of annual operating costs to external societal costs ranged from 1% to 11%, reflecting differences in energy sources and environmental impacts.

While the study offers valuable insights, it has limitations. Further research is required to refine the economic model and explore cost-effective mitigation solutions. Given the relatively small sample size of 17 projects in the study, future research should prioritize the expansion of the dataset. A larger and more diverse sample will enhance the generalizability of findings. Future research endeavours should focus on recognizing and evaluating additional correlated advantages and drawbacks linked to buildings within their public spaces. Nevertheless, this work enhances understanding of the environmental and economic dimensions of phosphate emissions.

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