Cultural eutrophication control through water reuse

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Abstract The increasing use of mineral fertilisers over the last decades has contributed to the appearance of numerous cases of water eutrophication, a new form of water pollution. The starting point of eutrophication is the increase of nutrient concentration (nitrogen and phosphorus) in a water mass, which is subsequently followed by an uncontrolled growth of primary producers and episodes of oxygen depletion due to microbial decomposition of algal organic matter. The excess nutrient loads reaching surface waters are usually associated to discharges from anthropogenic activities, which normally involve direct water usage instead of reuse of reclaimed effluents. Agriculture activities and livestock breeding are two of the main nutrient sources responsible for water eutrophication, as well as human – urban and industrial – wastewater discharges. Wastewater reclamation and reuse can be a suitable strategy for preserving the quality of natural waters, by suppressing effluent discharges and the associated nutrient contributions to receiving waters. Reuse of reclaimed water for agricultural and landscape irrigation as well as for environmental enhancement offers an adequate strategy for preserving natural water systems from eutrophication.

Keywords Cultural eutrophication; fertiliser production; pollution control; water reuse; irrigation; wetlands

Introduction

Without a doubt, one of the prominent forms of pollution in many natural waters all over the world is the so called eutrophication. Eutrophication is the word given to the increase in the concentration of nutrients (nitrogen and phosphorus) in the water and to all the subsequent phenomena: the increase of the primary production by phytoplankton or filamentous algae, the increase of the content of organic matter in water, the marked oscillations of pH values between day and night and the imbalance of the dissolved oxygen values between the surface layers and the deep layers of the water masses, especially in lakes, reservoirs and impoundments. Another effect of eutrophication is the reduction of the biodiversity of species in the ecosystem, due to the ability of some to thrive in these environments, since they are able to blossom in a short period of time after an input of nutrients in the system.

Most of the eutrophication occurring today is closely related to different kinds of human activities. Because of this, some ecology scientists call this phenomenon cultural eutrophication (Margalef and Prat, 1979). The spectacular increase in the Earth's population over the last century would not have been possible if it weren't for the green revolution and for the generalised use of mineral fertilisers, which have caused a substantial increase in the rate of food production. However, this extended use of mineral fertilisers has also produced an increase in the nitrogen and phosphorus in circulation all over the world (International Fertiliser Industry Association, 1998). These nutrients, which before being produced by chemical synthesis or torn out of the mines were outside the cycles of energy and matter, are now an active part of them and have an impact on the ecosystems as pollutants causing eutrophication.

The increase in the circulation of mineral nutrients all over the world is comparable to the increase in the circulation of carbon contained in the oil-derived combustibles. This carbon, formerly buried in deep-soil deposits for millions of years, has suddenly – in

Table 1 Total world production of nitrogen and phosphorus from 1961 to 1996 (International Fertiliser Industry Association, 1998a)

Year	Nitrogen millions of tons N/year	Phosphorus millions of tons P_2O_5/year
1961	12.4	10.8
1970	32.9	20.6
1980	62.9	34.0
1990	79.6	38.7
1996	86.9	32.7
Total 1961–1996	1920.1	1001.5

geological time scale – changed its ecological compartment and has entered the atmosphere as CO_2, increasing its concentration and contributing to the greenhouse effect. Other recipients for this extra carbon are living beings (plants, animals and humans) and the oceans. It is interesting to note the different degree of attention received by these two similar phenomena, and some scientists claim that the massive introduction of reactive nitrogen on the Earth over the last 50 years is nothing but a dangerous, large-scale biogeochemical experiment (Smil, 1997).

The amount of new nitrogen and phosphorus entering the global system each year is equivalent to the mass of these elements contained in the mineral fertilisers to be used in agriculture and landscape gardening. According to the International Fertiliser Industry Association (1998), 1.9 billion tons of nitrogen and 1.0 billion tons of phosphorus entered the cycle between 1961 and 1996 (Table 1). One must also take into account that these nutrients do not disappear from the environment, but a portion of them remain in the ecosystems as organic wastes, either industrial, animal (livestock) or human (biosolids), so their accumulative effect is not something to be overlooked. The general pattern of the use of nutrients is still mostly linear, with large amounts of new mineral fertilisers being produced and mined out each year, and with recycling processes often being poorly developed. Sometimes these organic wastes are not very carefully applied, causing pollution instead of acting for its abatement. Because of this, measures to prevent the generalisation of eutrophication should focus on achieving circulation of the great majority of these nutrients in the form of biomass during the maximum period of time. By achieving this, circulation out of the organisms would be minimal and chances of polluting water – whether surface water or groundwater- would be greatly reduced.

According to this reasoning, cultural eutrophication is nothing but the leakage of nutrients from the predominant production system. Current schemes usually give priority to primary usage and are not able to appropriately treat the production wastage, which becomes a source of pollution. If, from an ecological point of view, one concludes that these nutrient leakages causing eutrophication should not occur, then the correct weapons to be used to fight against generalisation of this problem all over the world would be correct recycling of waste together with a reduction of the consumption of new mineral fertilisers. One must also bear in mind that probably an important portion of this reactive nitrogen ends up in the atmosphere as molecular nitrogen (N_2) through denitrification, where it is the predominant element (78%). However, despite the fact that the largest portion (99%) of the nitrogenous fertilisers is produced from molecular atmospheric nitrogen (International Fertiliser Industry Association, 1998b), it seems advisable not to introduce more reactive nitrogen in the biosphere, reusing more effectively the nitrogen already in circulation and minimising its spreading into the ecosystems.

Something similar could happen with phosphorus, but in this case the main difference is that the phosphorus cycle does not have a gas phase and no phosphorus fertiliser can be produced from it. Instead, phosphorus in fertilisers can only come from the exploitation of phosphate rock deposits. According to Ingrid Steen, "Estimates of world phosphate reserves and availability of exploitable deposits vary greatly and assessments of how long it will take until these reserves are exhausted also vary considerably. Furthermore, it is commonly recognised that the high quality reserves are being depleted expeditiously and that the prevailing management of phosphate, a finite non-renewable source, is not fully in accord with the principles of sustainability." (Steen, 1998). Therefore, there is an even greater urge for the careful management of the phosphorus which is already circulating, and we should not let it be a pollutant because it is becoming clearer that it is a valuable resource.

Due to this, the present trend in the field of wastewater treatment, enforced by many legislations in different countries as a means of protection for sensitive receiving waters, is to reduce the concentration of nitrogen and phosphorus in the secondary effluents through its elimination in wastewater treatment plants (WWTP). However, the progressive reduction in the nutrients released by point sources is uncovering another form of pollution, less apparent and more difficult to fight against, which is diffuse pollution or non-point source pollution (Meinardi *et al.*, 1995; Somlyódy, 1995; Werner and Wodzak, 1995). Diffuse pollution due to nutrients is mainly caused by rainfall which rinses these nutrient-rich compounds – whether mineral fertilisers or some type of organic waste- which have been applied to the soil. Runoff from rainfall transports these nutrients to the nearest stream. The level of nutrients in this sort of pollution is difficult to quantify and sometimes it can be better detected and evaluated through analysis of the macroinvertebrate community rather than with the usual chemical parameters (Beck, 1996).

From the perspective of eutrophication and its causes, diffuse pollution produced by nitrogen and phosphorus compounds usually has its origin in agricultural areas where fertilisers are applied to the land and where livestock is raised. The degree of pollution in these areas easily correlates with the degree of care used in the management of fertilisers, whatever its origin might be (the lesser the degree of care, the higher the pollution). In Catalonia, NE Spain, where – according to estimates – 80% of the organic wastes produced are animal wastes from livestock, the desirable targets regarding the quality of natural waters will not be achieved until these organic wastes are managed in a more careful manner, since sometimes they are applied in excess to nearby fields in order to reduce disposal costs. Where

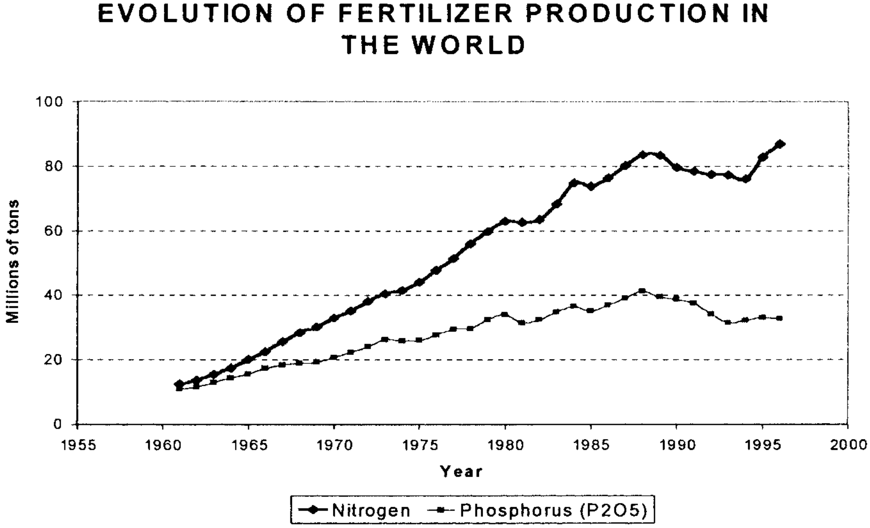

Figure 1 Evolution of fertiliser production in the world (International Fertiliser Industry Association, 1998)

livestock is raised intensively, these practices have a measurable impact on the quality of groundwater and it is not unusual to find nitrate concentrations above 10 mg NO_3-N/l (Montaner *et al.*, 1996), the upper limit in potable waters. Rational use of these wastes, applying them in agricultural doses according to the needs of the crops and soils, exactly as is done with the biosolids produced by the WWTP (Departament de Medi Ambient, 1994), would improve not only the yields – the crops would not be overfertilised – but would also be an effective measure to protect the quality of groundwater.

Discharges of treated effluents from WWTP generally have a lower impact on natural resources, but it is still possible to improve management in order to benefit from both the water and the remaining nutrients and to reduce their spreading in the environment (Brissaud, 1996; Faby *et al.*, 1998). If one considers that possibly the treatment of wastewater does not end by default with its discharge into the nearest stream, but possibly it ends with the discharge or the use of the treated water whereby the lowest environmental impact is achieved, other environmentally sound alternative practices appear, at least in those climates with a dry, hot season. Therefore, for a given well treated effluent, the best solution may not be its discharge – even if this complies with the law – if the receiving stream does not have the capacity for providing enough dilution, as usually happens in summer in many Spanish rivers.

Water reuse as a means of eutrophication abatement

Since quality standards are only applied to effluents prior to their discharge, there is a tendency to only see how nitrogen and phosphorus can be removed from wastewater in the WWTP and we tend to forget that these standards were set to avoid a negative impact on the receiving streams. Simply put, we tend to forget that, at least in some cases, there are other alternatives, like the reduction or elimination of the discharges of these treated effluents. Therefore, in agricultural areas and especially in dry climates, an interesting alternative to the usual wastewater treatment with biological nutrient removal would be the reuse of these waters for irrigation so the effective nutrient removal would occur through uptake by crops. As described by Johnson (1998) in the Wastewater Reuse Electronic Discussion Group, in the US ". . . we have millions of acres of farmland and the most limiting factor on crop yield is water, or the lack there of. These cities and small towns spend millions building treatment plants that discharge into our rivers millions of pounds of nitrogen and phosphorus (using the assimilative capacity of our rivers and streams as part of the sewage system), while a few miles away farmers are paying for fertiliser and praying for rain . . .".

Agronomical implications

Nutrient contributions from reclaimed water used for irrigation are not to be neglected. Instead, it is a stated fact that when typical secondary effluents are used for irrigation, in order to cover the needs of water from the crop, the amount of fertilisers introduced by the water might be a large portion of their needs (Mujeriego *et al.*, 1996; Sala and Millet, 1997). Table 2 shows the typical nitrogen species and concentrations to be found in different kinds of wastewater treatment plants.

The use of reclaimed water for irrigation causes major changes in agronomic management practices, compared to the usual situation when freshwater or groundwater are used. Except for the parameters related to the salt content of the waters, these changes are always due to the loss of independence between irrigation and fertilisation occurring when reclaimed water is used. Every time reclaimed water is used for irrigation, there is a nutrient contribution; the greater the irrigation dose, the higher the contribution, given a certain nutrient concentration. Because of this, it is very important to generate frequent information on these nutrient contributions during the irrigation season, so conventional fertilisers

Table 2 Main nitrogen chemical species to be found in reclaimed water according to the kind of treatment given to the wastewater

Kind of treatment	Main nitrogen species	Typical range mg N/l (total N)
Activated sludge	Ammonia Organic nitrogen	20–60
Extended aeration (with N/DN)	Nitrate Organic nitrogen	10–30
Conventional waste stabilization ponds	Organic nitrogen Nitrate Ammonia	20–40

would only be applied either as a complementary source of nutrients in case the irrigation could not cope with all the crop needs, or as a source of material for balancing the ratio between nutrients. Obviously, these systems are not easy to manage, but usually it is worthwhile going through all this complex process in order to save on fertilisers. According to the superintendent of the Golf d'Aro, formerly Golf Mas Nou, in Platja d'Aro, NE Spain, (personal communication), if it were not for the use of reclaimed water for irrigation, this golf course would have a higher annual fertiliser consumption, with an estimated cost of 40,000 $US, whereas the present cost lies between 15,000 and 20,000 $US (1 $US = 150 Spanish pesetas).

In the Costa Brava area, in NE Spain, where reclaimed water is supplied for irrigation to three golf courses and to some minor agricultural plots, information about the content of nutrients in the reclaimed water is generally given every month, so the users can adapt their fertilisation plans to what is being applied to the irrigation water. Tables 3 and 4 summarise the nutrient contributions by the irrigation water on two golf courses located on the Costa Brava which are using reclaimed water, and Figure 2 shows the quality of the different types of water at the Golf d'Aro water reuse site from the point of view of inorganic nitrogen (CCB, 1998).

Also important to note is the ratio between the different nutrients, especially the ratio between nitrogen and phosphorus, seeing how it varies because of factors such as the kind of wastewater treatment plant or the water management procedures. As summarised in Table 5, the water used for irrigation from Pond 1 at Golf d'Aro is specially rich in nitrogen and almost doubles the phosphorus content, because of: i) the relatively high values of

Table 3 Summary of the nutrient contributions due to the reclaimed water used for irrigation in the Golf d'Aro (Castell-Platja d'Aro) during 1997

Element	Area Irrigated by Pond 1	Area Irrigated By Pond 2	Recommended contribution	Percentage of contribution in area 1	Percentage of contribution in area 2
Nitrogen, kg N/ha. year	162	71	166	98	43
Phosphorus, kg P_2O_5/ha.year	83	49	100	83	49
Potassium, kg K_2O/ha.year	139	95	166	84	57

Table 4 Summary of the nutrient contributions due to the reclaimed water used for irrigation in the Golf L'Àngel (Lloret de Mar) during 1997

Element	Contribution by irrigation water	Recommended contribution	Percentage of contribution by irrigation water
Nitrogen, kg N/ha.year	108	166	65
Phosphorus, kg P_2O_5/ha.year	121	100	121
Potassium, kg K_2O/ha.year	160	166	96

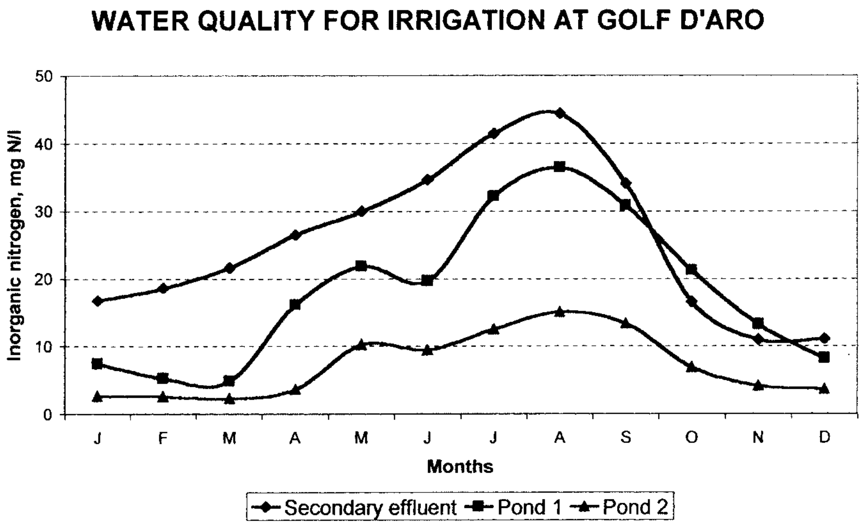

Figure 2 Inorganic nitrogen values of the different types of water at the Golf d'Aro water reuse site. Average values from 1990–1995

ammonia in the secondary effluent produced by a conventional activated sludge plant; and ii) the low hydraulic residence period of the water in the pond (minimum 7 days), which prevents major changes in the quality of the water. Instead, Pond 2 has a minimum residence time of 30 days, which allows improvement of the quality of the water – in this case, the loss of nutrients. Since the nutrient more easily lost is nitrogen, the ratio between the contributions of nitrogen and phosphorus is lower than the same ratio calculated with the data from Pond 1.

Finally, it is interesting to note that the lowest value of the ratio between nitrogen and phosphorus occurs with the water used for the irrigation of the Golf L'Àngel, which is an effluent produced by an extended aeration plant, despite the fact that in this particular case there are no storage ponds involved. When this water is used for irrigation, the phosphorus contributions, measured as P_2O_5, are even greater than the nitrogen contributions based on the analysis of all the nitrogen species in the effluent (organic nitrogen, ammonia, nitrite and nitrate).

Nutrient management in environmental reuse projects

One of the newest applications for reclaimed water is environmental use for the restoration of those aquatic ecosystems affected by desiccation or pollution. In this case, the approach of the reuse activity is the opposite of that for agricultural or landscape irrigation. Whereas in the latter case the efforts are aimed at preserving public health (the effluents are disinfected, with or without a previous filtration step) and usually no specific treatment for nutrient removal is applied, in the case of environmental reuse it is necessary to provide a process to remove these elements, because otherwise the final result would be the eutrophication of the receiving waters.

Table 5 Ratio of nitrogen to phosphorus contributions (kg N/kg P_2O_5) due to different kinds of reclaimed waters used for irrigation in 1997

Irrigation	Main features	Water entering the system	Ratio N/P_2O_5
Golf d'Aro, Pond 1	Minimum HRT = 7 days	Activated sludge effluent	1.96
Golf d'Aro, Pond 2	Minimum HRT = 30 days	Water from Pond 1	1.45
Golf L'Àngel	Without storage ponds	Extended aeration effluent	0.89

Apart from the pond systems, generally well understood and easy to operate, another interesting option for the removal of nutrients in secondary effluents are the constructed wetland systems. Their high productivity makes them specially interesting for this purpose, since they are able to remove a large portion of nutrients from the water. This water can then be safely deposited in sensitive areas with a lower risk of eutrophication. The constructed wetland systems have a double benefit: on one hand, they are very efficient at reclaiming the water, especially with nitrified effluents, whereas on the other hand they provide areas with a high ecological interest because of their role of refuge for wildfowl and other wild animals.

If, with the use of reclaimed water for irrigation, the fate of the nutrients is to become part of the crops' biomass, in the constructed wetland systems, part of the nutrients are used to create a trophic web and to enhance the development of different forms of life, starting with the dissolved inorganic compounds. The algae growing in these compounds will provide dissolved oxygen to the ecosystem and they will also be the source of food for other organisms like protozoa, insects or crustaceans who, in turn, will be the source of food for higher, predator organisms, including birds. Another portion of the nutrients is taken in by the macrophyte plants, which also provide shelter for these larger animals, especially for the waterfowl. So, these nutrients that otherwise could be pollutants if the water were discharged to the nearest water mass, turn into a complex, highly productive ecosystem which also cleanses the water.

In spring 1998, a new project of effluent polishing through a constructed wetland system started on the Costa Brava, Spain, funded by the European Union Cohesion Funds and the Consorci de la Costa Brava (Costa Brava Water Agency). In this project, the effluent of the Empuriabrava WWTP is further treated in a constructed wetland system and the reclaimed water is entirely reused at the Cortalet lagoon, in the Aiguamolls de l'Empordà Natural Park. In summer, this lagoon is affected by a desiccation process due to the excessive consumption of water for agricultural irrigation upstream of the Park and the reclaimed water acts as an alternative supply of water to overcome summer desiccation. Apart from the benefits of the improvement in the quality of the water (Table 6) and of being an alternative supply, an added benefit from this project is the zero discharge into the Muga river, which has been released from the inputs of nutrient caused by the secondary effluent that was previously discharged into this river. Another benefit is the creation of new wetland areas which have quickly been colonised by many different waterfowl species, which has enhanced this particular area of the Park. For the moment, the project is a complete success and it is rapidly gaining a reputation in the area as a model for sustainable water reuse for environmental purposes.

Table 6 Comparison of the average quality of the water produced by the Empuriabrava WWTP and the constructed wetland facility from January to June 1999

Parameter	Secondary effluent	Constructed wetland effluent
BOD, mg/l	4	8
SS, mg/l	7	40
PH	7.6	9.1
EC, dS/m	2.9	3.1
Ammonia, mg N/l	5.8	1.0
Nitrite, mg N/l	0.2	0.1
Nitrate, mg N/l	6.2	2.9
Inorganic nitrogen, mg N/l	12.2	4.0
Soluble orthophosphate, mg P/l	3.0	1.2

Conclusions

Monitoring of reclaimed water quality provides very useful information for the decision-making process required in water resources management, particularly when assigning reclaimed water quality to the most appropriate beneficial reuse alternative. Reclaimed water contains considerable amounts of nitrogen and phosphorus which can promote eutrophication of receiving waters; at the same time, agricultural and landscape irrigation requires systematic supplies of water and nutrients to be productive. A similar benefit can be obtained by using nutrients to develop trophic webs able to sustain wetland ecosystems, which have a high ecological value, but are in evident regression in many parts of the world.

Thus, reclaimed water use either for irrigation or for environmental enhancement can be much more than an alternative water discharge and should be considered an additional component of the overall environmental protection system, together with the wastewater treatment itself, that can be used for improving natural water quality. This new approach should help politicians, planners, and developers to understand how water reclamation and reuse can provide a final and essential step in an integrated environmental protection strategy.

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