Low technology systems for wastewater treatment: perspectives

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Abstract Low technology systems for the treatment of wastewater are sometimes presented as remnants of the past, nowadays supposedly only meant to serve developing countries and remote rural areas. However, considering their advantages and disadvantages together with enhanced treatment requirements and recent research and technological developments, the future of these systems still appears promising. Successful applications of low technology systems require that more care is taken of their design and operation than often observed. Correlatively, more efforts should be made to decipher the treatment mechanisms and determine the related reaction parameters, so as to provide more deterministic approaches of the natural wastewater treatment systems and better predict their performance.

Keywords Extensive systems; low technology; natural systems; wastewater treatment

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Introduction

Low technology systems, also called extensive or natural systems, are based on the imitation or adaptation of processes that occur naturally in soils and water bodies. They include mainly stabilization ponds, intermittent soil filtration and constructed wetlands. They incorporate few if any electro-mechanical equipment and are low energy consumers.

While big cities in developed countries unquestionably are to be served by sewage treatment plants based on conventional intensive technologies (physical–chemical treatment, activated sludge, etc.), conventional systems are in competition with low technology systems to treat the wastewater of medium and small-size communities. Indeed, with the exception of desert zones, large areas of land where extensive wastewater treatment facilities could be set up are seldom available in the vicinity of big cities where authorities are used to relying on sophisticated technologies and plants operated by highly skilled personnel to abide by discharge regulations and prevent failures that could damage the environment. Large towns can afford high treatment expenses, which is not the case for smaller communities.

On the contrary, though intensive techniques should not be discarded, there are strong arguments to claim that extensive sewage treatments are more appropriate for medium and small-size municipalities than conventional systems, the most popular of which are based on the activated sludge process. The perspectives offered to the development of natural wastewater treatment systems depend on (i) the balance between their advantages and disadvantages, (ii) the development of the treatment regulations, (iii) the continuation and success of ongoing researches and recent technological advances aimed at increasing the performance and reliability of these technologies and (iv) the efforts made to educate designers and operators who, unfortunately, are not always aware of the treatment processes, of the performance that can be expected and of the operational conditions required to make these systems efficient and sustainable.

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Advantages/disadvantages

Advantages

Though investment costs are not much lower than those of intensive techniques, extensive systems offer the decisive advantage of very low operation and maintenance (O&M) costs. Actually, no (or very limited) energy supply is required and as electro-mechanical equipment is reduced to a minimum, maintenance is relatively inexpensive. Power supply, which is an important part of the operation cost of conventional systems, is rapidly increasing due to the soaring cost of energy. As extensive techniques incorporate low technology equipment, O&M does not require highly skilled personnel and is not very time consuming. These advantages deserve the highest consideration when planning wastewater treatment in rural areas and developing countries. Indeed, as reported by Kengne *et al.* (2005), construction and O&M costs of conventional sewage treatment plants require large amounts of money that countries facing structural and financial adjustment cannot afford. The result is, for instance, that most of the conventional systems, especially activated sludge, present in the Sub-Sahara Africa, lack maintenance, are overloaded or simply out of order. In rural zones of developed countries, small community budgets, poor access to equipment, supplies and repair facilities, together with the difficulty linked to the O&M of many small plants scattered over large areas often preclude proper O&M of conventional systems and result in recurrent violation of discharge permits (US EPA, 2000).

All extensive and natural techniques allow significant to high microbial decontamination. Four to 5 log units removal of *Escherichia coli* can be obtained in stabilisation ponds (Brissaud *et al.*, 2005; Pearson *et al.*, 2005), more than 6 log units in shallow ponds (Von Sperling and Mascarenhas, 2005), up to 5 log units in batch operated reservoirs (Indelicato *et al.*, 1996) and 3 to 4 log units with infiltration percolation. One to more than 3 log units has been reported in vertical flow and horizontal flow constructed wetlands (Masi *et al.*, 2004; Baeder-Bederski *et al.*, 2004). Though decontamination performances are dependent on a number of factors, i.e. climatic conditions, the season of the year, the design and load and management of the plants, the potential to decontaminate wastewater is a very strong argument in favour of extensive techniques in many circumstances. Microbial decontamination is – or should be - the priority of sanitation strategies in most developing countries, particularly in tropical and arid regions where water reuse is on the agenda. Protection of bathing waters is of the utmost importance in tourist areas, such as the Mediterranean. In karstic areas, disinfection of wastewater is essential for the protection of groundwater quality. In water scarce countries, the most rewarding water reuse applications require pathogen removal.

In natural systems, sludge production is limited to the settling stage. As settling is performed in Imhoff tanks, septic tanks and ponds, most of the accumulated sludge is digested, the excess being removed twice a year from Imhoff tanks, 3–5 years from septic tanks and up to one year out of 15 for facultative ponds as demonstrated by Picot *et al.* (2005). Many vertical flow constructed wetlands are fed with raw wastewater that has just been degritted; sludge accumulates on the filters rather slowly. Molle *et al.* (2005) report sludge heights of 13 and 25 cm in the primary vertical filter of a plant designed for 1,600 p.e., after 9 and 15 years operation, respectively. SS mineralization rate was estimated to be more than 60% (Boutin *et al.*, 1997). Because the dry matter content was greater than 20%, sludge deposits were easily removed without damaging the reed rhizomes. Reducing both desludging frequency and the amount of sludge to be handled is a major advantage, not only in terms of labour saving but also because the regulations imposed on sludge disposal have been made so severe in several countries that the cost has dramatically increased.

Extensive techniques are reliable. Treatment units are gravity fed in many plants and therefore are not dependent on power supply; then, the main risks of failure events are linked to potential clogging of the infiltration systems and to possible submersion of the plants during storm events. When pumping is necessary, pumps, often doubled and easy to replace, are the only electro-mechanical tools required to assure a proper functioning.

Systems with a high detention time, such as stabilization ponds and reservoirs can buffer load variations, thus preventing the discharge of poorly treated water in the environment.

Extensive or natural techniques are sometimes classified as "green" techniques. Ponds and vegetated constructed wetlands and infiltration systems can be designed in order to enhance the aesthetic value of the plant settings, including "natural" shapes for the treatment units, islands, plant diversity, providing wildlife habitat, etc. However, wildlife access should be controlled in order to limit the presence of nuisance species and to prevent the detrimental impact of overpopulation of waterfowl, insects such as mosquitoes, floating macrophytes and even fishes.

Disadvantages

The main shortcoming of most extensive techniques is their large and often excessive footprints. They cannot, therefore, be applied in densely populated areas where land prices are often soaring. This is illustrated by the fate of many waste stabilization pond systems commissioned from the 1960s to the 1980s. As the population has increased and towns have sprawled into the neighbouring countryside, old waste stabilization ponds became overloaded and closer to the new settlements. In most cases, the capacity of the plant has been increased through the construction of a conventional biological treatment unit, the ponds – when they have not been decommissioned – being converted to a polishing stage. However other solutions that can be classified as natural systems or close to them are available. The most popular is the aeration of the primary ponds (Copin *et al.*, 2004). The subdivision of large ponds into smaller units is also very successful (Archer and Donaldson, 2003).

Another disadvantage is that, in many cases, low technology systems cannot meet all treatment objectives. If high organic matter removal is achieved in soil treatments and vertical flow constructed wetlands, COD abatement is hampered in ponds, reservoirs and other free water surface wetlands by algal cell content in the final treatment units. Though this particularity has been taken into account in several wastewater disposal regulations, e.g. E.U. Directive 91/271 EEC (EU, 1991), more stringent requirements are likely to be imposed in the near future. Fortunately, this drawback can be overcome by adding rock filters or constructed wetlands to polish the effluent (Tanner *et al.*, 2005). Nitrogen removal is temperature dependent. While even performances can be expected all the year long in hot climates, nitrogen reduction in stabilisation ponds and free water surface wetlands depends highly on the season in temperate and northern climates; low removal, if any, occurs during the cold seasons (Archer and O'Brien, 2005; Andersson *et al.*, 2005; Houweling *et al.*, 2005). In soil treatment systems and vertical flow constructed wetlands, ammonium nitrogen is effectively nitrified but without the possibility to remove nitrogen through denitrification. This is the reason why Cooper *et al.* (1999) recommend hybrid systems which combine vertical and horizontal flow constructed wetlands. Phosphorus may precipitate in ponds, reservoirs and free water surface wetlands provided the temperature is high enough, but is hardly eliminated in soil filtration systems and constructed wetlands. Several attempts to enhance phosphorus reduction through the utilisation of media capable of binding P – calcareous crushed rocks, calcite, apatite, ochre, iron slags – have not all been very successful (Arias and Brix, 2005; Shilton *et al.*, 2005).

Very stringent microbial criteria, i.e. ≤10 faecal coliforms per 100 mL, are not likely to be always met when using only low technology systems. Typically, free water surface systems cannot consistently supply effluents of less than 100 faecal coliforms per 100 mL. Indeed, recontamination by birds, rodents, amphibians and insects always occurs in natural environments. Though in these cases the meaning of current microbial criteria in terms of public health remains unclear, natural settings limit the quality of the effluents. Moreover, in temperate and cold climates, microbial decontamination in free water surface systems depends on the season, with lower performance in winter. Seasonal variations are much less marked in soil treatments. Low loads and deep vadose zones lead to very high microbial decontamination levels.

The efficiency of free water surface extensive technologies, particularly ponds and reservoirs, are dependent on meteorological conditions. Rainfall and evaporation result in differences between inlet and outlet flow rates. Tracer tests associated with records of climate parameters pointed to the key influence of temperature and wind on the hydrodynamic behaviour of ponds and the distribution of water detention times (Brissaud *et al.*, 2003). On the other hand, micro-organism die-off kinetics depends on temperature and solar radiation. Engineers are not accustomed to dealing with these contingencies; under-estimation of climate effects and poor understanding of hydrodynamics have contributed to the reputation of unreliability of the disinfection performances of extensive open systems.

Evaporation results in water losses inversely proportional to the water depth and proportional to the water residence time in free water surface bodies. Evaporation rate may reach values as high as 8.5 mm.day^{-1} and even more in arid regions. Therefore, it should be taken into account in pond design, particularly in those countries where evaporation is high and when treated water is to be reused in agriculture. Water losses can reach 20–30%, which results in a significant increase of salinity and tends to hamper water reuse in agriculture. Evaporation can be diminished through a reduction of the water detention time and water depth augmentation.

Potential adverse environmental impacts should not be underestimated when planning extensive wastewater treatment facilities. Odour nuisances and proliferation of offensive insects, such as mosquitoes and midges, may ruin valuable projects. In soil treatment systems, odour nuisance may occur when the applied wastewater remains at the soil surface for a long time, i.e. more than a few hours, after the application. This situation, which usually results from overloading or poor clogging control and is detrimental for the oxygen supply to the filter and the treatment efficiency, should be prevented through proper operation and management. In the case of underground distribution systems, odour nuisance can be due to aeration defects. Odour nuisances are likely to occur in ponds when sludge that has accumulated during the cold season starts being digested thanks to the Spring temperature increase. Offensive smells also result from temporary excess of organic load or from sludge accumulation. Several options can be taken to reduce the risk of offensive smells emitted by stabilisation pond systems (Copin *et al.*, 2004; Truppel *et al.*, 2005). One solution is to recirculate effluents from the second or third ponds to the inlet of the primary pond. An alternative solution consists in the mechanical aeration of the primary pond. Another option is to consider near desludging of the primary pond. Midge and mosquito proliferation can be fought against with either ecological methods (Kengne *et al.*, 2005) or pesticide spreading (Craggs *et al.*, 2005; Sweeney *et al.*, 2005).

Technology advances

Low technology systems face nowadays several challenges among which footprint reduction, enhanced discharged water quality requirements and better performance reliability and predictability seem the most important. Technology advances and recent research developments allow or are expected to allow us to face successfully these new objectives and assure the continuing development of natural wastewater treatment systems in various socio-economical contexts.

Footprint reduction

As the population is rapidly increasing in urban and sub-urban areas, land available at reasonable costs becomes every day scarcer. Therefore in these areas, plant footprint reduction will be a major asset in the competition between low technology and conventional systems. Several technological solutions have been proposed during the last decades. Thanks to small to moderate electric power consumption, facultative ponds can be replaced by high rate algal ponds – that can be part of Advanced Pond Systems (Craggs *et al.*, 2003) – or mechanically aerated ponds, thus reducing considerably the land surface required for pond systems. Introducing anaerobic ponds as a primary treatment stage has the same effect but does not require power supply; however, offensive smells are frequent in the neighbourhood of anaerobic ponds. As illustrated by Archer and Donaldson (2003), subdividing large ponds into smaller units may significantly improve the performance and save land surface. Another solution consisting in substituting vertical flow constructed wetlands for facultative ponds looks very promising.

Several attempts have been made to limit the land surface required by buried filters of on site domestic wastewater treatment systems. The recommended hydraulic load applied on sand filters should not exceed $0.03\,m^3\,m^{-2}$ per day for individual facilities and $0.05\,m^3\,m^{-2}\,d^{-1}$ for collective filters. This rather low load stems from three difficulties, the first one being to achieve a uniform distribution of wastewater at the surface of buried filters, the second the supply of oxygen and the third the management of clogging in confined and wet atmosphere. Several approaches allow increase of the hydraulic load. The first one consists in designing septic effluent distribution systems to provide a rather uniform spreading all over the filtrating beds; for this purpose it is highly recommended to feed the filter intermittently by pumping or using an automatic dosing batch, the flow rate being high enough to fill the distribution pipe network rapidly. Inserting distribution lines at the top of buried half pipes, as was proposed by the US EPA manual (2002) or similar systems lead to a more efficient and uniform use of the filters than the distribution through pipes inserted in gravel beds. Capillary forces in polyurethane sponge-like structures or geo-textile structures also improve water distribution over the filters. Half pipe leaching chambers and polyurethane and geo-textile structures provide for the circulation and renewal of the air over the filter, thus improving the oxygen supply, facilitating surface clogging management and allowing augmentation of the hydraulic load up to $0.13\,m^3\,m^{-2}\,d^{-1}$. The second approach consists in increasing the water content of the filter without diminishing the gas phase volume, which results in longer water detention time and increased treatment capacities. Different porous media have been tested successfully; it seems that hydraulic loads of $0.25\,m^3\,m^{-2}\,d^{-1}$ might be acceptable.

Enhanced requirements

Regulations and guidelines on the quality of treated wastewater either discharged in the environment or reused in irrigation or for other beneficial purposes, tend to become more stringent in many countries. More emphasis is put on the removal of nitrogen and phosphorus and on microbial decontamination. Treatment performance of low technology systems can be enhanced through either technological advances or combination of natural systems.

Though being already old concepts, baffles and rock filters should lead to considerable enhancement of pond system performance. Baffles can be designed on the basis of CFD modelling, which should improve their efficiency in the reduction of preferential pathways (Shilton and Mara, 2005). Rock filters are not that common in Europe. They have been used for years in the United States (Middlebrooks, 1995) and are part of current pond design in New Zealand (Archer and Donaldson, 2003). They are also used in Israel. A rock filter – the rock size being 40–80 mm – is a porous rock bed through which pond effluent travels, causing algae to settle out on the rock surfaces. Accumulated algae are then biologically degraded by bacteria growing on the biofilm wrapping on the rocks. In addition, significant ammonia removal and microbial decontamination can be achieved.

When microbial decontamination is at stake, innovative solutions such as the shallow ponds of Von Sperling and Mascarenhas (2005) and the batch operation of ponds and reservoirs (Juanicó and Dor, 1999) can provide high performance within relatively short detention times

Combining different natural systems, namely soil treatment and free water surface systems, offers the possibility to benefit from the advantages of each component of the treatment train. Though all possibilities have not yet been investigated, combining ponds and vertical flow constructed wetlands, infiltration percolation and horizontal flow constructed wetlands, vertical and horizontal flow constructed wetlands have proven to be effective.

Research

When the reliability of the natural systems stems essentially from their independency or low dependency on power supply, the simplicity of the electro-mechanical equipment and their buffer capacity – in the case of free water surface systems – performance prediction from the very design still needs to be improved. Low technology systems were originally based on empirical approaches. As these systems have successfully met the sanitation objectives of the communities they served, little need for scientific investigation was felt. Improving the reliability and predictability of extensive techniques as well as their performances requires not only technological innovation but also in-depth knowledge of the processes involved in the treatment and how they interact. Predicting the performance of a natural wastewater treatment systems demands that the relationships between the environmental and operation conditions and the quality of the final water are known. These relationships are expressed in the form of empirical or deterministic models. Models are often hybrid, partly empirical, partly deterministic. Though very helpful to the engineers, empirical models have several limitations; they cannot take all processes into account and they perform badly outside their calibration interval and when the implicit assumptions on which they have been elaborated are not verified. Deterministic models need the identification and mathematical expressions of the dominant mechanisms involved. This approach has been taken by Fritz *et al.* (1979) for the removal of nitrogen. However, while theory has been used since Marais (1974) and later developed by Mara and Pearson (1998) and others for the design of stabilisation ponds, most projects of soil treatment, constructed wetlands and even ponds are still designed on a purely empirical basis.

Stabilisation pond models combine theoretical water detention times with first order pollutant degradation kinetics. In fact, water detention times are highly dependent on meteorological conditions and therefore are not steady. Efforts are being made to calculate actual detention times as a function of the meteorological conditions through 3D CFD models. Expressing reaction kinetics in a deterministic form is hampered by the complexity of interactive processes occurring in free water surface systems; this is particularly true for microbial decontamination. For instance, light penetration in ponds, a key factor of algal photosynthesis, oxygen production and micro-organism inactivation, has not yet been completely elucidated, despite the results of recent research (Davies-Colley *et al.*, 2005; Heaven *et al.*, 2005).

Deterministic models of organic matter and nitrogen oxidation in soil treatment are available (Bancolé *et al.*, 2003). However, more calibration tests should be made, particularly as regards biomass development; thus a precious tool for clogging control would be available. Progress has been made in the understanding of the influence of the microbial ecosystem on bacterial indicator inactivation. Deterministic modelling of the transfer of micro-organisms, considered as colloids, in unsaturated porous media submitted to intermittent infiltration, is expected to allow more accurate predictions of microbial decontamination (Auset *et al.*, 2005).

Up to now, the approach of wastewater treatment in constructed wetlands has been mainly empirical. This might be due to the fact that a deterministic modeling has looked hardly feasible due to the introduction of plants rooted in the filters. However, more recently efforts are being made to characterize and model the hydraulics of these systems and, later on, the pollution degradation processes (Dittmer *et al.*, 2005; Schmid *et al.*, 2005).

Conclusion

Taking into account the economic situation of many countries, the development of economically sound sanitation strategies ensuring the protection of water resources, relies on (a) the availability of wastewater treatment techniques that meet disposal standards at low investment and O&M costs; (b) require low O&M skills and (c) are reliable. Thus, extensive technologies are likely to be preferred to intensive processes, particularly for those facilities that are to serve small and medium-sized communities. Investment costs of extensive wastewater treatment techniques are not much lower than those related to intensive technologies. Most low technology systems require large areas of available land and cannot be applied in areas that are too densely populated. However, extensive techniques do offer decisive advantages: very low O&M costs, easy O&M and high microbial decontamination potential.

Though technological innovation and transfers of recent research findings to engineering practice have enhanced the potential performances of these techniques, very stringent standards can hardly be met with high reliability. This is the case for health related criteria and also for nutrient removal. When the need for imposing very restrictive water quality criteria is demonstrated, combining low technology and conventional systems can be an option, particularly when a high microbial decontamination is required. As an example, combining infiltration percolation and ultra-violet irradiation is very effective and at a relatively low cost (Salgot *et al.*, 2002).

As many countries are now considering the equipment of small and middle-size communities, the future of natural systems looks promising, provided more care is taken of their design and operation than often observed. The current design of extensive treatment plants – consultants often use nothing more than a rule of thumb – should be improved to provide more predictable performances and reliable disinfection. These techniques should be taken into more consideration in the educational programmes of engineers and technicians.

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