Royal HaskoningDHV
Enhancing Society Together

Reimagining wastewater phosphorus removal and recovery

Strict regulations for environmental phosphorus limits will require holistic solutions and innovative technology if we are also to achieve a sustainable and circular phosphorus management cycle

Eutrophication – a visible sign of phosphate pollution

Rivers and waterways are delicate ecosystems that require careful management to protect them from agricultural, industrial, and domestic impacts – and satisfy the expectations of recreational access. But increased awareness of the need for good water quality has brought greater scrutiny from the public and the press [1].

Algal bloom – one of the most striking signs of a watercourse being out of balance – is caused by the increase in phosphorus and other nutrients in lakes and river systems by a process known as eutrophication. These dense, green carpets of algae on the water's surface can be toxic to humans and other animals and prevent light penetration and oxygen absorption, creating ecological "dead zones" that kill fish.

Many countries are taking steps to reduce phosphorus levels in waterways to combat the challenge of eutrophication. In the UK, for example, the Water Industry National Environment Programme (WINEP) implemented £5.2 billion of expenditure in the current AMP7 investment period (2020–2025) to improve water quality [2], with around 50% of this cost associated with new phosphorus drivers at more than 780 wastewater treatment works (WwTWs). However, all indications are that the next investment cycle (AMP8) will affect an even greater number of sites with lower discharge limits for phosphorus [3].

Meeting these new guidelines poses a significant affordability challenge – particularly in the current financial and political climate. But it also puts further pressure on the water companies' Net Zero 2030 targets due to the requirements for energy and chemically intensive end-of-pipe solutions.

While these changes pose a challenge to the water sector, alternative sustainable phosphorus management approaches could bring a range of benefits. Engagement with stakeholders outside the industry to improve catchments can alleviate flood risk, improve water resources, and lead to better food production, cleaner waters, a healthier society, and greater biodiversity. All of which can reduce the pressure on water companies.

In conjunction with this, technological innovation within treatment works can deliver more efficient phosphorus removal and implement phosphorus recovery, where this finite material is recovered in a range of valuable forms for beneficial reuse.

In this white paper, we'll explore the following:

- The challenge of managing phosphorus – a limited and valuable resource
- How the water industry can identify novel catchment approaches
- The importance of phosphorus removal from wastewater
- The state-of-the-art technology used to recover and valorise phosphorus

[1] www.theguardian.com/environment/2018/jul/17/plantwatch-phosphate-fertilisers-leading-widespread-pollution

[2] www.gov.uk/government/publications/developing-the-environmental-resilience-and-flood-risk-actions-for-the-price-review-2024/water-industry-national-environment-programme-winep-methodology

[3] www.royalhaskoningdhv.com/en/markets/water/uk-water-utilities/amp8-facing-future-challenges

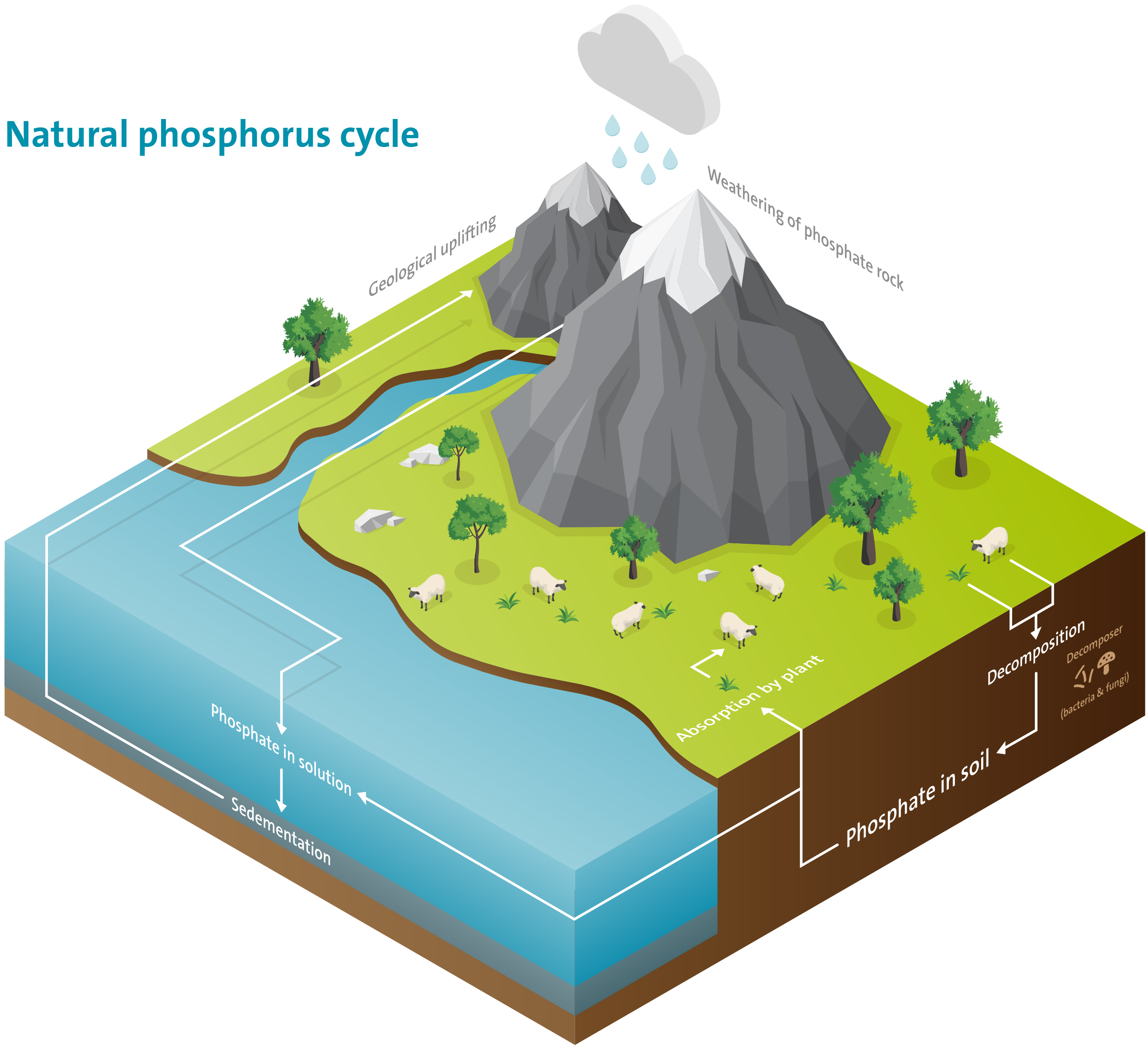
Getting the phosphorus balance right

It's estimated that half the world's food production relies on phosphate fertilisers [4]. In fact, such is the demand from agriculture that 90% of the world's mined phosphate rock is used in food production.

Most of that phosphate comes from minerals found in only a handful of countries, such as China, the USA, and Morocco, although a large underground deposit of high-grade phosphate rock has recently been discovered in Norway [5].

It's hard to predict exactly how long these reserves will last because we're still yet to reach peak demand. But phosphorus is an essential building block of life, and our increasing demand for phosphate rock is a sign that we haven't been able to close the loop on the phosphorus cycle.

Natural phosphorus cycle



Our incomplete phosphorus cycle [6]

The natural phosphorus cycle is inherently circular, operating on geological timescales. However, increasing demand for phosphorus in agriculture is breaking this cycle as:

1. Phosphate-rich rock is mined, processed, and transported
2. Phosphates are spread on fields as fertiliser to increase crop yields
3. Plants take up inorganic phosphate from the soil
4. Plants are harvested for human or animal consumption

Part of the problem is that current ways of using phosphorus are inefficient and unsustainable; globally, only about 20% of the phosphorus used in agriculture ends up on people's plates. It's estimated that 40% of the phosphorus in fertiliser is lost during application, and the excess run-off from fields goes into water courses. So whilst agriculture can impact watercourses directly, the food we consume also poses a downstream risk to watercourses as we ultimately end up excreting this phosphorus into the sewerage system.

As we saw in the introduction, too much phosphorus in water leads to eutrophication and river death. In the UK, for example, the river Wye and its tributaries suffer from the effects of intensive chicken farming [7]. But the blame cannot solely fall on modern agriculture as phosphorus from human activity is also present in wastewater.

It's a significant issue, and reimagining the way we tackle this problem requires solutions that target different stages of the phosphorus cycle to protect watercourses and recover the phosphorus for beneficial use. However, in this paper, we'll focus on three areas:

- Upstream catchment solutions
- Wastewater treatment - phosphorus removal
- Wastewater treatment - phosphorus recovery

[4] go.ipoint-systems.com/blog/how-to-recycle-phosphorus-the-most-little-known-scarce-resource
[5] www.euractiv.com/section/energy-environment/news/great-news-eu-hails-discovery-of-massive-phosphate-rock-deposit-in-norway
[6] www.sciencelearn.org.nz/resources/961-the-phosphorus-cycle
[7] www.theguardian.com/environment/2022/oct/09/chicken-farms-may-explain-decline-of-the-river-wye-tests-suggest

Catchment solutions: Working with nature

Nature-based solutions (NbSs) use the power of natural processes in innovative ways to tackle ecological and environmental challenges such as water quality, climate change, and flood risk [8]. Incorporating natural processes into design and construction leads to resilient and sustainable solutions that benefit society, biodiversity, and the economy [9].

A holistic, catchment-based approach to phosphorus management can improve river water quality by employing NbSs to prevent phosphorus from entering river systems. This can reduce the impacts from agriculture and other diffuse pollution sources and provide final tertiary "polishing" of effluent from wastewater treatment works before discharge.

Using a catchment-based approach also allows for flexible consenting and phosphorus offsetting, whereby water quality can be improved without over-reliance on costly and carbon-intensive solutions to meet very low phosphorus consents from wastewater treatment works discharges.

Furthermore, on a catchment scale, it may be possible to deliver NbS schemes that improve river water quality and tackle the bigger resilience issues of flooding, sewer spills, and drought – and provide improved amenity value for the local community.

However, identifying what land use changes could and should be made on a catchment scale – and the qualitative and quantitative impacts these would have – is hugely complex.

Designing solutions for nutrient neutrality [10]

In the UK, Natural England and Natural Resources Wales have issued guidance for new developments that provide overnight accommodation in the catchments of National Site Network sites (Special Areas of Conservation and Special Protection Areas). Local Authorities cannot grant planning permission if these sites are under pressure from nutrient loading unless it can be clearly demonstrated that they are "nutrient neutral" and will not increase nutrient loading [11].

This puts significant pressure on developers, water companies, and regulators to implement solutions to mitigate the impacts of existing sources of nutrients from treated effluent discharges and agricultural runoff and create capacity for new development.

Potential approaches to delivering nutrient neutrality include:

- NbSs that use natural physical, chemical, and biological processes to reduce the sources of nutrients within a catchment. These include establishing wetlands, wet woodland, and in-channel silt traps.
- Runoff management solutions that aim to reduce nutrient supply by managing surface runoff and sediment supply. These include land use change, sustainable drainage systems (SuDS), and riparian buffer strips.
- Wastewater management solutions, which aim to reduce nutrient loadings from treated sewage effluent discharges. These include upgrades to existing treatment works and replacing septic tanks with efficient Package Treatment Works.
- Demand management solutions, which aim to reduce nutrient loadings by reducing the production of wastewater at source. For example, by reducing water usage in residential properties through the installation of water-efficient fixtures and fittings.

Partnering with stakeholders and nature

It's important to note that large-scale projects such as habitat creation, watercourse diversion, or rewilding require the water sector to partner with local, regional, or even national authorities. In-depth knowledge of both socio-economic and physical systems is key to successfully implementing NbS projects. And for large projects to succeed, it requires multidisciplinary teams and extensive coordination of stakeholders.

Working together, these teams can solve an important part of the phosphorus puzzle: helping to prevent the excess from farms and fields from entering the ecosystem and improving water management to reduce other impacts such as flooding events and wastewater storm spills. These multi-benefit approaches have the potential to access funding from many different sources to support ambitious new projects while reducing the financial burden on the water sector.

Questions remain, though, around how the regulator can support catchment-led approaches to phosphorus management where the benefits may be harder to monitor and the outcomes potentially less predictable than for traditional end-of-pipe consents. But even with these solutions, the fact remains that municipal wastewater will always contain phosphorus. So, innovation is required to provide improved sustainable approaches for its removal and recovery.

[8] www.thesourcemagazine.org/integrating-nature-based-solutions-into-wastewater-treatment
[9] naturebasedsolutions.ireport.royalhaskoningdhv.com
[10] www.royalhaskoningdhv.com/en/services/nutrient-neutrality
[11] planninghouse.co.uk/the-basics-of-nutrient-neutrality

The need for more sustainable wastewater phosphorus removal

Historically, wastewater treatment plants have removed phosphorus by adding a coagulant such as ferric or alum. But these chemicals come at a cost, and a disproportionate amount will have to be used to reach the low phosphorus levels set by WINEP. This is because the lower the required phosphorus effluent concentration, the ratio of coagulant to phosphorus must increase.

As well as adding to operating costs and potential supply chain risks, producing and transporting these chemicals increases the carbon footprint of wastewater treatment. The Carbon Accounting Workbook (CAW) developed by UK Water Industry Research (UKWIR) requires the carbon footprint of these chemicals to be included as Scope 3 emissions in the water companies' carbon accounting [12].

Conventional approaches to phosphorus removal that combine biological and chemical processes are well-established but may not be efficient enough to meet the lowest phosphorus limits – and increasingly pose a significant risk to Net Zero 2030 targets. So it's essential that innovative approaches are employed in AMP8 to alleviate the over-reliance on chemicals.

[12] ukwir.org/Carbon-accounting-workbook

The business case for phosphorus recovery

A recent report into the global phosphorus problem recommends a “50/50/50” goal: a 50% reduction in global phosphorus pollution driven by a 50% increase in the recycling of phosphorus by the year 2050 [13].

But, for us to begin closing the loop in the phosphorus cycle, any solutions must enable the removed phosphorus to be recovered in a form where it can be valorised in new market opportunities – and where there is a strong business case to support this.

This business case may not only be based on the value of the product recovered but also on the financial benefits to the wastewater treatment works that may be derived from the recovery of the phosphorus. For example, through reduced capital costs (upgrades to treatment works may not be required if phosphorus liquor loads are reduced) and operational costs (reduced maintenance costs from pipe fouling, lower chemical costs for phosphorus removal).

To date, phosphorus recovery has been generally limited to the production of struvite, a slow-release fertiliser for agriculture. But phosphorus can be recovered in other forms, for example plants that incorporate a ferric treatment have the potential to also recover vivianite – an important material in the manufacture of lithium iron phosphate used to make lithium-ion batteries [14] – from digested sludge.

Phosphorus recovery is usually carried out on the return liquors from sludge treatment where phosphorus concentrations are an order of magnitude higher than in the wastewater. As more biological phosphorus removal processes are used, this increases the phosphorus release within sludge treatment and so improves the business case for phosphorus recovery from the return liquors.

The regulatory requirements to achieve “end-of-waste” status for products from wastewater haven’t always been straightforward, but EU regulatory changes meant that from July 2022, clarity was provided on allowing wastewater-derived phosphorus products to be incorporated into existing fertiliser supply chains [15]. This provides a more pragmatic approach to generating new, sustainable phosphorus-based products from wastewater.

[13] www.opfglobal.com
[14] pubs.rsc.org/en/content/articlehtml/2017/ra/c7ra06308c
[15] eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R1009&qid=1655169675070

Tackling phosphorus together, for a better future

The problem of phosphorus and how to manage it presents a variety of challenges. But the latest innovations provide opportunities to tackle them – from catchment-based solutions that prevent agricultural runoff to ways of upgrading existing treatment plants and new methods for phosphorus recovery.

Other initiatives include incentivising farmers with a phosphates credit scheme [16] or adding phytase to poultry feed to make phosphate more bioavailable and minimise the amount that's excreted [17].

There's a range of options but no one-size-fits-all solution. You need to apply the right technology to the right use case. But, when approached correctly, the effects can be impressive.

For example, 60 years ago, the Thames was declared a biologically-dead river thanks to pollution from heavy industry and sewage discharge. But upgrades to sewage works and strict regulations limiting sewage discharges including reducing phosphorus release. In addition, installing oxygenators has maintained oxygen at a level sufficient to support growing fish populations. Today, around 125 species of fish are regularly recorded, and the Thames is one of the world's cleanest rivers flowing through a city [18].

[16] www.wessexwater.co.uk/environment/catchment-management/somerset-phosphorus
[17] www.allaboutfeed.net/animal-feed/feed-additives/phytase-a-vital-feed-additive
[18] theconversation.com/from-biologically-dead-to-chart-toppingly-clean-how-the-thames-made-an-extraordinary-recovery-over-60-years-180895

Royal HaskoningDHV: Your partner in phosphorus management

At Royal HaskoningDHV, we provide the knowledge, experience, and technology that help clients rise to the challenge of managing phosphorus more sustainably. From catchment-wide modelling to the latest in wastewater treatment, here are some of our solutions.

1. Catchment solutions

A unique natural systems modelling approach

Royal HaskoningDHV has partnered with Viridian Logic to create WaterNbS [19]. This unique process uses the WaterNbS-Scan model to assess the impact of land-use change across a whole catchment, using 5m grid squares to give a high level of granularity.

WaterNbS-Scan allows different priorities to be assigned and ranks the impact of NbS interventions. It does this by incorporating an understanding of the connectivity and interactions of water movement through a catchment to identify cascading benefits such as flood mitigation, reduction in nutrient pathways, or improved habitat connectivity to support biodiversity. WaterNbS-Scan's output is a rapid ranking of land use changes tailored to the desired outcomes; the WaterNbS process then uses this ranking to support investment decisions. Several UK water companies are currently exploring WaterNbS to develop alternative approaches to delivering AMP8 solutions.

Developing a phosphate calculator

Royal HaskoningDHV's pioneering phosphate calculator work on the Somerset Levels and Moors project was fundamental in developing a deep understanding of the nutrient neutrality issue. As well as identifying suitable solutions, we produced a phosphate budget, a site screening exercise to identify suitable mitigation land, designed wetlands for phosphate removal, and undertook a water usage and efficiency assessment. The study was completed in February 2022 and was the first of its kind to be published [20].

Royal HaskoningDHV has since replicated this work in support of other Local Authorities throughout England, including authorities in Berkshire, Cornwall, Derbyshire, Devon, Hampshire, Northumberland, and Shropshire. Our team is working to develop partnerships with stakeholders and long-term strategies to achieve nutrient neutrality.

2. Phosphorus removal

Nereda®: Sustainable low phosphorus removal

Royal HaskoningDHV's Nereda technology is a single-tank biological process where the purifying biomass grows as a quick-settling granular sludge containing both aerobic and anoxic/anaerobic zones. This enables different biological processes to happen simultaneously, including biological phosphate removal [21].

The result is a wastewater treatment process capable of achieving an effluent with low phosphorus (and nitrogen) concentrations. Importantly, Nereda's small footprint can easily be incorporated into new plants (including retrofitted to Sequencing Batch Reactor (SBR) plants). It also provides options for side stream or hybrid treatments to supplement existing processes.

Nereda can typically be guaranteed to achieve a 1 mg/l total phosphorus (TP) consent without any chemical requirements, with actual values significantly lower than this. However, for TP consents below 0.5 mg/l, any biological phosphorus process would typically be expected to require an additional tertiary chemical treatment stage.

Recent trials on full-scale Nereda plants in the UK and the Netherlands have shown that a small chemical dose before the Nereda plant, such as a ratio of iron to phosphorus of 1:1, can reduce TP to below 0.3 mg/l. As consents tighten, this offers the opportunity for significant capital savings, as tertiary treatment is not required, as well as reduced operational costs due to the very low chemical requirements.

Since 2005, Nereda has become well-established, and there are more than 107 projects worldwide at the time of writing. In the UK alone, Nereda plants treat a Population Equivalent of more than 850,000 and meet a range of nutrient removal requirements, including phosphorus.

BiOPhree®: Achieving ultra-low phosphorus levels

Whereas Nereda and other biological treatment processes remove phosphorus within secondary treatment, BiOPhree® is a tertiary treatment that instead of using chemicals to remove phosphorus, it uses ion-exchange media to capture phosphorus in a concentrate stream ready for beneficial re-use [22].

The BiOPhree® material will continue to capture all phosphorus until it's saturated – which, depending on system size and feedwater quality, can take days, weeks, or even months. And research has shown that effluent with less than 0.01 mg/l ortho-P (10 parts per billion phosphorus) can be produced.

These exceptionally low concentrations mean that sites can meet consent limits by treating just a portion of the flow. And as it's a physical process, the throughput can be rapidly scaled up and down as required.

Royal HaskoningDHV is partnering with Aquacare® to further develop this technology, and following a series of EU-funded trials around Europe, pilot-scale demonstrations are commencing in the Netherlands in September 2023, with a view to wider deployment from 2024 onwards.

3. Phosphorus recovery

In 2012, the Chartered Institution of Water and Environmental Management (CIWEM) estimated that wastewater treatment could recover 95% of the phosphorus from urban wastewater – concentrated in sewage sludge [23]. CIWEM highlighted the need to develop new technology to use biosolids for agricultural land application and for better phosphorus stewardship more generally.

Crystalactor®: Creating value-added commodities from wastewater

Developed in 1980, the Crystalactor process is well established, with over 80 installations worldwide. The technology allows phosphorus to be recovered from municipal and industrial water through continuous crystallisation [24]. Crystalactor precipitates and pellitises minerals from water and has been deployed to recover many products for different applications.

Depending on the quality and composition of the influent water, different additives can be dosed to produce a variety of pellets. For example, phosphate can be removed as vivianite pellets struvite pellets or as calcium phosphate pellets. The preferred route typically depends on the influent composition. Crystalactor's intelligent controller reduces the chemical, operational, and maintenance costs through predictive control of the pellet bed. It ensures a fully automated process operation, reliable performance, and an optimised and energy-efficient treatment.

A range of minerals, including phosphorus-based products, can be recovered in valuable forms from municipal and industrial wastewater using Crystalactor technology

BiOPhree®: The potential for phosphorus recovery as well as removal

As well as achieving ultra-low phosphorus levels, the "catch-and-release" nature of BiOPhree® means the phosphorus that accumulates in the ion exchange media is captured as a concentrate product stream when the media is regenerated on a periodic basis. This regeneration process takes about two hours.

This means that unlike passive media approaches for phosphorus removal – such as using ochre or Polonite-based materials that require disposal once saturated – the BiOPhree® media material is continually reusable. And by recovering phosphate and redeploying it as a raw material, the BiOPhree® technology has the potential to contribute to a circular and sustainable phosphorus cycle. Where BiOPhree® is deployed on smaller sites, it's envisaged that the filter cartridges may be routinely replaced and taken to a centralised regeneration hub to recover the phosphorus before redeployment. Demonstration trials in the Netherlands will assess the optimum regeneration strategy and include market testing of the product.

Wastewater biopolymers to optimise phosphorus fertilisers [25]

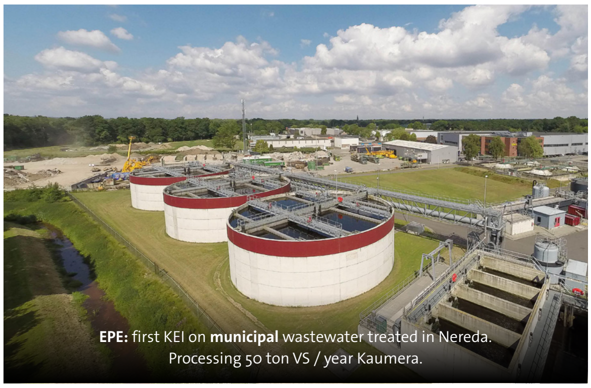
Royal HaskoningDHV developed Kaumera gum as a biopolymer resource extracted from aerobic granular sludge from the Nereda wastewater treatment process. While Kaumera is not itself a form of phosphorus recovery, once isolated, Kaumera gum can be used in a range of ways, including to maximise the use of phosphorus.

The gum is an excellent coating material for slow-release fertilisers and can be used as a biostimulant in agriculture. Or it can be implemented as a binding agent to help pelletise powdery phosphorus-containing materials such as struvite. Trials have shown that Kaumera biostimulant significantly enhances nutrient uptake and reduces fertiliser demand.

Additionally, many fertilisers are coated in fossil fuel-derived polyacrylamide (PAM), but future regulations may ban using PAM for land application [26].

Research is underway to assess the use of Kaumera as a sustainable slow-release fertiliser coating. Recently, OFWAT awarded £6 million of funding to the United Utilities-led project "Biopolymers in the Circular Economy" which will demonstrate Kaumera biopolymers in biostimulant and fertiliser applications [27].

Zutphen: first KEI on **dairy** (only industrial).
Processing 1,400 ton DS / year of sludge; max 350 ton VS / y Kaumera.


EPE: first KEI on **municipal** wastewater treated in Nereda.
Processing 50 ton VS / year Kaumera.

First commercial scale product delivery in 2020 from Zutphen and in 2021 from EPE

[19] www.wateronline.com/doc/royal-haskoningdhv-partners-with-viridian-logic-to-prioritise-nature-management-0001
[20] www.somerset.gov.uk/planning-buildings-and-land/phosphates-on-the-somerset-levels-and-moors-ramsar-site/somerset-solutions-report-march-2022
[21] nereda.royalhaskoningdhv.com
[22] www.royalhaskoningdhv.com/en/newsroom/news/working-together-with-aquacare-to-maximise-phosphate-recovery
[23] www.ciwem.org/assets/pdf/Policy/Policy%20Position%20Statement/Phosphorus.pdf
[24] www.royalhaskoningdhv.com/en/services/crystalactor
[25] www.royalhaskoningdhv.com/en/services/kaumera
[26] www.fertilizerseurope.com/wp-content/uploads/2019/08/The_EU_s_push_for_bidegradable_polymers_in_mineral_fertilizers.pdf
[27] waterinnovation.challenges.org/winners/bice

Royal HaskoningDHV
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Royal HaskoningDHV: pioneering wastewater management

Royal HaskoningDHV has over 140 years of expertise in collecting and treating wastewater, and we are constantly developing innovative solutions to address the challenges society faces.

But challenges on this scale cannot be solved alone. We would like to acknowledge our research collaborators and partners for their contributions to the projects and technologies mentioned in this paper.

If you want to talk with us about any solutions we've discussed, get in touch.

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For more information visit our website:
royalhaskoningdhv.com