Without phosphorus, life is not possible. A fundamental element of life, it is essential to natural ecosystems and agricultural production. However, human activities (agriculture, wastewater, urban expansion, industry) are profoundly changing its cycle. Among the consequences, aquatic ecosystems are disrupted, algae proliferate and then decompose by consuming the oxygen needed by many species: this is called eutrophication. Moreover, phosphorus is not a renewable resource. On a global scale, estimates of future consumption predict that phosphate deposits will be depleted within one to two centuries. Controlling phosphorus flows in the environment is therefore essential to restore degraded environments and to secure human nutrition. This article presents the key mechanisms of the phosphorus cycle, restoration solutions and the medium-term management challenges of this resource.

1. How does the phosphorus cycle work?

**Phosphorus** is an essential component of living matter (DNA, cell membranes, enzymes, bone, ATP) but it is a rare element in the natural environment (< 0.1% of the mass of terrestrial rocks). It is found as calcium, iron and aluminum phosphates in volcanic and sedimentary rocks. On continental surfaces, phosphates are dissolved by the alteration (mineralogical degradation process) by dissolving the rock under the effect of the rainwater. The plants take the phosphates thus solubilized and use them to produce organic matter during the **biosynthesis** process. Phosphorus is then transferred along the food chain by plant consumption by animals. It is again solubilized by the decomposition of dead matter by microorganisms.
On a petit échelle (lac, fleuve, forêt, pâturage), le phosphore suit une succession de **organic** (monde vivant) et **mineral** (après décomposition du monde vivant) phases. Sur un échelle plus grande, le phosphore introduit dans les écosystèmes par *water erosion* et *leaching* (le processus de transport de solute par l’eau de pluie des sols à la nappe phréatique et ensuite aux rivières) est porté par les rivières vers les zones côtières où il fertilise les eaux côtières. Ces eaux sont généralement très productives en termes de phytoplancton (Figure 1).

Phosphore, qui ne possède pas de phase gazeuse, a une forte affinité pour les particules de sol et de sédiments (Tableau 1). Relégué dans les transports de sédiments dans les environnements aquatiques, le phosphore des continents sédimentent le fond de l’océan. Son cycle naturel mondial ne se trouve pas complètement en équilibre entre les pertes continentales et l’accumulation au fond de l’océan. Il est dit naturellement **“open”** à l’échelle de la biosphère. C’est clairement différent des cycles naturels de l’azote qui circulent dans un vrai loop entre l’atmosphère et d’autres compartiments de la Terre. En introduisant des phosphates à partir de la mine de roches phosphatées (fertilisants phosphatés et phosphates utilisés comme détergents en lavage), l'homme amplifie l’**imbalance** dans le cycle naturel du phosphore.

### Tableau 1. Distribution du phosphore dans les grands compartiments de la Terre.

<table>
<thead>
<tr>
<th>Compartiment</th>
<th>Stock en tonnes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphère</td>
<td>≈ 0 t</td>
</tr>
<tr>
<td>Hydrosphère</td>
<td>8,6 x 10^{15} t (sédiments)</td>
</tr>
<tr>
<td>Roches terrestres</td>
<td>25,6 x 10^{15} t</td>
</tr>
<tr>
<td>Matière vivante</td>
<td>2 x 10^9 t</td>
</tr>
</tbody>
</table>

### 2. Quelles sont les formes de phosphore ?

Le phosphore est trouvé dans la forme dissoute ou particulaire. Le phosphore dissous comprend des formes inorganiques de phosphates ortho (ions mono-phosphates HPO_{4}^{2-} et di-phosphates ions H_{2}PO_{4}^{3-}) et des formes organiques dans le processus de minéralisation (décadie processus de dégradation du matériau organique par des bactéries heterotrophes [end-tooltip]) de matériau de mort (phosphoprotéines, phospholipides). Les phosphates ortho (traditionnellement référencé sous PO) joue un rôle essentiel dans le fonctionnement des écosystèmes car ils sont la seule forme **biologiquement disponible** (signifie un élément accessible aux plantes pour la collecte et l'assimilation) pour les plantes. Ils sont présents dans les eaux poreuses des sols et des sédiments et dans la colonne d’eau des environnements aquatiques. En prenant les plantes pour produire le matériau organique (biosynthèse : le processus de production de matériau organique par une entité vivante (by photosynthesis for example for plants), ils sont alors libérés par le processus de minéralisation du matériau de mort sous l’action de bactéries heterotrophes qui utilisent l’oxygenation dissoute de l’eau pour oxidiser et minéraliser le matériau organique de mort.
Orthophosphate concentrations in natural environments are very low in the order of 10 µg phosphorus/litre (in the case of alpine lakes or pelagic marine waters). In environments highly disturbed by human activities, they can reach several hundred µg phosphorus/litre.

**Particulate phosphorus** is either organic or mineral. The *organic fraction* corresponds to all the phosphates of organic animal and vegetable matter, living or in the process of mineralization (Figure 2). It can represent a significant part of particulate phosphorus: up to 50% in river sediments in agricultural areas for example. The *inorganic fraction* can be present in two forms; crystalline phosphorus (calcium, iron or aluminium salts) which is among the least soluble forms and phosphorus fixed or adsorbed on the surface of the particles and its constituents (calcium carbonate, iron and aluminium hydroxides, clay, organic matter).

These fixed or adsorbed forms, which can be mobilized, are in permanent exchange with the dissolved forms thanks to the **adsorption** and **desorption** mechanisms. In aquatic environments, this property of ion-exchange particles strongly influences orthophosphate concentrations. Indeed, these ions are very sensitive to the **adsorption** capacities of the particles (total exchange surface, particle size). Particulate matter therefore plays a "buffer" role in orthophosphate ion concentrations.

### 3. What are the sources of phosphorus from human activities?

Like all living things, man needs phosphorus. Its daily food intake is about 1.5 g of phosphorus. The increase in the world population has considerably increased food needs. To feed humanity, agriculture has grown widely in the last century and has gradually intensified and industrialized. To maintain high productivity of agricultural systems in this context, soil phosphorus removed by crops must be renewed.
The use of guano (fertilizer made from seabird excrement) and the discovery during the 20th century of industrial production processes for phosphate fertilizers from phosphorus-rich rocks led to an expansion in the use of this resource on a global scale. The use of phosphate fertilizers has spread widely in Europe and North America, with inputs well in excess of the needs of cultivated plants. In response to the collective incentive for rationalization, Europe experienced a sharp decline in contributions in the 1990s. This reduction has not had any impact on agricultural yields and, since then, the consumption of phosphate fertilizers has remained stable. On the other hand, the emerging Asian countries with booming economies (China in the lead) have intensified their agriculture in recent decades and are now the largest consumers (Figure 3). In the near future, agricultural development in African and South American countries is likely to further increase global demand.

In addition, the reduction in production costs since the 1960s has led to the widespread use of mineral phosphate in everyday industrial products (agri-food, matches, metallurgy, detergents in the form of polyphosphates in laundry). The use of polyphosphates in laundry has led to a very large increase in the amount of phosphorus in domestic wastewater. The use of polyphosphates has been phased out in Europe since the end of the 20th century.

Recent and massive introductions of phosphorus into the environment, erosion of cultivated land (diffuse sources) and increased domestic wastewater (point sources) are contributing to the rapid increase in phosphorus concentrations in aquatic environments. Significant stocks have been built up in the environment such as overfertilized agricultural soils or river sediments that accumulate phosphorus. Understanding this new distribution of phosphorus stocks on the planet’s surface is crucial for better management of this limited and non-renewable resource [1].

4. Excess phosphorus and eutrophication

The environmental pollution caused by phosphorus, particularly in aquatic environments, has increased the interest in this element for several decades. It is considered to be the main responsible for the eutrophication process. Etymologically, the word eutrophication means “well nourished”. The term eutrophication refers to the consequence of hyperfertilisation of water into nutrients (phosphorus and nitrogen), the ultimate point of which is dystrophication (ecological imbalance) [2].

Eutrophication manifests itself in an increase in algal biomass and deoxygenation of the water column, itself caused by heterotrophic mineralization of the organic matter produced.

Eutrophication affects rivers, lakes and coastal areas. In addition, eutrophication can lead to a disruption of the structure of planktonic stands. For example, the proliferation of unwanted algae such as Dinophyceae and Cyanobacteria, some species of which can produce toxins. Deoxygenation can promote the release of sediment-associated pollutants (metals, micropollutants). Not to mention the economic impacts on bathing areas (toxic algae) and drinking water production (obstruction of pumping filters, establishment of parasitic fauna in networks, development of tastes and odours incompatible with the notion of consumption, etc.).
During the biosynthesis process, algae need carbon (C), nitrogen (N) and phosphorus (P). Algae growth is conditioned by the ratio in which they remove nutrients (Redfield ratio C: N: P = 106:16:1). This ratio refers to the molar elemental composition of carbon, nitrogen and phosphorus in an algal cell. If these elements are present in these ratios in the aquatic environment there is no growth limitation. If one of these elements is missing, it is called an algal growth limiting factor (nitrogen or phosphorus limitation for example). In this report, phosphorus is often referred to as the main limiting factor in algal growth. Its responsibility is clearly demonstrated in freshwater aquatic environments where nitrogen is largely in excess. In contrast, for coastal marine environments, nitrogen (in the form of nitrates; see Nitrates in the Environment) is often referred to as the main factor in eutrophication. This is the case, for example, in Brittany, where nitrates of agricultural origin are responsible for the spectacular proliferation of green algae on beaches (Figure 4).

As early as the 1960s, many cases of eutrophication were reported worldwide. First, the studies were conducted on lake environments (lakes and reservoir dams) where disturbances are most severe, such as the large North American lakes or, closer to home, the large alpine lakes (Lake Geneva, Bourget and Annecy). This extensive work leads to a classification of disturbance intensity based on the main indicators of trophic status of water bodies (Table 2).

Table 2. Threshold values for classifying the trophic status of water bodies

<table>
<thead>
<tr>
<th>Statut trophique</th>
<th>Phosphore total (µg/L)</th>
<th>Chlorophyll a (µg/L)</th>
<th>Transparence (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra-oligotrophe</td>
<td>&lt; 5</td>
<td>&lt; 2,5</td>
<td>&gt; 6</td>
</tr>
<tr>
<td>Oligotrophe</td>
<td>5-10</td>
<td>&lt; 8</td>
<td>&gt; 3</td>
</tr>
<tr>
<td>Mésotrophe</td>
<td>10-30</td>
<td>8-25</td>
<td>3-1,5</td>
</tr>
<tr>
<td>Eutrophe</td>
<td>30-100</td>
<td>25-75</td>
<td>1,5-0,7</td>
</tr>
<tr>
<td>Hypereutrophe</td>
<td>&gt; 100</td>
<td>&gt; 75</td>
<td>&lt; 0,7</td>
</tr>
</tbody>
</table>

Chlorophyll a: refers to a photosynthetic pigment in plants that allows photosynthesis through light. Chlorophyll a is used as an indicator of the plant biomass of an ecosystem: indicator of the intensity of algal development in waters. Transparency: limit of light penetration.

These threshold values make it possible to prioritize water bodies. Oligotrophic refers to a nutrient-poor environment with reference to its phosphorus concentration. A hypereutrophic environment is, on the contrary, the ultimate stage of degradation. The term mesotrophic refers to a transitional environment between ultra-oligotrophic and hypereutrophic. In rivers, attention to eutrophication problems is more recent. Rivers are considered as self-purifying systems, capable of digesting and discharging far downstream disturbances at a given point in the hydrographic network. However, the problem is very real in large rivers, with the proliferation of microalgae (phytoplankton refers to plant plankton in aquatic environments (microalgae), as in smaller rivers, where aquatic plants (macrophytes refer to aquatic plants rooted in sediments or floating on the water surface). In addition, significant nutrient inputs to rivers inevitably affect receiving coastal environments, lagoons, fjords and estuaries, which are themselves subject to serious eutrophication problems on a global scale.

5. How to restore eutrophic environments?
The first work to combat eutrophication first focused on reducing point phosphorus inputs. In many industrialized countries in Europe and North America, the collection of domestic wastewater, the reduction of polyphosphates in laundry and the treatment of phosphorus in wastewater treatment plants have significantly reduced phosphorus inputs to aquatic environments.

This management policy, which was very effectively applied from the 1980s onwards to restore the waters of Lake Geneva on the French-Swiss border, has made it possible, for example, to gradually reduce phosphorus concentrations in the lake's waters (Figure 5). To achieve the objective of reducing eutrophication set by the CIPEL (International Commission for the Protection of Lake Geneva Waters), efforts have also focused on the management of diffuse sources from the watersheds refers to the geographical area drained by a river and its tributaries. Its surface is delimited by the topography. The drained water converges towards an agricultural outlet.

With the accumulation of phosphorus in agricultural soils, and despite measures to limit erosion the process of detachment and transport of soil particles due to precipitation and water runoff (grass strips) and reduction of phosphate fertilizer inputs, the problem of diffuse sources of agricultural origin remains relevant. Mechanisms for transferring phosphorus from agricultural sources are still being studied to identify the role of hydrology on transport modes. It is noted that the restoration process is very long (several decades) from diagnosis, decision making and action to visible results.

How far should we go in reducing phosphorus inputs to aquatic environments? Aren't we going to radically change the way aquatic environments work? The issue of reducing phosphorus inputs has recently entered the public debate in Europe. This is reflected in the demands of professional fishermen on Lake Geneva who have been observing a decline in fish stocks for several years and are asking for more phosphorus in the lake to increase the productivity of the ecosystem.

While eutrophication is declining in Europe, the situation is critical in some emerging global regions where extremely rapid urban growth and agricultural development are still not taking environmental quality into account.

References and notes


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