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Application of stable isotopes in freshwater nutrient management: opportunities and challenges

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Nutrient pollution of freshwaters remains a pervasive global challenge, with a substantial proportion of monitored water bodies continuing to fail quality standards despite sustained regulatory investment. Nutrient concentration monitoring data, whilst standardised and threshold-interpretable, offer limited insight into nutrient provenance, transformation, and legacy accumulation within complex catchment systems. Additional geochemical methods could address these gaps and enable more reliable, diagnostic assessments of water quality. This policy and practice review synthesises the published evidence base for stable isotope analysis of dissolved nitrogen and phosphorus compounds in English freshwaters, focusing on nitrate ($\delta^{15}\text{N-NO}_3$ and $\delta^{18}\text{O-NO}_3$), ammonium ($\delta^{15}\text{N-NH}_4$), and phosphate-oxygen isotopes ($\delta^{18}\text{O-PO}_4$). Here, nitrogen and phosphorus isotope systems are evaluated in combination, reflecting their co-driving role in eutrophication and the diagnostic advantages of multi-isotope approaches. Stable isotope approaches can provide empirical diagnostic information across four policy-relevant domains, including: supporting nutrient source apportionment for constraining catchment models, identifying internal loading and legacy nutrient sources, assessing nutrient attenuation zones, and evaluating the effectiveness of management actions. Multi-isotope frameworks can often reduce ambiguity in source identification where the selected tracers provide independent and complementary information on sources or processes. Stable isotope methods are currently absent from regulatory and management frameworks examined here; viable integration options are identified and assessed, from near-term deployment as supplementary investigative tools in persistently failing water bodies, through development of shared protocols and guidance, to longer-term contribution to management and investment frameworks. Current legislative reform provides a relevant, if uncertain, window for incorporating these methods more systematically within routine environmental governance.

KEYWORDS

ammonium isotope, freshwater management, multi-isotope, nitrate isotope, nitrogen isotope, phosphate oxygen isotope, stable isotope, water quality monitoring and management

1 Introduction

Nutrient pollution, specifically the enrichment of freshwaters with phosphorus and nitrogen, is a pervasive and unresolved water quality issue for aquatic ecosystems worldwide (De Jonge et al., 2002). Elevated nutrient concentrations drive eutrophication, characterised by the excessive growth of algae and aquatic plants, causing biodiversity loss, ecosystem

degradation, and oxygen depletion globally. Harmful algal blooms (HABs), which frequently develop under eutrophic conditions, produce toxins harmful to humans, livestock, and wildlife. HABs also impose socioeconomic costs on drinking water treatment, recreation, fisheries, and tourism (Paerl and Otten, 2013). Considerable international policy and management effort has sought to tackle nutrient pollution, with mixed effectiveness. A large proportion of monitored European freshwater bodies continue to fail nutrient quality standards, despite implementation of the European Union (EU) Water Framework Directive (WFD) and Nitrates Directive (European Environment Agency, 2022; 2024). Comparable long-term trends are observed in the United States and Canada, with rising eutrophication across Latin America, Africa, and Asia since the 1990s (United Nations Environment Programme, 2016; Wassen et al., 2022).

England exemplifies this water quality issue and associated policy challenges, providing a useful case study for countries with long-established nutrient regulation, combining a mature statutory framework, dense long-term monitoring, sustained regulatory investment and persistent failure against nutrient standards. Approximately 61% of rivers and 72% of lakes failed their respective phosphorus concentration standard for good ecological status under the WFD in 2022 (AtkinsRéalis, 2025; Environment Agency and Natural England, 2025a). Similarly, despite a decline in nitrate concentrations in English rivers since the late 1990s, approximately 55% of land in England remains designated as a Nitrate Vulnerable Zone, reflecting ongoing risk from agricultural nitrate pollution (Defra, 2025). The limited effectiveness of nutrient-control policies and management practices partly reflects the complexity of interactions between nutrient dynamics and ecological quality. For example, reductions in phosphorus concentrations in English water bodies have outpaced reductions in nitrogen in recent decades (Environment Agency and Natural England, 2025b), shifting nutrient balances in ways that can alter phytoplankton community composition, promote HABs, and alter overall ecosystem function (Paerl and Otten, 2013; Varis and Zhao, 2026). Nutrient cycling within water bodies can further shift nutrient speciation, bioavailability and hence primary productivity, including the incidence of HABs (Reynolds and Davies, 2001).

Historically, the most significant sources of nutrient pollution have been catchment-derived, principally agriculture, wastewater discharges, and atmospheric nitrogen deposition. However, river and lake sediments are increasingly recognised as a major internal source, with nutrients transformed and recycled biologically and geochemically in ways that sustain elevated concentrations despite reductions in external inputs and delay ecological recovery by years or decades (De Jonge et al., 2002; Søndergaard et al., 2003; Goody et al., 2026). This legacy load can contribute significantly to total concentrations in systems that have received sustained inputs over many decades (Søndergaard et al., 2003; Moorhouse et al., 2024), meaning that achieving water quality targets requires consideration of this full complexity of aquatic nutrient dynamics.

Freshwater nutrient management is typically governed by multi-layered regulatory frameworks that vary between countries but share common structural features (Wassen et al., 2022; Varis and Zhao, 2026). Water management is a devolved responsibility within the United Kingdom (UK), and the regulatory, investment and

modelling frameworks described here are specific to England, with separate but comparable arrangements operating in Scotland, Wales and Northern Ireland. In England, freshwater management is delivered through River Basin Management Plans (RBMPs) developed under the UK WFD. This is supported by key statutory instruments including the Environment Act 2021, which sets out binding targets for reducing nutrient pollution, and the Water Environment (WFD) (England and Wales) Regulations 2017, which together outline programmes of measures to achieve good ecological and chemical status for water bodies. Delivery is supported through investment mechanisms such as the Water Industry National Environment Programme (WINEP), which directs water company funding towards pollution-reduction measures, and Environmental Land Management Schemes (ELMS), which fund agricultural interventions based on the principle of public money for public good (UK Parliament, 2021). Nutrient concentration data underpin statutory reporting and compliance assessment; in England, the Environment Agency operates a tiered monitoring programme comprising surveillance, operational, and investigative monitoring networks, measuring soluble reactive phosphorus, total phosphorus, and nitrate and/or ammoniacal nitrogen against statutory thresholds set to protect ecological function. This is a powerful, standardised approach, which enables a direct assessment of water quality and its potential impact on aquatic ecosystems. However, it offers limited insight into the relative importance of multiple nutrient sources, the role of biogeochemical processing in augmenting nutrient availability along hydrological pathways, or the mechanism by which management does, or does not, reduce nutrient loading to water bodies.

Nutrient concentration data also inform spatially distributed load-apportionment models such as Source Apportionment GIS (SAGIS) in England, used by regulators and water companies to estimate sectoral nutrient losses from point sources and land segments (Saad et al., 2011; Comber et al., 2013; 2018; Mockler et al., 2016). While essential for strategic planning, such tools rarely account directly for legacy nutrient supply from sediments, soils, or groundwater (Wellen et al., 2015; Jackson-Blake et al., 2017), or for unmonitored diffuse sources such as leaking phosphate-dosed mains water (Goody et al., 2017). Additional diagnostic approaches that can attribute nutrient sources with greater precision, account for legacy stores, and provide clearer evidence of whether management interventions are delivering their intended outcomes could therefore support progress towards water quality standards and improved ecosystem health.

This policy and practice review is intended for environmental regulators and practitioners, including water utilities, agricultural advisors, and catchment co-ordinators, as well as researchers and funding bodies who could support the development and uptake of stable isotope methods for freshwater nutrient management. Here, 'policy' is used to refer broadly to the regulatory frameworks, decision-making processes, and investment mechanisms through which nutrient management is implemented, rather than to formal statutory instruments alone. Stable isotope composition can be measured on a range of environmental samples in both aquatic and terrestrial environments. This review focuses on dissolved phosphorus and nitrogen compounds in waters, given their central role in eutrophication. Previous aquatic isotope reviews

have typically treated nitrogen and phosphorus separately (e.g., Kendall et al., 2007; Xue et al., 2009; Davies et al., 2014; Venkiteswaran et al., 2019; Pfahler et al., 2022; Matiatis et al., 2023). However, as eutrophication is driven by the interacting dynamics of both nutrients, this review examines the capability of multi-isotope frameworks and isotope-informed modelling approaches to provide more complete and diagnostically powerful bases for understanding and managing nutrient pollution.

While the scientific application of these methods in freshwater research is well documented, how this evidence base relates to environmental regulation remains considerably less developed. Using English case studies, this review appraises isotope approaches for both their scientific capability and their fit within the policy, funding and governance frameworks through which nutrient management decisions are made, and identifies the opportunities, challenges, and barriers to integration, with principles transferable across regulatory contexts globally. This review is a narrative synthesis rather than a systematic review; the English evidence base was assembled through structured searches of Web of Science and Google Scholar, with iterative reference-list searching, screened for studies reporting stable isotope compositions of dissolved nitrogen or phosphorus species in English freshwaters (see [Supplementary Material](#)), while the international literature was searched illustratively rather than exhaustively.

2 Stable isotopes as diagnostic tools in water quality science

Isotopes are atoms of the same element with the same number of protons but different numbers of neutrons, and therefore different masses. While isotopes of an element share chemical properties, this difference in mass means that physical, biological and chemical processes will preferentially use either the “lighter” or “heavier” stable isotope, a process called “fractionation”. This leads to small differences in the ratio of heavy to light isotopes in elements within environmental samples, over space and time. Stable isotopes do not decay, meaning that measuring the ratio between different isotopes of the same element can provide information about the processes that have influenced the sample material being analysed. Stable isotope ratios are reported as the ratio of heavy to light isotopes using delta notation (δ), which expresses the deviation of a sample’s isotope ratio from an internationally recognised standard reference material, in parts per thousand (per mille, ‰).

Environmental processes such as evaporation, nutrient uptake and photosynthesis alter the isotope ratio of elements in water, organic matter, dissolved nutrients and sediments. The analysis of stable isotopes of nitrogen ($\delta^{15}\text{N}$), oxygen ($\delta^{18}\text{O}$), carbon ($\delta^{13}\text{C}$), sulphur ($\delta^{34}\text{S}$), and hydrogen ($\delta^2\text{H}$) in environmental samples can provide information about the origins of materials and biota and about the environmental processes that have shaped them (Smith and Lacey, 2024). In the context of freshwater nutrient management, the nitrogen and oxygen isotope compositions of nitrate ($\delta^{15}\text{N}\text{-NO}_3$ and $\delta^{18}\text{O}\text{-NO}_3$) and nitrogen isotopes of ammonium ($\delta^{15}\text{N}\text{-NH}_4$) have been used in a large number of studies globally to constrain nitrogen sources and cycling within both surface waters and groundwaters (Heaton, 1986; Kendall et al., 2007; Gooddy et al.,

2016; Venkiteswaran et al., 2019; IAEA, 2020; Matiatis et al., 2023, and references therein). More recently, phosphate oxygen isotopes ($\delta^{18}\text{O}\text{-PO}_4$) have emerged as a complementary tool for tracing phosphorus sources and biological cycling (Gruau et al., 2005; Davies et al., 2014; Gooddy et al., 2015; 2018; 2026; Smith et al., 2021; Pfahler et al., 2022, and references therein). Stable isotopes of the water molecule itself ($\delta^{18}\text{O}\text{-H}_2\text{O}$ and $\delta^2\text{H}\text{-H}_2\text{O}$) are also typically used alongside nitrogen and phosphate oxygen isotopes, to trace hydrological pathways and quantify the contributions of different water sources to river flow and lake hydrology, providing essential interpretive context for nutrient isotope data (Venkiteswaran et al., 2019; Matiatis et al., 2023). Table 1 summarises these principal stable isotope systems relevant to aquatic nutrient pollution assessments and the interpretive value each provides for water quality monitoring.

Across these studies, stable isotope data are often complementary to, rather than a replacement for, concentration measurements. Whilst concentration data provide information about the quantity of a nutrient at a given time and place, isotope data can provide additional information about provenance and transformation that concentrations alone do not. Despite their established utility in academic water quality research, including a substantial body of English-based evidence outlined in this review (see [Supplementary Material](#)), stable isotope approaches have seen limited integration into environmental regulatory and management frameworks and underpinning tools for nutrient management in England, as in most countries internationally. The reasons for this, and the conditions under which greater integration might be achievable, are considered throughout the review.

2.1 Stable isotope applications

The application of stable isotope analysis can largely be categorised as being used for: 1) identifying sources of nutrient pollution, and 2) tracing nutrient utilisation and biogeochemical cycling. These two signals are, however, rarely independent of one another and must be considered together (Kendall and Aravena, 2000; Kendall et al., 2007; Denk et al., 2017). Modelling approaches that have been used in conjunction with these stable isotope methods to aid interpretation are also outlined (Phillips et al., 2005; Parnell et al., 2013; Lewicki et al., 2022).

2.1.1 Dissolved nitrogen isotopes

Application of dual nitrogen and oxygen isotope ratios of nitrate ($\delta^{15}\text{N}\text{-NO}_3$ and $\delta^{18}\text{O}\text{-NO}_3$) is a well-established geochemical approach to constrain sources of nitrogen in aquatic ecosystems and to trace the transformations that nitrogen undergoes as it moves through catchment systems (Xue et al., 2009; IAEA, 2013; 2020; Venkiteswaran et al., 2019; Romanelli et al., 2020; Matiatis et al., 2021; 2023). Different nitrogen sources carry characteristic isotopic signatures that reflect the biogeochemical processes involved in their production (Kendall et al., 2007; Xue et al., 2009). Synthetic fertilisers typically yield lower $\delta^{15}\text{N}\text{-NO}_3$ values, reflecting the atmospheric nitrogen from which they are derived, whilst manures and sewage effluents tend to produce higher values due to fractionation associated with ammonia volatilisation and

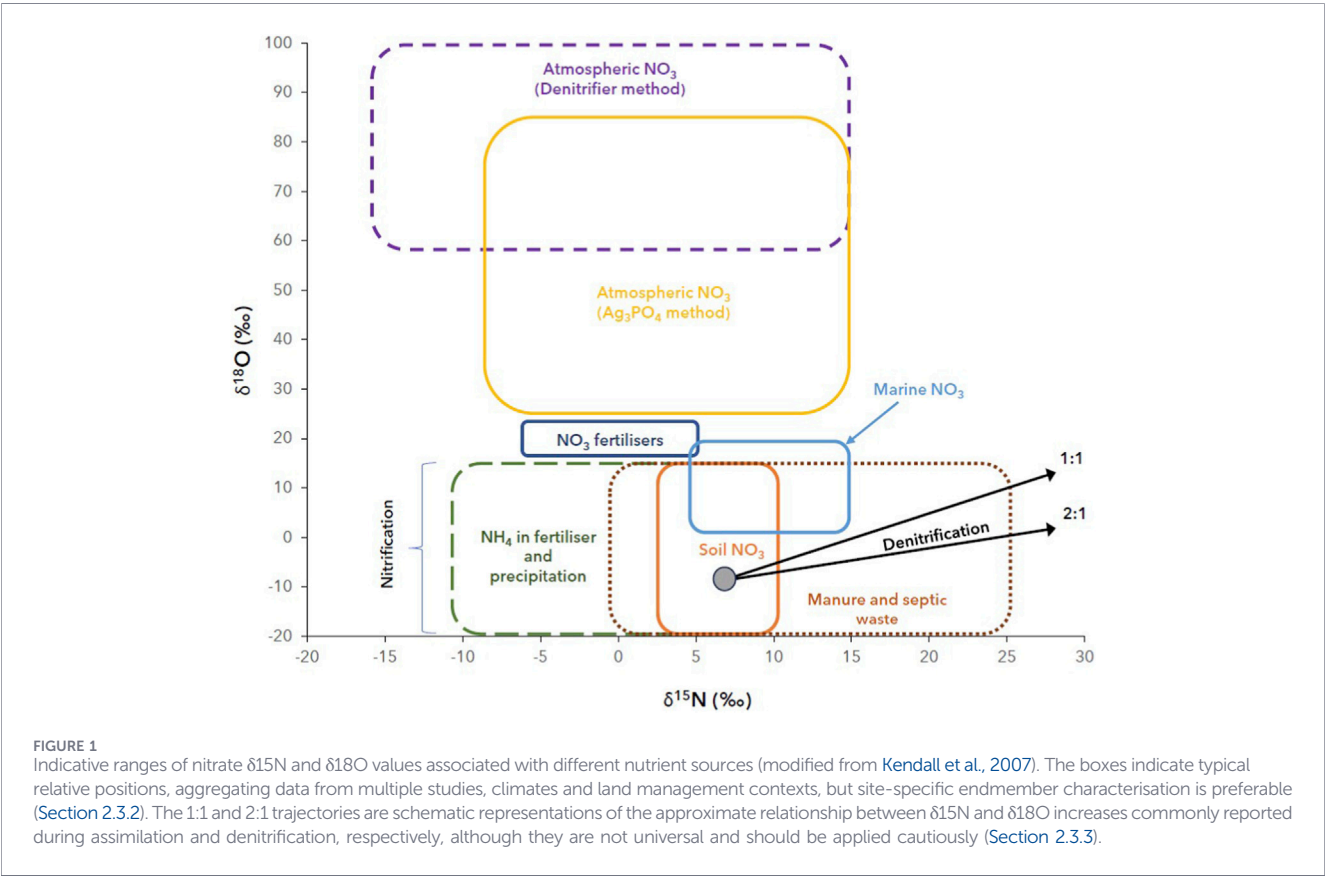
TABLE 1 The principal stable isotope systems relevant to freshwater nitrogen and phosphorus pollution assessments and their interpretive value for water quality monitoring and environmental management (modified from Kendall et al., 2010).

Isotope system	Interpretive value
Nitrate $\delta^{18}\text{O}$ and $\delta^{15}\text{N}$	Evaluate the different sources of nitrate; role in the production of algae and degree of recycling; evidence for denitrification, assimilation and nitrification
Ammonium $\delta^{15}\text{N}$	Constrain different sources of ammonium; role in the production of algae and degree of recycling; evidence for ammonia volatilisation
Phosphate $\delta^{18}\text{O}$	Assess the different sources of phosphate; information about the extent of biological recycling; assess biogeochemical recycling pathways; evaluate P-limitation of algal growth
Water $\delta^{18}\text{O}$ and $\delta^2\text{H}$	Tracer of water sources and mixing; useful for evaluating flow contributions from different tributaries and groundwater; sensitive indicator of evaporation

microbial decomposition. Whilst typical isotopic ranges of these source categories are widely utilised to interpret stable isotope data in the published literature (Figure 1; Kendall et al., 2007; Xue et al., 2009), they should be interpreted with considerable caution. The isotopic values for different sources overlap, and globally aggregated

reference ranges may not be representative of the specific hydrogeological, climatic, or land management context of any given catchment. Site-specific characterisation of source isotopic values, supported by complementary hydrochemical data, is therefore preferable.

More fundamentally, the isotopic composition of nitrate measured in rivers and lakes is rarely a direct expression of source signatures alone, being modified by biological and geochemical transformations occurring across the catchment and within the water column, hyporheic zone and sediments. In oxygenated waters, nitrification produces nitrate from ammonium, while assimilation transfers dissolved inorganic nitrogen into algal, microbial or particulate organic pools, typically increasing the $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ in residual nitrate and $\delta^{15}\text{N}$ in residual ammonium (Kendall et al., 2007). In low-oxygen sediments and benthic zones, denitrification, dissimilatory nitrate reduction to ammonium (DNRA) and anaerobic ammonium oxidation (anammox) provide further pathways for nitrate reduction, ammonium production and fixed nitrogen removal (Xue et al., 2009; Granger and Wankel, 2016; Denk et al., 2017). These transformations and their qualitative isotope effects are summarised in Figure 2. Their apparent magnitude and direction depend strongly on oxygen availability, substrate supply, transport and residence time, and coupling between processes. For example, Wells et al. (2019) showed that denitrification isotope effects in freshwater systems are strongly influenced by the interaction between benthic



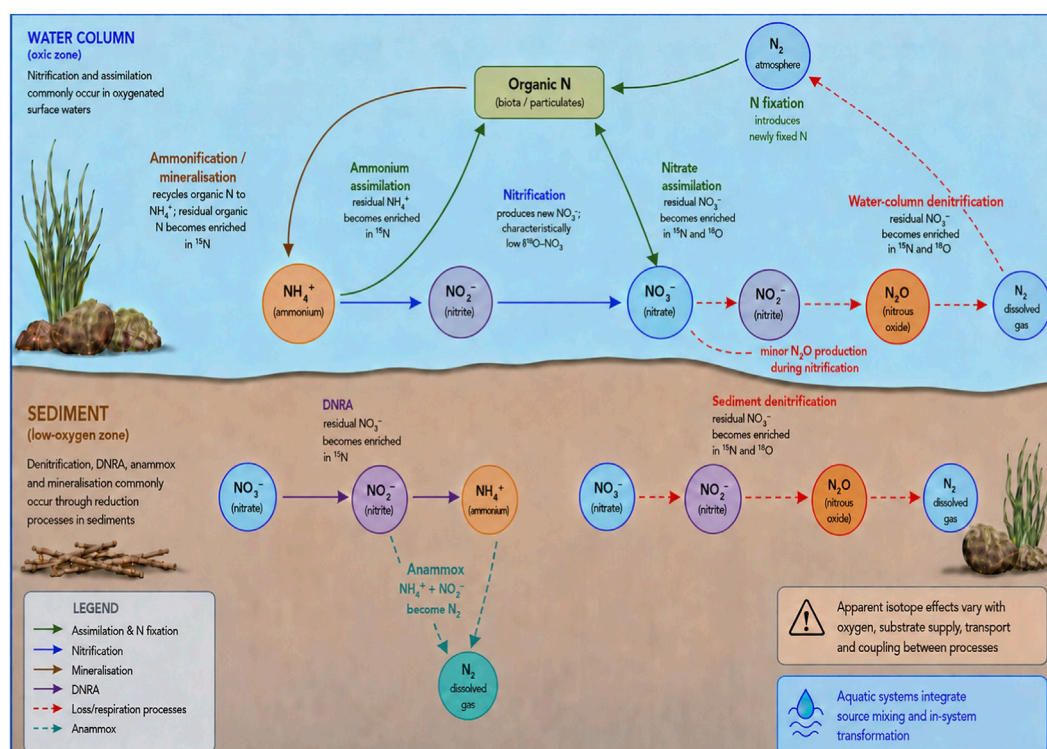


FIGURE 2

Conceptual summary of the key nitrogen-cycle processes affecting dissolved inorganic nitrogen in aquatic systems, shown separately for the oxygenated water column and the low-oxygen sediment zone. Arrow colour denotes process type, and dashed arrows denote pathways that remove fixed nitrogen from the system, comprising denitrification and anammox. Isotope effects are described qualitatively and by direction only. Reported fractionation factors vary widely with oxygen availability, substrate supply, transport regime, residence time and coupling between processes. Note: nitrate produced by nitrification derives oxygen from both ambient water and dissolved O₂, in proportions that vary with organism and conditions, so its $\delta^{18}\text{O}$ depends on $\delta^{18}\text{O}\text{-H}_2\text{O}$ and $\delta^{18}\text{O}\text{-O}_2$ rather than taking a fixed value.

processing and transport and therefore cannot be treated as fixed process-specific values.

The key interpretive point is that measured $^{15}\text{N}\text{-NO}_3$ and $\delta^{18}\text{O}\text{-NO}_3$ values integrate both nutrient source inputs and subsequent biological processing. This means that nitrate isotope data can be highly diagnostic, but only when interpreted in relation to the hydrological and ecological setting in which samples are collected. Cooler or lower-flow periods may preserve source information more clearly where biological processing is limited, whereas warmer, more productive or low-oxygen conditions may enhance assimilation, denitrification or benthic processing and therefore shift isotope values away from original source signatures (Venkiteswaran et al., 2019; Matiatos et al., 2021). These changes are not necessarily an interpretive problem, as they can also provide useful evidence for where and when nitrogen is transformed or removed within the system. Robust interpretation requires supporting hydrological, chemical, and ecological context, including information on flow conditions, dissolved oxygen, nutrient concentrations, residence time, and potential sediment-water interactions.

Additional complementary isotope proxies that have been productively but less widely applied include the analysis of the nitrogen isotope composition of ammonium ($\delta^{15}\text{N}\text{-NH}_4$), which provides additional constraint on nitrogen sources and transformation pathways (e.g., ammonia volatilisation) and

extends the interpretive capacity (Goody et al., 2016; Venkiteswaran et al., 2017). Site preference, the position of the heavy nitrogen atom within the dissolved nitrous oxide (N_2O) molecule, offers a further constraint on how the dissolved inorganic nitrogen pool is being processed, independent of the source composition of the nitrate or ammonium from which it is formed (Lewicka-Szczebak et al., 2020; Chen et al., 2025). The mass-independent oxygen isotope anomaly of nitrate ($\Delta^{17}\text{O}$) has also been applied for nitrogen source attribution in upland and peri-urban catchments, where atmospheric nitrate formed via photochemical oxidation carries a distinctive positive $\Delta^{17}\text{O}$ signal, enabling its use as a tracer of recently deposited atmospheric nitrate in streams (Michalski et al., 2004). However, dual nitrate isotope analysis remains the most widely and routinely applied nitrogen isotope approach in catchment studies globally and has consequently attracted the greatest attention with respect to potential integration into regulatory monitoring and management practice.

2.1.2 Phosphate oxygen isotopes

Phosphate oxygen isotopes ($\delta^{18}\text{O}\text{-PO}_4$) are a more novel but increasingly applied tool for investigating phosphorus sources and cycling in aquatic systems (Davies et al., 2014; Pfahler et al., 2022). As with dual nitrate isotopes, the interpretive power of $\delta^{18}\text{O}\text{-PO}_4$ derives from the fact that both the sources of phosphate and the

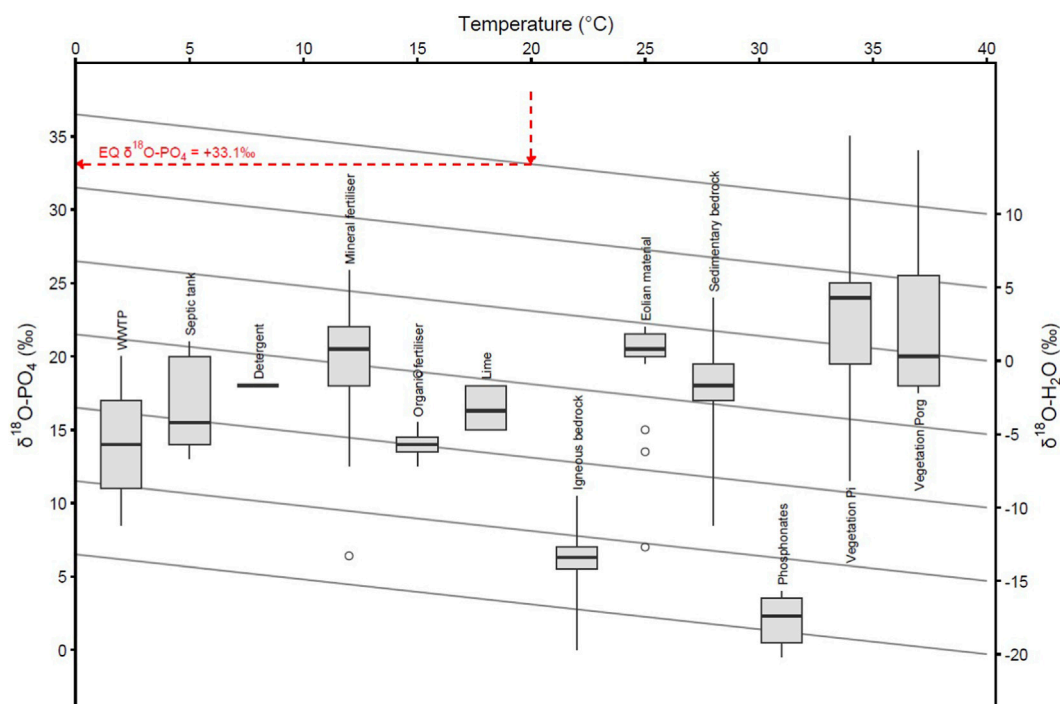


FIGURE 3

Phosphate oxygen isotope ($\delta^{18}\text{O}-\text{PO}_4$) values for a range of common phosphorus source endmembers (grey boxplots). Igneous and sedimentary bedrock values are from [Smith et al. \(2021\)](#), and all other source data are from [Pfahler et al. \(2022\)](#) and references therein. Grey lines represent the expected phosphate oxygen isotope equilibrium ($\text{EQ}\delta^{18}\text{O}-\text{PO}_4$) as a function of temperature for a series of source-water oxygen isotope values, following the equation of [Chang and Blake, \(2015\)](#), $\text{EQ}\delta^{18}\text{O}-\text{PO}_4 = -0.17T + 26.5 + \delta^{18}\text{O}-\text{H}_2\text{O}$ (as rearranged by [Pistocchi et al. \(2017\)](#) and presented in [Smith and Lacey, \(2024\)](#)). The right-hand axis gives the water oxygen isotope value ($\delta^{18}\text{O}-\text{H}_2\text{O}$) to which each equilibrium line corresponds. The red dashed line offers an example of $\text{EQ}\delta^{18}\text{O}-\text{PO}_4 (= +33.1\text{‰})$ at a measured temperature of 20°C and a $\delta^{18}\text{O}-\text{H}_2\text{O}$ value of $+10\text{‰}$. The source ranges shown are independent of temperature and are not to be read against the temperature axis; they are presented alongside the equilibrium relationship to allow comparison of measured source values with the equilibrium composition expected for a given water temperature and $\delta^{18}\text{O}-\text{H}_2\text{O}$. All values are approximate, compiled or digitised from figures within cited publications.

biological processes that transform it leave distinctive imprints on isotopic composition, and, equally, that these two signals interact and must be considered together rather than in isolation. Different phosphorus sources carry characteristic $\delta^{18}\text{O}-\text{PO}_4$ signatures reflecting their origin and the processes involved in their production. Igneous bedrock and phosphonates tend to yield more negative values, whilst fertilisers and vegetation sources tend to produce more positive values ([Pfahler et al., 2022](#); [Smith et al., 2021](#); [Figure 3](#)). As with nitrate isotopes, however, the isotopic fields of different sources overlap, and site-specific endmember characterisation is essential. This is highlighted by [Gooddy et al. \(2018\)](#), who showed that wastewater phosphate oxygen isotope signatures differed significantly between the USA and Europe, confirming that globally derived reference values cannot be applied without local verification.

The principal complication in interpreting $\delta^{18}\text{O}-\text{PO}_4$ for source apportionment in aquatic systems is that enzyme-mediated biological activity cleaves the phosphate P-O bond, promoting oxygen exchange between phosphate and surrounding water and driving the $\delta^{18}\text{O}-\text{PO}_4$ values towards a temperature-dependent equilibrium, irrespective of the original source signature ([Davies et al., 2014](#)). This biological overprinting presents a more pervasive challenge for interpreting $\delta^{18}\text{O}-\text{PO}_4$ data because phosphorus is cycled at rapid rates in many freshwater systems, with dissolved

inorganic phosphorus turnover times measured in hours to days in productive systems ([Paytan and McLaughlin, 2012](#)). Consequently, the original source signature of phosphate can be partially, or entirely overwritten more rapidly and completely by biological cycling, making the conditions under which $\delta^{18}\text{O}-\text{PO}_4$ can be used for source apportionment more restrictive. Evaluating whether a measured value is approaching equilibrium requires the equilibrium composition itself to be calculated, which depends on both the oxygen isotope composition of the ambient water and the *in-situ* temperature ([Chang and Blake, 2015](#); [Figure 3](#)). Temperature must therefore be recorded at the time and location of sampling rather than assumed from seasonal or regional averages, particularly in thermally variable, stratified, or groundwater-influenced systems.

Furthermore, different enzymes involved in phosphorus cycling induce isotopic fractionation to different degrees and in different directions, meaning that the $\delta^{18}\text{O}-\text{PO}_4$ composition of environmental phosphate reflects not only source mixing but also the type and intensity of biological processing that has occurred ([Blake et al., 2005](#)). This has led to productive applications of $\delta^{18}\text{O}-\text{PO}_4$ within pollution studies to distinguish active biological phosphorus turnover from more passive transport, and to differentiate between intracellular recycling of legacy nutrients and extracellular enzymatic hydrolysis of organic phosphorus

(Davies et al., 2014; Ji et al., 2017; Depew et al., 2018; Gooddy et al., 2026), processes that have direct relevance to understanding phosphorus cycling within freshwater systems and broader eutrophication dynamics.

Yi et al. (2024) provide a well-constrained illustration of how source and process signals can be disentangled in practice, tracking $\delta^{18}\text{O}\text{-PO}_4$ values along the flow path of a shallow lagoon-lake system adjacent to Lake Biwa, Japan, across four seasons. The study successfully distinguished externally loaded agricultural phosphorus from biologically recycled phosphorus and demonstrated that the degree of biological overprinting varied predictably with season and water residence time, showing that where these controls can be independently characterised, biological cycling need not preclude meaningful source apportionment. In contrast, Elsburly et al. (2009) found that $\delta^{18}\text{O}\text{-PO}_4$ values measured in the surface waters of Lake Erie, USA, could not be attributed to any of the analysed external source inputs, with the authors attributing this to phosphate release from sediments during anoxic events. This illustrates that where source signatures are insufficiently distinct and biological transformation is pervasive, $\delta^{18}\text{O}\text{-PO}_4$ may be more informative as a tracer of internal cycling processes than of external source apportionment.

2.1.3 Multi-stable isotope approach

There is growing recognition that combining multiple stable isotope systems within a single study yields more robust interpretations than any individual system can achieve alone (Gooddy et al., 2016). The core advantage is that overlapping sources and processes can be better resolved through cross-validation, and that different isotope systems can simultaneously constrain both the origin of nutrients and the transformations they undergo over space and time. As indicated, concurrent measurement of $\delta^{18}\text{O}\text{-H}_2\text{O}$ and $\delta^2\text{H}\text{-H}_2\text{O}$ alongside nutrient isotope systems is increasingly standard practice, providing the hydrological context necessary to separate mixing effects from biogeochemical transformation signals and to avoid misattributing dilution or concentration effects to source changes (Lapworth et al., 2013).

More broadly, the greatest interpretive gains from multi-isotope approaches are achieved through selecting and combining systems that address specific process questions in a way that is guided by the known biogeochemical characteristics of the catchment under investigation (Glibert et al., 2019). The pairing of nitrogen and phosphorus isotope systems is particularly well-suited to this principle, given that the two nutrient cycles are biogeochemically coupled and their isotopic signals can therefore provide complementary and mutually constraining evidence on both sources and processes that neither system could achieve independently. Gooddy et al. (2016) demonstrated this through a multi-stable isotope framework applied to the River Beult, United Kingdom, cross-validating nutrient sources and resolving ambiguities caused by overlapping endmember signatures. Similarly, Liu et al. (2023) applied phosphate oxygen alongside nitrogen, carbon and water isotopes in the Tuojiang River, southwest China, demonstrating that nitrogen isotopes could assist in resolving phosphorus sources where $\delta^{18}\text{O}\text{-PO}_4$ values from different source types overlapped, with findings used to

inform targeted pollution control for both nutrients concurrently.

Nitrate isotopes have also been combined with other tracers such as boron, sulphate, and strontium isotopes which commonly co-migrate with nitrate, to constrain sources further where individual systems remain insufficient (Nestler et al., 2011). Boron isotopes are the most well-established pairing, as nitrate and boron frequently share transport pathways, and reflect different source and process controls (Widory et al., 2005). Distinct $\delta^{11}\text{B}$ signatures associated with sewage, fertilisers, and animal manures can therefore help to strengthen source apportionment where nitrate isotopes alone are ambiguous. However, the gain from adding isotope systems depends on each tracer constraining something the others do not, a condition that dual nitrate isotopes and their pairing with water isotopes meet routinely. Beyond established combinations, further tracers could add cost without improving resolution where sources overlap across all available tracers, where endmembers are poorly characterised, or where all systems are strongly overprinted by in-system processing. Multi-isotope studies should therefore be developed for clearly defined research objectives and implemented within the context of catchment-specific source and process dynamics.

2.1.4 Source apportionment using modelling approaches

Isotope-enabled modelling approaches are used to quantify the proportion of different nutrient sources in a sample using isotope data. Isotope mixing models including SIAR, MixSIAR, coSIMMR and IsoSOURCE, have been widely applied in academic studies (Gibrilla et al., 2020; Ji et al., 2022; Zhao et al., 2023; Becher Quinodoz et al., 2024; Li et al., 2025). These models combine mixing equations and the isotope compositions of possible nutrient “endmembers” with the isotope ratios of the samples themselves and rely on the assumption that sources simply mix together and are not altered afterwards. Of these, SIAR, MixSIAR and coSIMMR are Bayesian approaches, meaning that rather than returning a single solution, they estimate posterior probability distributions for the proportional contribution of each source and express uncertainty through credible intervals (Phillips et al., 2005; Parnell et al., 2013; Govan et al., 2024). Model-derived source-contribution estimates are therefore probabilistic and conditional on the specified endmembers, priors and model structure, which should be reported and considered during interpretation. However, the outputs from these models can be used for informing management decisions and, where confidence intervals are small, in statistical modelling of future conditions (Stock et al., 2018; Ji et al., 2022).

The most common application of these source apportionment models is to use dual nitrate isotope data to estimate the proportion of nitrate originating from multiple potential sources, such as manure, sewage, soils, fertilisers, and atmospheric deposition (Xue et al., 2009). For example, SIAR modelling of dual nitrate isotopes in the Wen-Rui Tang River, with a rural-urban catchment network in China, showed that

sewage was the dominant nitrate source (56%–76%), with smaller contributions from nitrogen fertiliser (9%–21%) and soil nitrogen (8%–20%) (Ji et al., 2022). However, significant variations in river and source nitrate isotope signatures can limit the applicability of these models, since small shifts in isotope ratios can result in large shifts in the estimated contributions from nutrient sources. Model results are therefore influenced by sampling design, temporal variability in endmember isotope composition and by the extent to which endmembers have distinct isotope compositions (Xue et al., 2012; Chen et al., 2026).

One approach to overcoming the limitation of single-system isotope mixing models is to combine multiple isotope systems, such that the outputs of one system can cross-validate and constrain those of another, reducing the risk that process-driven isotopic shifts are misattributed to source variation. Chen et al. (2026) demonstrated this in shallow groundwater in the Xingyun Lake watershed, China, simultaneously apportioning nitrate and phosphate sources using a combined $\delta^{15}\text{N}\text{-NO}_3$, $\delta^{18}\text{O}\text{-NO}_3$ and $\delta^{18}\text{O}\text{-PO}_4$ framework within SIAR modelling. By treating nitrogen and phosphorus source apportionment jointly rather than independently, the study was able to exploit the biogeochemical coupling between the two nutrient cycles to provide mutually constraining evidence on source contributions, an interpretive advantage that single-nutrient approaches cannot offer. However, joint nitrogen and phosphorus applications rest on a further set of assumptions: that the same sources deliver both nutrients in a consistent manner; that source-specific concentrations and N:P balance are known well enough to weight contributions where concentration dependence is incorporated; that covariance among endmembers is represented rather than assumed absent; and that the two nutrients are not subject to sufficiently different transport and transformation behaviour to decouple their signals between source and sampling point.

A second approach is to use a model that represents nutrient removal and transformation directly rather than assuming it has not occurred. For example, processes such as denitrification and biological uptake preferentially remove the lighter isotopes, leaving the remaining nitrate isotopically heavier and shifting it towards the signature of sewage and manure (Figure 2). Where these processes are active, standard mixing models will tend to overstate the contribution from those sources. The FRAME family of models, developed initially for trace gases, addresses this by including both mixing and removal in the same equation and by estimating how much of the original nitrate has been consumed alongside the source proportions (Lewicka-Szczebak et al., 2020; Lewicki et al., 2022). TimeFRAME extends this to repeated sampling through time, so that samples collected close together inform one another rather than being treated as unrelated, which reduces noise in the estimated contributions (Harris et al., 2024). The trade-off is that these models offer much less scope than MixSIAR for allowing source contributions to vary with site, season or catchment characteristics, and estimating removal alongside mixing reduces the number of sources that can be distinguished from a given set of isotope tracers. In practice the choice depends on which limitation matters more for a given catchment: where nitrate is being actively removed in-stream, accounting for that

process is the priority, whereas where removal is limited, the flexibility of the established mixing models can be more valuable.

2.2 Key strengths of stable isotope approaches

Stable isotope data offer a suite of methodological, analytical, and interpretive advantages that make them particularly powerful and complementary tools for understanding nutrient sources, processes, and trends in support of policy, management, and investment decisions. Here, we outline how key strengths of isotope approaches have been demonstrated in case studies from English freshwaters. Full details of these case studies are provided in the [Supplementary Material](#). Where relevant English case studies were unavailable, illustrative examples from the international literature are used to supplement the evidence base.

2.2.1 Greater insight about sources and processing of nutrients

Concentration data provide a snapshot of how much of a nutrient is present at a given moment, but they offer limited insight into the underlying processes that shape nutrient dynamics. In contrast, stable isotope data can reveal diagnostic and mechanistic information that concentration measurements alone cannot capture, including the sources of nutrients and the pathways through which they are transformed in the environment. This was demonstrated in the River Wensum, Norfolk, where dual nitrate isotopes revealed that most riverine nitrate originated as microbially processed agricultural nitrogen, with subsequent work confirming the importance of nitrification and denitrification in influencing nitrate dynamics within the catchment (Wexler et al., 2011; Wexler et al., 2012). In the Thames Basin, ammonium-nitrogen and dual nitrate isotope analysis identified a legacy landfill as a significant point source of ammonium, demonstrating that this source contributed ~15% of the downstream ammonium load (Gooddy et al., 2014). Additionally, in the River Beult in Kent, combined dual nitrate isotope and phosphate oxygen analysis revealed seasonal shifts in source dominance, with diffuse agricultural inputs prevailing during high flows and wastewater sources becoming dominant during baseflow conditions (Gooddy et al., 2016). These examples demonstrate that stable isotope approaches can resolve source contributions and transformation processes that concentration monitoring alone is unable to distinguish.

2.2.2 Stability of source signatures and temporal representativeness

Nutrient concentrations often fluctuate rapidly (hourly to daily) in response to hydrology, storms, or diurnal cycling (McDowell et al., 2024). This can obscure underlying source signals or process trends. In contrast, isotope ratios tend to be less sensitive to these fluctuations and are therefore less “noisy”, often better reflecting changes in nutrient dynamics over longer timescales (weeks to months), depending on the residence time of the system (Glibert et al., 2019). For example, in a time series from three English

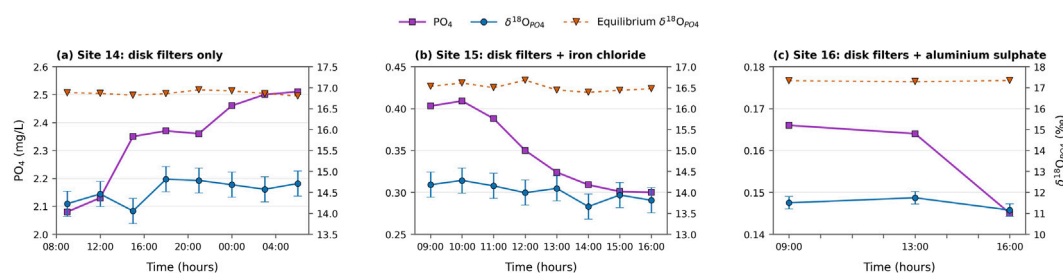


FIGURE 4

Time series of phosphate concentration (purple squares), phosphate oxygen isotope composition (blue circles) and calculated isotopic equilibrium (orange triangles, dashed) in final effluent from three English wastewater treatment works (WWtW), redrawn from data in Gooddy et al. (2018) (British Geological Survey © UKRI 2018). Site numbers correspond to the following WWtW and tertiary treatment types: (a) Benson, disk filter treatment only; (b) East Shefford, disk filters with iron chloride dosing; and (c) Cholsey, disk filters with aluminium sulphate dosing. One sample was collected at each time point; error bars denote one standard deviation on the $\delta^{18}O$ - PO_4 measurement. At all three sites the measured $\delta^{18}O$ - PO_4 remained several per mille below the calculated equilibrium composition, indicating that effluent phosphate had not equilibrated with ambient water and therefore retained a distinguishable source signature. Phosphate concentrations varied over the sampling period while $\delta^{18}O$ - PO_4 remained comparatively stable, indicating stability of the source endmember composition at these sites.

wastewater treatment works, phosphate concentrations in treated effluent showed marked diurnal variation while the $\delta^{18}O$ - PO_4 composition remained comparatively stable, indicating that the endmember signature persisted even as the concentration signal did not (Gooddy et al., 2018; Figure 4).

Similarly, where mixing between sources of contrasting isotopic composition dominates receiving water composition, changes in flow alter concentration without altering isotope ratios. This was observed in the River Beult, where nitrate and phosphate isotope compositions were comparable between high and low flow conditions despite large shifts in concentration, indicating that dilution rather than biological turnover was the primary control on the concentration signal over the period sampled (Gooddy et al., 2016). However, the timescale an isotope measurement represents is a property of the system and the sampling design rather than of the measurement itself: a single grab sample remains an instantaneous measurement however stable the underlying source signature, whereas composite or passive sampling integrates over the deployment period. Sampling design must therefore also account for higher frequency variation, for example, storm-driven mobilisation of different source pools, changes in the relative contribution of groundwater and surface pathways, or episodic nutrient transformation.

2.2.3 Improve and validate catchment models

Incorporating isotopic data into nutrient transport or biogeochemical models can help narrow the range of plausible output values and clarify which nutrient pathways dominate inputs (Matiatos et al., 2023). In the River Wensum study, integration of dual nitrate isotope data with solute transport data improved estimates of denitrification rates and highlighted groundwater flux as a significant pathway for nutrient input to the river (Wexler et al., 2011). Similarly, isotopes traced nutrient pathways in the Boxford experimental wetlands in the River Lambourn catchment, refining a conceptual model and constraining estimates of water residence time (Johnes et al., 2020). However, to date, formal coupling of isotope data with the operational water quality models which underpin management and

investment decisions in the UK remains unexplored. The potential for doing so is demonstrated by international examples, including work on the Qihe River Basin in China where coupling isotopic endmember modelling with a process-based catchment model (SWAT) improved the accuracy of nitrate source apportionment for diffuse agricultural sources (Li et al., 2025), and by the growing body of national, regional and catchment scale isotope-aided modelling across the globe (Kendall et al., 2010; Matiatsos et al., 2023; Rogers et al., 2023). Developing equivalent approaches in an English regulatory context represents a notable gap in the evidence base.

2.2.4 Investigating systems with low nutrient concentrations

Identifying nutrient sources using concentration data alone is particularly difficult in systems where nutrient levels are low. Small absolute differences between sources become difficult to resolve against background variability. Stable isotope methods offer an advantage in this respect, as they can be applied effectively across the full range of nutrient concentrations, including oligotrophic systems where concentration-based attribution is least reliable, although this may require larger volumes of sample. For example, in the Thames Basin, nitrogen isotope analysis enabled the identification and quantification of ammonium inputs from a legacy landfill site despite low concentrations (Gooddy et al., 2014). Similarly, dual nitrate isotope analysis in oligotrophic lakes of the English Lake District allowed nitrate derived from atmospheric deposition to be distinguished from that produced by in-lake nitrification, a distinction that would have been indiscernible from concentration measurements alone (Grefe et al., 2025). Many oligotrophic systems in England are designated under the Habitats Regulations as Special Areas of Conservation or under the Wildlife and Countryside Act as Sites of Special Scientific Interest, where the diagnostic challenge of identifying nutrient sources at low concentrations is directly relevant to condition assessment and management under statutory conservation obligations.

2.2.5 Applicability across freshwater systems

Stable isotope approaches offer the advantage of cross-system applicability, allowing comparisons to be drawn between different aquatic ecosystems and hydrological settings in ways that are particularly valuable for integrated catchment management. Rather than being confined to a single system type, isotopic methods can serve both site-specific diagnostic purposes and broader regional syntheses, providing a common investigative framework across diverse environments (Glibert et al., 2019). In England, stable isotope methods have been successfully applied across a range of contrasting aquatic systems, including a groundwater-dominated chalk catchment (River Wensum), a peri-urban floodplain (Thames Basin), a lowland river underlain by clay (River Beult), and upland lakes (Lake District), demonstrating that the approach is not limited to particular hydrogeological or land-use contexts. While the framework itself transfers between systems, its application must be adapted to the setting, as endmember compositions and the extent of biological overprinting reflect catchment-specific conditions including geology, climate, management practice and ecological setting, which vary considerably between countries.

Groundwater systems represent a further important application, where isotope methods are among the most established diagnostic tools for tracing nutrient sources and transformation in aquifers and hyporheic zones, and groundwater-surface water interactions are a significant nutrient delivery pathway in many English catchments, reinforcing the value of isotope approaches within integrated catchment investigations (Gooddy et al., 2014; Wexler et al., 2011). The value of this cross-system comparability is further illustrated by Grefe et al. (2024), who demonstrated consistent and comparable nitrate isotope patterns between rivers and lakes in the Lake District, with isotopic signatures revealing connectivity between surface waters and nearshore groundwater inputs in the Windermere catchment that concentration data alone could not have resolved.

2.2.6 Sample size requirements and analytical precision

Nitrate and ammonium isotope analyses can be conducted on a single water sample and only require a relatively small volume of water (~3–10 mL) in meso- or eutrophic systems (Altabet et al., 2019). These isotope systems can therefore normally be analysed from samples collected as part of routine monitoring efforts without significant logistical burden (Kendall et al., 2010). Phosphate oxygen isotope analysis requires much greater sampled volumes, typically 2–10 L for meso- or eutrophic systems. However, developments in passive sampler technologies and technological advances in analytical equipment are enabling smaller volumes of water to be collected and analysed (Ishida et al., 2022b; Wang et al., 2024). Similarly, samples for both nitrogen and phosphate analysis can be pre-concentrated using anion or cation exchange resins prior to analysis, enabling assessments in oligotrophic waters (Kendall and Caldwell, 1998; Ishida et al., 2022a).

The analytical precision of stable isotope methods is high, which makes them powerful tools for detecting subtle differences in nutrient sources and transformation processes. Typical analytical

precision achieved by isotope ratio mass spectrometry (IRMS) is around $\pm 0.4\text{‰}$ for $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ of nitrate and $\pm 0.3\text{‰}$ – 0.4‰ for $\delta^{15}\text{N}$ of ammonium (Altabet et al., 2019). This allows reliable discrimination of source materials that commonly differ by several per mille. Analysis can be less precise for phosphate oxygen measurements, often reporting reproducibility in the range of $\pm 0.5\text{‰}$ – 1.0‰ due to multi-step chemical purification and lower sample yields (Davies et al., 2014; Nisbeth et al., 2022; Pfahler et al., 2022). Despite this, isotope precision for both elements is adequate for environmental tracing, given that natural variations between sources typically span 5‰–20‰. Analytical precision is rarely the limiting factor in English systems, which are typically characterised by high nutrient loads and relatively dominant sources, and the more likely constraint is endmember separation rather than measurement resolution.

2.2.7 Case for investment

The analytical costs of stable isotope analysis are not insignificant but are broadly comparable to other geochemical and molecular techniques already used in environmental monitoring and assessment contexts, such as environmental DNA analysis (Environment Agency, 2016). Improved understanding of nutrient sources and pathways through stable isotope analysis has the potential to enable more targeted and cost-effective management interventions, with the consequent savings in misdirected expenditure potentially offsetting the analytical costs of the approach itself (Kendall et al., 2010). This argument is supported by a cost-benefit assessment of the Alsace aquifer in eastern France, where a €1 million dual nitrate isotope investigation was suggested to have had the potential to avoid much of the €26 million spent on aquifer restoration between 1988 and 2002, including €2.5 million in farming practice changes, €10 million for a new treatment plant at a large brewery, and €14 million in additional household costs (IAEA, 2013). While this calculation rests on the assumption that isotope evidence would have translated directly into better-targeted management responses, it demonstrates that investment in improved source diagnosis has the potential to generate returns exceeding its cost.

2.3 Challenges for applying stable isotope methods

Despite their clear strengths, the application of stable isotope techniques in freshwater nutrient management is subject to several important limitations and practical challenges that affect data interpretation, analytical feasibility, regulatory relevance, and confidence in source apportionment. These limitations are critically examined primarily using English case studies, with selected international examples drawn upon where English evidence is limited or unavailable.

2.3.1 Complexity of interpreting stable isotope data

Multiple factors influence the stable isotope composition of any environmental sample, meaning that additional contextual

information is required to support robust interpretation of isotopic data. The nature of these additional requirements varies with the purpose of the study and the environmental setting but typically includes site-specific characterisation of the isotopic composition of local nutrient sources or endmembers, isotope fractionation factors describing how isotopes partition between different substances or phases, and supporting hydrological data (Venkiteswaran et al., 2019; Matiatos et al., 2023). Without thorough site-specific calibration, interpretation of observed isotope signals can be ambiguous or carry substantial uncertainty (Glibert et al., 2019). Furthermore, where biogeochemical processes are active, the isotope signal observed at any given sampling point may reflect a combination of upstream source composition and within-reach transformation, and disentangling these contributions requires either supporting process data, careful sampling design that minimises the influence of active transformation, or explicit incorporation of fractionation effects into the interpretive framework. This intricacy is illustrated by the Lambourn catchment wetland study, where the hydrological complexity of the system meant that stable isotope data alone were insufficient to resolve nutrient sources and pathways, and multiple additional geochemical tracers were required to support a robust interpretation (Johnes et al., 2020).

2.3.2 Overlapping isotope signatures of nutrient sources

A recurring challenge for stable isotope source apportionment is that the isotopic composition of different nutrient sources can be similar or overlapping, making unambiguous discrimination between sources difficult or in some cases impossible. In the River Beult, nitrate isotope investigations were hampered by overlapping isotopic compositions of agricultural and sewage nitrate within the catchment, though the addition of phosphate oxygen isotope analysis provided some capacity to resolve sources that the nitrate system alone could not distinguish (Gooddy et al., 2016). Where the isotopic mixing space is not well constrained or endmember compositions are poorly separated, source apportionment can yield wide uncertainty bounds or become effectively non-identifiable, a problem that is particularly acute when relying on a single isotope system, as demonstrated through model sensitivity analyses (Jin et al., 2019; Silberberger et al., 2021). This limitation reinforces the case for thorough endmember characterisation and multi-isotope approaches where the additional tracers can support source attribution but also highlights that there will be catchment contexts in which isotopic source apportionment is inherently limited regardless of analytical quality, and where complementary chemical or hydrological evidence is essential to constrain interpretations.

2.3.3 Model dependence and error propagation

The parameters and assumptions on which isotope mixing models rest are consequential and are frequently under-reported. All mixing models assume that the sampled mixture derives only from the specified sources, and that the isotopic composition and variance of each endmember have been adequately characterised

over the relevant spatial and temporal range. The number of sources that can be reliably distinguished is also limited. As more sources are included, results become increasingly dependent on the assumptions built into the model, and in extreme cases, the outputs largely reflect the initial assumptions rather than the data themselves. Furthermore, a fundamental limitation of most existing isotope mixing models is that they attribute all observed isotopic variability to differences in source contributions, without explicitly representing in-system transformation processes such as denitrification, nitrification, and biological assimilation. Where these processes have fractionated sample isotopic composition prior to model entry (particularly through denitrification), source contribution estimates can be biased, as the model cannot distinguish process-driven isotopic shifts from genuine variation in source proportions (Xue et al., 2012).

The most common approach to address this is to use supporting hydrochemical evidence, such as dissolved oxygen concentrations, ammonium to nitrate ratios, proportional shifts in $\delta^{15}\text{N}\text{-NO}_3$ vs. $\delta^{18}\text{O}\text{-NO}_3$ (at 2:1 ratio; Figure 1) or chloride concentrations, to screen out samples showing clear evidence of transformation before model entry, reducing process-driven noise in the input data (Xue et al., 2012). However, the 2:1 ratio is an approximation that does not hold universally in freshwater contexts, where varying contributions of $\delta^{18}\text{O}\text{-H}_2\text{O}$ values, multiple nitrogen sources, and differing patterns of ammonium and nitrate uptake can produce trajectories that superficially resemble denitrification (Venkiteswaran et al., 2019). Pre-screening data based on dual isotope trajectories alone may therefore not reliably identify all forms of process-driven isotopic modification (Granger and Wankel, 2016). A more formal solution is to incorporate process-specific isotopic enrichment factors (ep/s) as correction terms within the SIAR framework, although this is uncommon in practice. Yu et al. (2020) and Jin et al. (2025) both demonstrated that explicitly incorporating spatially and temporally variable enrichment factors in SIAR produced meaningfully different source contribution estimates in groundwaters compared to uncorrected model runs, confirming that neglecting these corrections introduces significant uncertainty. Models that represent removal directly, such as FRAME and TimeFRAME (Section 2.1.4), relocate this dependence rather than removing it, since the enrichment factor must still be specified as a prior and reported values for freshwater denitrification vary considerably (Lewicki et al., 2022; Harris et al., 2024). Notably, Harris et al. (2024) found that performance improved less through the choice of model structure than through better constrained endmembers and enrichment factors.

No approach currently resolves the tension between source and process signals in isotope data, and this remains an important methodological gap. Incorporating covariates or fractionation factors is possible, but existing models are not well designed for this level of complexity, and doing so can propagate into wide uncertainty bounds on estimated source contributions (Parnell et al., 2010; Heikkinen et al., 2022). Formal sensitivity analysis of SIAR confirmed that small variations in isotopic composition of the dominant source produced large shifts in overall source apportionment outputs, whilst minor sources carried substantially higher uncertainty (Ji et al., 2022). This confirms that model outputs

are most reliable when the dominant endmember is well constrained and isotopically distinct from competing sources. Mixing model outputs should therefore be treated as probabilistic estimates rather than definitive attributions, and are most robustly interpreted alongside independent process indicators, hydrochemical data, and catchment-specific knowledge rather than in isolation.

2.3.4 Spatio-temporal resolution and temporal lags

As set out in [Section 2.2.2](#), the timescale represented by an isotope measurement is determined by system residence time and sampling design rather than by the measurement itself, and this has direct consequences for sampling strategy. The spatial and temporal resolution of existing stable isotope studies has typically been limited by sample logistics and analytical costs, with most isotope studies adopting a seasonal or campaign-based sampling approach, typically over 1 year, to evaluate seasonal source contributions and processes, with limited insight into short-term nutrient dynamics ([Sebilo et al., 2006](#); [Gooddy et al., 2014](#)). Storm-driven pulses, short-lived discharge events and diurnal productivity cycles may therefore be under-represented in isotope datasets if sampling is limited to seasonal campaigns or stable baseflow conditions. In catchments where storm events mobilise a large proportion of diffuse agricultural inputs, isotope sampling targeted only at baseflow may therefore provide an incomplete picture of annual source contributions, and should be interpreted alongside high-frequency concentration, flow and hydrochemical data. Similarly, in systems with long groundwater residence times, isotope signals may lag behind changes in the dominant nutrient source by weeks to months. These considerations do not reduce the diagnostic value of isotope data, but they reinforce the need to match isotope sampling strategy to the management question, particularly where source attribution is required during or immediately after high-flow events ([Mayer et al., 2002](#)).

Additionally, isotope studies have typically been undertaken using a small number of representative sites within a catchment rather than across the denser monitoring networks that exist for concentration surveillance ([Gooddy et al., 2016](#); [Jin et al., 2019](#); [Ji et al., 2022](#)). [Chen et al. \(2026\)](#) explicitly noted this as a limitation of their own study, observing that quantitative identification and uncertainty analysis of contributions to both nitrate and phosphate in groundwater would require higher spatial and temporal sampling efforts to improve the reliability of source apportionment at the watershed scale. While isotope data are still useful and informative where they are collected, these studies cannot currently substitute for network-scale concentration monitoring. Wider integration of isotope measurements into regulatory monitoring frameworks could enhance isotope data availability in both space and time, enabling cumulative improvements in the resolution and interpretive power of isotope-based assessments.

2.3.5 Analytical challenges and cost

Stable isotope analysis relies on specialised instrumentation that requires substantial capital investment and dedicated technical expertise for operation and maintenance. Environmental samples must undergo extensive preparation and pre-processing prior to analysis, including

chemical extraction, purification, and conversion to a measurable gas phase ([Altabet et al., 2019](#); [Adu-Gyamfi and Pfahler, 2022](#)). These procedures are considerably more time and labour intensive than standard laboratory protocols for determining nutrient concentrations. This is particularly true for studies in low-nutrient systems where large sample volumes are often needed, and additional time is spent on the preconcentration approaches described in [Section 2.2.6](#). Consequently, laboratory turnaround times for isotope analysis range from two to four weeks even for relatively straightforward analyses, compared with same-day or next-day results for routine concentration measurements. These factors contribute to a relatively high cost per sample and lower sample throughput than automated methods routinely used for concentration analysis.

Per-sample prices from commercial and university laboratories vary with batch size, sample matrix and nutrient concentration, and differ between countries but are not insignificant. Per-sample price is also only part of the cost of an investigation, which also requires repeat field sampling of source endmembers and across a range of flow conditions, large-volume collection and preconcentration for $\delta^{18}\text{O-PO}_4$, replicate analyses, supporting hydrochemical and flow measurements, and specialist time for design, modelling and interpretation. Total investigation costs also scale with the level of confidence the evidence must carry. Exploratory investigation, intended to generate hypotheses about dominant sources or processes, can accommodate wider uncertainty provided the direction of inference is robust, whereas formal regulatory applications would require accredited methods, documented chain of custody and a proven interpretive framework, with correspondingly higher costs; isotope methods are not currently positioned to meet an enforcement-use standard.

While multi-isotope approaches can better constrain nutrient sources and processes, they also inevitably increase project costs due to the need for multiple processing steps and analyses. Phosphate oxygen isotope analysis is particularly laborious, involving multiple sequential dissolution, precipitation, and purification steps with careful quality control at each stage ([Nisbeth et al., 2022](#)). It is also currently only undertaken at a small number of specialist laboratories globally. By contrast, more recent advances in dual nitrate isotope methodology, including the titanium reduction method ([Altabet et al., 2019](#)), have substantially reduced preparation time and per-sample cost, making nitrate isotope analysis more accessible for studies requiring higher sample throughput and more extensive spatial or temporal coverage. The analytical burden therefore varies considerably between isotope systems and should be a factor in study design when considering the feasibility of isotope-based approaches within monitoring programmes operating under resource constraints.

All isotope measurements require normalisation against internationally distributed reference materials. For nitrate, USGS32, USGS34, USGS35 and IAEA-NO3 are well established. For ammonium, standards include IAEA-N1, IAEA-N2, USGS25 and USGS26 and the silver phosphate reference materials USGS80, USGS81 together with B2207 (Elemental Microanalysis), provide the basis for calibration for phosphate oxygen. Consistent use of these materials and clear reporting of the normalisation procedure are essential if isotope values are to be

compared reliably between laboratories and over time. This is a practical prerequisite for any programme seeking to report or use stable isotope data.

2.3.6 Limited direct applicability to current threshold-based regulatory frameworks

Many regulatory frameworks for nutrient management share a common reliance on nutrient concentration or load data as the primary evidential basis for compliance assessment. Isotope data, by contrast, provide information about sources and processes rather than loads, and do not map directly onto existing compliance metrics. This represents a fundamental limitation on their regulatory utility, where isotopic evidence offers no clear equivalent to concentration thresholds and load targets around which current frameworks are structured. Whilst endmember modelling can translate isotopic source apportionment outputs into load contributions, these estimates are probabilistic in nature and therefore cannot immediately or readily substitute for the direct, auditable concentration measurements on which regulatory decisions are currently based.

3 Opportunities for policy and practice

The preceding review identifies both where stable isotope methods provide information on nutrient sources and transformations that concentration monitoring cannot, and where careful study design is needed to avoid over-interpretation. We now consider where isotope monitoring data and modelling approaches could most usefully support policy and practice. These opportunities are not proposed as replacements for existing concentration-based monitoring, but as targeted diagnostic applications where isotope evidence could strengthen the interpretation of nutrient pressures and inform the design and appraisal of management options.

3.1 Strengthening source apportionment and catchment modelling

Regulatory source apportionment models in England including the SAGIS framework, which combines sectoral load estimates within the Environment Agency's SIMulation of CATchments (SIMCAT) software for river water-quality modelling, provide a well-established and strategically important basis for estimating sectoral nutrient contributions and directing management effort at catchment scale (Comber et al., 2013; 2018; Environment Agency, 2024). These frameworks are calibrated primarily on concentration data and are necessarily designed for catchment-wide planning at scale. Model uncertainty can arise in catchments where source contributions are heterogeneous, where groundwater nutrient pathways are significant, or where biogeochemical transformations substantially modify concentrations of certain nutrient species.

Stable isotope data can complement these concentration-based approaches by providing an independent empirical basis for source attribution. Mixing model outputs can be incorporated directly into existing frameworks to provide additional constraint on the relative

contributions of nutrient sources, including the distinction between contemporary external loading and legacy nutrient release that concentration-only parameterisation struggles to resolve. This would be particularly valuable in investigative contexts described above, where the uncertainty associated with concentration-based attribution may be considerable (Wickham et al., 2006; Robertson et al., 2009; Wellen et al., 2015). Such isotope-enabled approaches remain sensitive to endmember definition and isotopic overlap, and their outputs should be interpreted probabilistically rather than deterministically, but the breadth of academic literature demonstrates their capacity to identify sources and processes not well characterised by concentration-based approaches alone.

More generally, process-based catchment models used for scenario testing, including Integrated Catchment Model (INCA-P or INCA-N) and Soil and Water Assessment Tool (SWAT) applications, have been shown to produce similar fits to observed concentration data using different model assumptions, while generating very different projections of how water quality might respond to future management measures (Beven, 2006). Isotopes can provide a more demanding test of model performance in these contexts, where a model required to reproduce both observed concentrations and isotope ratios simultaneously must represent the correct biogeochemical processes at realistic rates, rather than simply matching concentration outputs. This reduces the risk that calibration is achieved through compensating parameter errors that produce the right result for the wrong process reasons and can therefore strengthen confidence that model projections reflect real system behaviour rather than artefacts of calibration.

3.2 Internal loading and legacy nutrients

Internal nutrient cycling, including the release of phosphorus from bed sediments (internal loading), regeneration of decaying organic matter settling through the water column and recycling within algal cells, is increasingly recognised as a reason that lakes and reservoirs are not recovering despite substantial reductions in external nutrient inputs (Moorhouse et al., 2024; Tammeorg et al., 2024). This has been observed in the UK's most ecologically and culturally significant water bodies, including the Windermere catchment (Moorhouse et al., 2024), Loch Leven (Spears et al., 2012), Lough Neagh (Rippey et al., 2022), and the Norfolk Broads (Phillips et al., 1999). Similar issues are observed internationally, for example, modelling of nearly 6,000 large lakes across the United States found that internal phosphorus loading exceeds external loading in over a quarter of water bodies during dry summer periods (Borah et al., 2025). Concentration-based water quality classification can identify that a water body is failing phosphorus standards but cannot easily distinguish whether failure is driven by ongoing external loading or by internally recycled legacy sediment phosphorus. This distinction is consequential for investment decisions, since measures focused on reducing external inputs will not resolve internal loading problems, and expenditure on catchment measures in systems dominated by internal nutrient recycling may produce limited ecological improvement until sediment legacies are addressed through in-lake restoration.

Phosphate oxygen isotopes offer a potential means of distinguishing internal from external phosphorus sources,

because phosphate released from internal processes carries a distinct isotopic signature that is not erased on release (Jaisi et al., 2010). Sedimentary phosphate exchanges oxygen with porewater rather than with the overlying water column, and porewater temperature and $\delta^{18}\text{O}\text{-H}_2\text{O}$ commonly differ from surface conditions, so the sediment pool does not sit at equilibrium with the water body into which it is released (Wei et al., 2026). Internal loading is therefore identifiable on the same basis as any other source, provided the sediment endmember is characterised directly rather than assumed to lie at equilibrium. This has been demonstrated in Lake Erie, where a distinct isotopically heavy phosphate source was attributed to redox-mediated release from anoxic sediments (Elsbury et al., 2009; Paytan et al., 2017). In two stratified lakes in China, measured sediment $\delta^{18}\text{O}\text{-PO}_4$ corresponded closely to deep water values and was distinguishable from the isotopically light signature of organic phosphorus remineralisation higher in the water column, allowing the two internal supply pathways to be separated and their relative contributions to surface concentrations quantified (Wei et al., 2026).

Other internal cycling processes including microbially mediated release can also be traced. This is particularly important for riverine systems which are continuously mixed and whose uppermost sediments are themselves an active site of phosphorus cycling, rather than being physically separated from surface waters as in stratified lakes. Gooddy et al. (2026) show what this means in practice along a 100 km stretch of the River Nene, pairing $\delta^{18}\text{O}\text{-PO}_4$ with lead isotopes in river water, surface sediments and sediment cores. The shallowest sediments recorded present-day biogeochemical cycling while deeper layers of the cores preserved a record of historical pollution. Lead isotopes, which are unaffected by these biological processes, independently identified where the sediment phosphorus had come from and when it accumulated, allowing legacy stores to be separated from contemporary inputs and identifying sewage, agricultural and urban sources as dominant in different reaches. Diagnosing internal loading therefore means sampling both water column and sediments at depth, measuring the sediment directly rather than assuming its composition, and, in mixed systems such as rivers, pairing phosphate isotopes with a second tracer. Distinguishing between these drivers has direct diagnostic value where internal cycling is identified as the dominant contemporary source, and where focused efforts on reducing external loads may be insufficient to achieve water quality objectives.

3.3 Nutrient attenuation zones

Riparian wetlands, hyporheic zones, and floodplain soils are key regions within catchments for biogeochemical nitrogen and phosphorus attenuation. Denitrification and phosphorus sorption in these zones can substantially reduce nutrient loads delivered to surface waters (Johnes et al., 2020). However, the spatial targeting of agri-environment schemes and nature-based solutions rarely incorporates direct evidence of where natural attenuation processes are most active (Hansen et al., 2024). Concentration monitoring and mass-balance modelling approaches are generally unable to confirm whether these processes are occurring, at what rates, or in which specific catchment locations. Conversely, isotope data

could provide additional empirical evidence to support such assessments; examples from the River Wensum (Wexler et al., 2011; Garrard et al., 2023) and River Lambourn experimental wetlands (Johnes et al., 2020) illustrate the diagnostic potential of isotope data for this purpose. This information is not readily obtainable from concentration monitoring alone and yet is important for informing spatial targeting of nature-based solutions.

3.4 Evaluating the outcomes of management interventions

A further application of stable isotope methods that has received less attention in the reviewed literature is their use in evaluating whether implemented management measures have achieved their intended changes in delivery and distribution of nutrients. Nutrient monitoring data are subject to confounding influences including flow variability, lag times in hydrological response, and the contribution of legacy nutrient stores that are largely independent of contemporary management. For example, recent analysis has shown that although phosphate concentrations have declined at many monitoring sites in England since the 1980s, these reductions have not been consistent (Environment Agency, 2026). Stable isotope data could provide a supplementary line of evidence and address some of these limitations by indicating whether the relative contribution of targeted source types has changed, even in systems where overall concentration responses are not yet apparent or are obscured by hydrological variability.

This opportunity is illustrated by work on the Abbotsford-Sumas transboundary aquifer in British Columbia and Washington State in which a decade of voluntary agricultural management changes did not produce a detectable decline in nitrate concentrations in young groundwater, but isotope data revealed a measurable shift in the dominant nitrogen source from animal manure to inorganic fertiliser (Wassenaar et al., 2006). This source shift was itself a consequence of the management practices, and the authors indicate this would have been undetectable from concentration data alone, illustrating how isotope data can reveal whether the composition of nutrient loading has changed even in the absence of a detectable concentration response.

As with any management assessment, applying isotope methods to evaluate intervention effectiveness would require planning in advance. Key study design considerations include a pre-intervention baseline that captures isotopic variability across the range of flow conditions likely to be encountered afterwards, contemporaneous sampling of comparable catchments where no intervention has taken place and repeat characterisation of source endmembers in both periods rather than assuming they remain constant.

4 Recommendations and options for integration

The evidence reviewed in Sections 2 and 3 demonstrates the considerable diagnostic potential of stable isotope approaches for freshwater nutrient management, alongside practical and methodological challenges to their wider adoption. The following recommendations identify feasible and cost-proportionate pathways

for integration into policy and practice in England, presented in approximate order of near-term feasibility and intended to complement rather than replace established monitoring, modelling, and decision-making processes.

In the near term, isotope-based approaches could usefully supplement existing investigation and evidence-gathering processes within the RBMP framework. Several applications are particularly amenable to this context: isotope-based source apportionment as a supplementary line of evidence in persistently failing water bodies to validate model-based attribution; phosphate oxygen profiling of water and sediment in lake and river systems where internal nutrient loading is suspected but cannot be confirmed from concentration data; isotope surveys of denitrification and phosphorus retention to inform the spatial targeting of riparian and floodplain interventions; and before-and-after isotope monitoring in catchments receiving high-value management investment through WINEP or agri-environment mechanisms, to provide complementary evidence on whether implemented measures have altered the relative contribution of nutrient sources. For each of these applications the appropriate isotope system, sampling design and interpretive basis will differ, and will depend on catchment characteristics including the number and separation of contributing sources, hydrological setting, residence time and the intensity of in-system biogeochemical processing, as outlined in earlier sections.

WINEP and the broader Ofwat innovation funding landscape offer potential pathways for initiating isotope-based investigations at the catchment scale. Water company innovation funds, including those supported through Ofwat's Water Breakthrough Challenge and Innovation Fund, have previously enabled the testing of novel monitoring and source apportionment approaches (Ofwat, 2026), and may similarly provide a mechanism for piloting isotope methods in operationally relevant settings. Collaborative projects involving water companies, environmental agencies, research institutions, and catchment partnerships could allow methodological and interpretive experience to be accumulated in a structured way, demonstrate the applied value of isotopic evidence, and build the evidence base needed to inform subsequent decisions about wider uptake.

Greater uptake of isotope studies would require shared technical guidance, analogous to existing UK technical standards, clarifying when isotope investigations are likely to be most informative, which analytical approaches suit different contexts, and how isotope-derived evidence should be communicated and considered in decision-making processes. Such guidance would need to express the uncertainties inherent in isotope-based inference in terms accessible to non-specialists and should be developed alongside training for regulatory staff and water company practitioners to support effective commissioning and interpretation.

A practical prerequisite for broader uptake is a more consistent methodological and analytical infrastructure. The UK has relevant national capacity through the NERC National Environmental Isotope Facility (NEIF) network, research organisations such as the British Geological Survey and the UK Centre for Ecology and Hydrology, and established academic researchers in isotope geochemistry, though this capacity is not currently configured to support application at scale. Extending UKAS accreditation to isotope methods relevant to nutrient source investigations, developing standardised sampling and reporting protocols, and exploring options for batch processing to reduce per-sample costs would each help to lower barriers to wider application, as would the creation of a national reference dataset of isotope

endmember signatures for key UK nutrient sources hosted by an open-access data centre. These requirements would also apply internationally wherever the techniques are used routinely, although capacity, accreditation arrangements and turnaround times differ between national research and regulatory infrastructures.

Over a longer timeframe, there may be scope for isotope-based evidence to contribute to formal evidence frameworks that inform regulatory and investment decisions. This might include its use in spatial targeting of agri-environment interventions, informing the evidence base underpinning nutrient management for designated sites under the Habitats Regulations and improving the representation of specific nutrient sources and pathways within widely applied catchment models such as SAGIS-SIMCAT. Any movement in this direction would require transparent communication of uncertainty to non-specialist decision-makers, engagement with statutory nature conservation bodies and legal advisers, and the accumulation of sufficient domestic experience to support a robust UK-specific evidence base. The development of isotope-constrained variants of catchment models that directly simulate isotope dynamics is a longer-term ambition that may offer a pathway towards progressive adoption in decision support models, where sustained investment in model development and cross-sector collaboration is available.

5 Discussion

Stable isotope methods occupy a distinctive position within the diagnostic toolkit available to freshwater scientists and environmental managers. By providing information on nutrient sources and transformation that concentration measurements cannot yield, integrating signals over time in ways that can reduce the influence of hydrological variability, and being applicable across all major freshwater system types, stable isotope methods offer capabilities that genuinely complement existing monitoring approaches. Multi-isotope frameworks have proven capable of resolving source contributions and transformation processes in complex, multi-pressure catchments where concentration data alone generate substantial ambiguity, provided the selected tracers carry independent information and the relevant endmembers are separable.

However, the literature base also remains limited, with systematic characterisation of isotopic endmember signatures for key domestic nutrient sources, including agricultural runoff, private septic systems, and point-source discharges being incomplete. The available English evidence base is notably skewed toward lowland arable and wastewater-dominated catchments in southern and eastern England; it should not be assumed that the endmember separation or degree of biological overprinting observed in the studied catchments is representative of all systems. Cases in which isotope data do not fully resolve source attribution are nonetheless informative, revealing system complexity and biogeochemical overprinting that concentration monitoring would leave invisible (Granger and Wankel, 2016; Granger et al., 2017; Depew et al., 2018) and reinforce the importance of deploying isotope methods as part of a broader evidence framework rather than in isolation.

Barriers to the uptake of isotope methods can broadly be grouped into three categories. Analytical cost, sample volume requirements, and limited laboratory capacity are primarily logistical challenges that could be reduced with targeted investment and continued technological

development. The treatment of fractionation within mixing models and the need for systematic endmember characterisation, are methodological constraints that require further development of both methods and the underpinning evidence base. A third category comprises more fundamental limits on when isotope approaches are most effective, such as biological overprinting of $\delta^{18}\text{O-PO}_4$ in highly productive systems, overlap between source signatures that limit unambiguous source attribution, and the lack of a direct pathway from isotope evidence to regulatory compliance metrics. These limitations do not necessarily weaken the diagnostic value of isotope approaches, but they do help to define the circumstances in which isotope evidence is likely to be most, and least, informative.

International experience shows that stable isotope methods are already being used to support nutrient source apportionment, groundwater protection and catchment diagnosis in a range of policy-relevant contexts (IAEA, 2020), although uptake has been geographically uneven and is concentrated in countries with active isotope geochemistry research communities or established engagement with the IAEA's water quality programmes. The conditions most associated with successful applications are clearly defined management questions, dedicated funding mechanisms, and early engagement with regulatory end-users. Experience with the integration of other novel monitoring tools into English environmental regulation, including environmental DNA and geochemical sediment source fingerprinting (Collins et al., 2020), suggests that the pathway from research demonstration to routine application typically requires a decade or more, and has depended critically on method standardisation, accreditation, and the development of fit-for-purpose guidance.

Overall, there is a clear opportunity to move beyond *ad hoc* academic application and explore the potential for use of isotope evidence within catchment investigations, investment appraisal and evaluation of management outcomes. The evidence reviewed here suggests that there is a robust scientific basis for exploring such incorporation on a context-sensitive basis, and that the principal barriers to doing so are primarily practical and methodological. When conditions for effective application are met, stable isotope methods may support improved diagnostic understanding within nutrient management investigations and, in turn, support more targeted and proportionate management responses to a persistent and consequential environmental challenge.

5.1 Future research priorities

Realising the potential of stable isotope methods will require focused and coordinated research investment in several areas. The most immediate priority is the systematic characterisation of nitrogen and phosphorus isotope endmember signatures for country-specific nutrient sources, which is a prerequisite for reliable source apportionment. This should be accompanied by field trials of isotope-informed catchment investigation across landscapes representative of major land-use types, providing the empirical foundation needed to evaluate performance under operationally realistic conditions. With respect to the legacy phosphorus problem specifically, further investigation is needed into the spatial and temporal variability of sediment phosphate oxygen isotope signatures and the fractionation processes associated with nutrient release across different water body types and land-use histories. This work would benefit from parallel development of lead isotope profiling in river and lake sediment

core records, which could provide reliable chronologies for sediment phosphorus accumulation and improve interpretation of its contribution to contemporary water quality pressures. Continued development of passive sampler technologies and low-concentration analytical methods for $\delta^{18}\text{O-PO}_4$ analysis would also improve the practicality of routine phosphate oxygen isotope monitoring by reducing the logistical demands of sample collection and preservation.

Bayesian mixing models also require further methodological development. Conventional mixing models need to move beyond source attribution towards the explicit representation of biogeochemical transformation processes, whilst models that already represent removal, such as TimeFRAME, need greater flexibility to accommodate spatial and temporal variation in source contributions. Both require inter-comparison and calibration against tracer datasets and catchment models to improve their reliability, particularly with respect to the treatment of fractionation and endmember uncertainty. The conditions under which joint nitrogen and phosphorus apportionment can be reliably applied, including the treatment of concentration dependence and endmember covariance, also remain unestablished.

Comparative evaluation of tracer combinations would also be valuable. Very few published studies report the inference that would have been obtained from a subset of the measured tracers alongside the full multi-isotope result, and in the absence of such paired comparisons the incremental value of each additional isotope system, relative to its analytical cost, remains poorly quantified. Alongside this, the co-development of decision-support frameworks with regulatory end-users will be essential to ensure that isotope outputs can be interpreted and acted upon within existing governance structures. This could be achieved through structured workshops and collaborative events between regulators, water companies, catchment partnerships and researchers, and tested against real catchment investigations.

Overall, freshwater nutrient pollution is a global challenge, and the limitations of concentration-based monitoring and load apportionment modelling in diagnosing its causes are shared by regulators and practitioners across the world. England, with its policy-rich regulatory environment, strong domestic research base, and forthcoming investment cycles, is well placed to demonstrate how isotope evidence can be embedded meaningfully into freshwater nutrient management, providing a model for how the diagnostic gap between monitoring and effective intervention might be narrowed elsewhere. Equally, there is much to be gained through collaboration with countries where isotope methods are more advanced in practice, to overcome remaining methodological and institutional barriers to uptake through international collaboration and shared investment, an endeavour that the scale and urgency of the global nutrient pollution challenge fully justify.

Author contributions

SW: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review and editing. LH: Conceptualization, Data curation, Investigation, Methodology, Validation, Writing – original draft, Writing – review and editing, Funding acquisition. DG: Validation, Visualization, Writing – review and editing. AS: Validation, Visualization, Writing – review and editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. During the preparation of this work, the authors used Claude (Anthropic; Sonnet 4.6 and Opus 4.8) to assist with writing R code for figure generation, and for minor editing and formatting of manuscript text. The authors also used ChatGPT (OpenAI; GPT-5.5 Thinking with OpenAI image-generation tools) to assist with the creation and iterative refinement of Figure 2. The prompts used to generate and revise Figure 2 are provided in the Supplementary Material.

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Supplementary material

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