Small Communities Decentralized Wastewater Treatment: Assessment of Technological Sustainability

A.G. Capodaglio*, A. Callegari*, D. Cecconet*, D. Molognoni*

* DICAr, University of Pavia, Via Ferrata 3, 27100 PAVIA, Italy, Email: capo@unipv.it

Abstract
In many Countries, small communities are required to treat wastewater discharges to increasing standards of lesser environmental impacts, but must achieve that goal at locally sustainable costs. While biological membrane treatment (MBRs) is quickly becoming the industry standard for centralized wastewater treatment plants, and would also be ideally suited also for small plants potentially subject to relatively large hydraulic load variations, its investment and operating costs are usually high for that class of applications. Consequently, small treatment plants are generally configured as anoxic or aerated biological tanks with little sedimentation, making them quite susceptible to hydraulic loads transient and sludge quality changes. As an alternative, Constructed Wetlands Systems (CWSs) are gradually and successfully being introduced in many Countries. CWSs are designed to utilise the natural functions of wetland vegetation, soils and their microbiological populations to treat wastewater. Pretreatment occurs by filtration and settling, followed by bacterial decomposition in a natural-looking lined marsh. A new technology, a new type of membrane-like aerobic reactor initially designed for the degradation of hydrocarbon-derived groundwater contaminants, was recently tested for treating domestic, with performance similar to that of MBRs. Examples from the above applications are illustrated and compared in this paper. The paper also discusses merits and drawbacks of the various illustrated technologies, in view of their sustainability potential, and according to the new development paradigms for urban water systems, that encourage the development of local water-cycle clusters with local reuse and recycle of the resource, and possible local recovery of energy and/or materials.

Keywords
Decentralized wastewater treatment, small communities, wetlands, membranes, BCR, MBR, UASB

INTRODUCTION

About half of the world population currently lives in rural areas. In the EU, almost 30% of the overall population of the former CEE (Central and Easter European) countries (42 million people) lives in settlements with less than 2,000 inhabitants, while the percentage is less than 20% in the western part. Many other areas of the world show a preponderantly rural character, although this tendency is slowly decreasing, due to the ongoing urbanization phenomenon. A large part of this population is still waiting for proper sanitation systems, or is aiming to improve the efficiency of existing ones and scale-up environmental protection and resources recovery. In most cases, centralized treatment systems for rural communities or peri-urban areas in low income countries would result in long-term debt burdens for the population (Parkinson and Tayler, 2003), therefore system decentralization appears as a logical solution to tackle the problem, as these facilities can usually be built to fulfil current needs and be expanded as need arise. Even in developed countries, cities are gradually losing their character of densely concentrated settlements and are gradually sprawling to the countryside: the urban area of Paris now counts over 11 million inhabitants (up from about 4.5 millions in the early 1900's) and extends well beyond the original urban administrative boundaries (over 17000 km^2 versus the *Ville de Paris*'s initial 2850 km*2*). In areas where construction of a sewage collection system is not considered economically viable, decentralization is becoming quite popular: as an example, 25% of the population in the US is already served by small, decentralised WWTPs (UNEP, 2002).
Sustainable decentralized sanitation focuses on on-site treatment and on recycling of resources contained in domestic wastewater, *in primis*, water itself. Other resources that can be readily

recycled are: bio-energy (from transformation of organic material), and nutrients (mainly nitrogen and phosphorus). Decentralisation could therefore contribute to the continuing progress and completion of the Millennium Development Goals, promoting environmental sustainability and reversing loss of environmental resources. This tendency will be more relevant in the next future, thanks to new global pressures towards water management paradigms change, from waste-oriented approach to resource-recovery and water reuse ones. Such a move to decentralized water management even in developed countries' urban areas, could be essential in order to improve system resiliency, efficiency, lost or diminished environmental functions, and resource recovery (Novotny and Brown, 2007). In this context, the term decentralized also qualifies systems serving small portions (clusters) of the urban area, according to hydrology, landscape and local ecology considerations.

With most of the developed world urban water infrastructure close or past its useful design lifespan (usually 50-60 years), and thus due to undergo substantial rehabilitation/refurbishment in the next decade, switching to smaller, cluster-base systems could not only be a sustainably-wise sensible solution, but, in the long term, a financially sound one, as well.

Decentralized Wastewater Treatment

Decentralized wastewater treatment (DWT) is used to treat and dispose, *at or near the source*, relatively small volumes of wastewater, originating from single households or groups of dwellings located in relatively close proximity (indicatively, less than 3 km maximum), not served by a central sewer system connecting them to a regional wastewater treatment plant (WWTP). DWTs still need a local collection system, yet this will be much smaller and less expensive than those used for conventional centralized treatment. DWT can be a sensible solution for communities of largely different sizes and demographics in countries at any level of development, but, like any other WWTP system, DWTs must be properly designed, maintained, and operated to provide optimal benefits. In general, almost all current wastewater treatment technologies could theoretically be applied into a decentralized setting, considering also that the definition of decentralized may vary in size from a few to a few thousand people served; not all of these technologies constitute, however, sensible choices. Advantages of DWTs are several: they can effectively and efficiently treat domestic sewage to protect health, water quality, and support local water supplies, since wastewater treated by decentralized systems is more likely to remain in the local watershed. Using decentralized systems may thus make it easier for a community to implement local water reuse schemes for nondrinking purposes, and hence reduce inappropriate demand for treated drinking water. Energy and resources local reuse can also be facilitated by such systems, sometimes in combination with other waste (e.g. organic solid) disposal facilities (Capodaglio et al., 2016a).

The simplest form of DWT consisted historically of a simple underground septic tank (cesspool), which both settled suspended solids, and achieved some degree of anaerobic digestion. In hot climates, septic tanks can remove up to 50% of the organic load of "normal strength" sewage, but usually they achieve little in the way of pathogen reduction, requiring post-treatment (adding cost and complexity to the system) to achieve environmental standards. In some Eastern EU Countries, this technology still supplies as much as 70% of wastewater processing, sometimes as a pre-treatment (Istenic et al., 2015; Boguniewicz and Capodaglio, 2016). As a result of strict EU legislation, existing infiltration or percolation system (sand/soil non-planted filters) formerly used as post-treatment for such installations, are gradually being dismissed in these countries.

Another common class of DWT systems are waste stabilization ponds, that include anaerobic ponds, facultative ponds (combining aerobic and anaerobic processes), and purely aerobic maturation ponds. The obvious advantage of pond systems is their simplicity, while another is the long retention times that favour pathogen abatement. Ponds could also produce secondary economic benefits, as maturation ponds may provide a good environment for growing fish, such as tilapia, which would be an advantage in rural, developing areas. Effluent from these ponds may have fairly high algae concentrations, so it is also good for irrigation, and minimize the level of nitrates entering the ground water. The main disadvantages of waste stabilization ponds is that they require relatively large land areas (US EPA, 2015). For this, and other reasons, more compact, aerobic DWT technologies have often been adopted where land availability is an issue.

Most decentralized systems take advantage of gravity flow, rather than pumping, may incorporate septic tanks at the source, resulting in reduced costs and energy demand, and can easily be scaled up to the needed size in communities with rapid growth, thus using wisely energy, money and land. Advanced DWTs can achieve treatment levels comparable to centralized wastewater treatment systems, and can be designed to meet specific treatment goals, handle unusual and peculiar site conditions, and address local environmental protection requirements. Therefore, DWTs mostly comply with new paradigms for sustainable urban development (Capodaglio et al., 2016b).

DWTs STATE OF THE ART TECHNOLOGIES

In addition to traditional Imhoff tanks and small activated sludge-based plants with sludge separation traps, several other process technologies are being preferentially developed, among all the available ones, for use in DWT systems. Applicability of these technologies may depend on the characteristics and climate of their proposed location: general climatic conditions, wastewater strength (dilution) and variability, land availability and local recycle/reuse requirements may strongly influence the feasibility or operational outcome of an installation. The main influencing factors in a DWT's technology choice are: treatment efficiency in that specific condition, low O&M requirements, operational reliability and future, gradual expansion possibilities, favourable economics.

Constructed wetlands

Constructed wetlands (CW) are being used throughout the world as DWT systems, with a diversity of design and operational features that can be adapted to treat domestic, agricultural and industrial (mostly agro-food) wastewaters. Use of CWs for small to medium size settlements is increasing sharply in Mediterranean countries due to favourable climatic conditions, although even in northern EU countries, such as Poland, Estonia and Lithuania, positive experiences with CWs have been reported (Mander et al. 2001). These systems, contrary to common prejudice, when properly designed and maintained, can be operated even under cold Baltic climate conditions with good treatment efficiency of organic substances.

Constructed wetlands have several inherent advantages compared to traditional systems, including: very low capital costs, less infrastructure, lower operating costs, simplicity of design and ease of operation. They include surface-flow, subsurface-flow, vertical-flow, and hybrid systems. In order to build facilities that combine the best concepts of the existing technology, multi-stage (hybrid) CW systems have been proposed, consisting of a succession of stages such as: primary treatment by Imhoff tank, 1st stage horizontal subsurface flow (HSSF) system, 2nd stage vertical subsurface flow (VSSF) system, and possibly additional HSSF/VSSF stages (Behrends et al., 2006). Such multiple stages systems are now becoming more common, due to their higher tolerance to flow, load and waste characteristics variations, and their generally lower footprint. Multi-stage CWs have shown to provide excellent secondary and tertiary treatment for municipal and domestic wastewater with variable operative conditions in small-to-medium size installations (500–5000 P.E.), in different climates. An eventual final, open, shallow-water stage may also be adopted, to enhance effluent oxygenation prior to discharge, and provide solar UV disinfection.

CWs offer reliable and steady removal of TSS and organic matter (in the long-term, over 97%), allowing to obtain very low concentrations in the effluent both in low and high inlet concentrations situations. Removal of nutrients has been observed at about 70-86% for ammonia, and 60-70% for Total N, with unit area (U.A.) requirements as low as 1.5 to 2 m^2/P.E. in warm climates (like Italy and Spain). In cold climate countries (e.g., Poland, Estonia, Lithuania) the required U.A. ranges usually from 5-12 m^2/P.E. Reported operating costs are quite low, about 0.1€ /m^3 treated wastewater, with construction costs related for the most part to the land surface needed (Masi et al., 2013).

Membrane Biological Reactors

One of the most promising technologies capable of fulfilling current wastewater treatment requirements in traditional facilities are biologic membrane filtration processes, usually called Membrane Bio-Reactors (MBRs). MBR technology integrates biological degradation of wastewater pollutants with membrane filtration, ensuring effective removal of organic and inorganic contaminants and biological material from domestic and/or industrial wastewaters, and has become a proven alternative to traditional activated sludge systems. The filtration component (in MBRs, pore size is typically < 1 µm) dispenses the need for gravity clarification of the effluent, that could constitute a critical treatment bottleneck in small systems under highly varying hydraulic loads and even induce process failure (Capodaglio, 2002). Use of membrane systems in decentralized treatment of household (domestic) wastewater was described by several researchers (Meuler et al., 2008; Blstakova et al., 2009; Pikorova et al., 2009; Chong et al. 2013). MBRs, when properly operated, have also shown the capability to effectively remove nutrients and, to some degree, micropollutants, from a waste stream (Abegglen et al., 2008).
Generally, treatment of residential wastewater by MBR systems would produce effluent with non-detectable TSS, BOD concentration (less than 2 mg/L), ammonia-nitrogen concentration of less than 0.5 mg/L, fecal coliform count of less than 20 per 100 mL and, with proper design, total nitrogen concentration of less than 5 mg/L. MBR application to domestic wastewater can remove more than 96% COD, 90% TSS and 90% TN. Application to segregated domestic wastewaters (black, with COD_{ave} 1220 mg/l, and grey, with COD_{ave} 250 mg/l) from a housing neighbourhood showed removal efficiencies greater than 96% COD, 99% TSS, 89% TN and 100% coliforms for black water treatment, and greater than 95% COD, 94% TSS, 92% TN and 100% coliforms for grey water treatment, with specific energy demands of 2.3 and 1.7 kWh/m^3 treated wastewater, respectively (Atasoy et al., 2007).
Comparative advantages with respect to traditional treatment techniques include smaller footprint, high loading rate capabilities, modularity and disinfected/highly clarified effluent immediately suitable for reuse. Consequently, MBR technology could play a prominent role in DWT systems. Limitations inherent to these processes are the cost of membranes themselves, high maintenance and energy requirements, and the progressive loss of filtration capacity due to medium fouling.

Non-membrane, biomass retention systems

A technology quite similar to MBRs, consisting of a reactor with suitable filters for biomass separation, was proposed by Capodaglio and Callegari (2016c), after successfully testing it with poorly-treatable organic contaminants (Capodaglio et al., 2010, Capodaglio and Callegari, 2015). The Biomass Concentrator Reactor (BCR) consists of an aerobic reactor vessel, in which a mixed liquor formed by wastewater (in this case, domestic) and biomass is kept in suspension by means of fine bubble aeration, positioned at the bottom of the vessel. The treated effluent is filtered by a membrane-like medium, with pore size of about 20 µm for solids separation purposes, just like a MBR. In this case, however, due to the coarser characteristics of the filter, effluent filtration occurs by gravity only with a maximum head loss in the order of 2-3 cm.
Laboratory tests with these systems showed average COD removal efficiencies of 93-97% In the

same tests, specific flux through the membrane was approximately constant at 22 L/m^2-d, a very low value compared to the rated filter capacity. Consequently, the filtration capacity of the membrane remained substantially constant during the tests and no backwashing became needed. It has been observed that similar systems with gravity flow can sustain continuous operation for up to 1 year without incurring in operatively dis-habilitating fouling (Zhang et al., 2006). This is contrary to similar trials conducted with actual membranes (pore size 0.1 μm) in similar conditions, where the medium filtration capacity decreased by 77% after just 3 months, requiring membrane sostitution and/or regeneration (Pikorova et al., 2009).
The system, similarly to MBRs, can be modified to achieve nitrogen removal. Such systems have shown to achieve 95-97% COD and 75-79% N removal, figures absolutely comparable to those of MBRs (Scott et al, 2013).

Anaerobic digestion systems: UASBs

Today, anaerobic digestion is traditionally used to process residual sludge from large centralized WWTPs, allowing energy recovery in the form of biogas. Anaerobic digestion, however, was originally the first technology used for DWTs, in the form of septic tanks (i.e.: Imhoff tanks), with poor treatment performance (usually 30-50% COD and 60% TSS). More modern forms of anaerobic digestion are currently considered an attractive, sustainable and suitable technology for on-site wastewater treatment due to their low energy consumption, relatively small space requirement and simple reactor design. As no oxygen is needed, the high costs of aeration are avoided, and sludge handling costs are dramatically lower, as the production of sludge is 3–20 times lower than in aerobic systems. Although efficiency and effectiveness of anaerobic processes are enhanced by a more concentrated substrate and higher operating temperature, better suited to take advantage of the lower process kinetics characteristic of anaerobes, these processes are actually applicable to many types of wastewater and environmental conditions, even to diluted wastewater at low process temperatures.
Today, UASB (Upflow Anaerobic Sludge Blanket) systems are among the most used high-rate anaerobic digesters for treatment of wastewaters. Originally developed for industrial wastewater treatment (Lettinga et al., 1983), UASB design required several adaptations for practical application with domestic wastewater, that has typically lower COD concentrations. This resulted in lower methane production, insufficient to heat the process reactors to the more favourable mesophilic temperature range (35-45^{o}C). Full scale UASB applications initially showed excellent results under tropical conditions (T > 20-25°C), with COD removal efficiencies around 75% at 6 h HRT (van Haandel and Lettinga, 1994). UASB are nowadays widely used in Brasil and other countries in South America, India, Indonesia and Egypt due to low construction and operational costs (Kalogo and Verstraete, 2000), even though their nutrient removal capability is very low.
UASB application at lower temperatures is feasible, in these conditions however, low hydrolysis rates were found to cause deterioration of the overall anaerobic reactor performance. Soluble COD can be efficiently converted to methane at temperatures as low as 5°C but, for successful application of anaerobic treatment of domestic sewage under such conditions, incoming suspended solids must be separated from the waste stream before entering the methanogenic reactor, by purely physical pre-treatment (i.e., primary clarifiers, or mesh filtration), or by applying a sequence of two sequential reactors in series, in which the first is designed to entrap and (partly) hydrolyse solids, or by providing surface area for biomass attachment and growth in the reactor above the sludge blanket (Lew et al, 2004). In these conditions, biogas generation diminishes considerably with decreasing temperature, and about 50% of it may escape the system with the effluent (Uemura and Harada, 2000), making its recovery unprofitable, save for local use of small isolated communities. This, however, is of secondary importance compared to the general economic benefits of the process under these terms, somehow undermining the intrinsic merits of anaerobic processes as

energy recovery technologies, consisting of low initial investment, low energy for operation, lower sludge production and easier maintenance than conventional aerobic processes. Table 1 summarizes experimental results from UASB applications to domestic wastewater treatment.

Table 1. Summary of UASB application in decentralized domestic WW treatment

Temperature (^oC)	HRT (hrs)	COD removal (%)	TSS removal (%)	Source
13-15	10-11	54-58	75-85	Alvarez et al, 2005
30	8	85	-	Behling et al, 1997
20	10-48	60-75	-	Singh, Viraravaghan, 1998
8-40	8	65-85	65-85	Khan et al. 2015
17	48-96	74-78	51-54	Jamal & Mahmoud, 2009
10-28	6	42-78	-	Lew et al., 2011
30-35	10	54-72	-	Mahmoud, 2008
25-30	9	79-81	-	Rizvi et al., 2015
24	48-96	81-82	56-58	Shayad & Mahmoud, 2008

SUSTAINABILITY ISSUES

Sustainability, although not explicitly mentioned in the relevant EU or national legislation, it is key to implement wastewater systems. The main objectives of these systems are to protect and promote human health by providing a clean environment and breaking the cycle of disease. The "most appropriate technology" in any situation is the one that turns out to be economically affordable, environmentally protective, technically and institutionally consistent and socially acceptable for the specific application. In other words, sustainable. When improving an existing and/or designing a new sanitation system, sustainability criteria related to the following aspects should be considered:

(1) Health and hygiene: minimizing risk of exposure to pathogens and hazardous substances that could affect public health from the toilet to the point of disposal (or reuse);
(2) Environment and natural resources: considering energy, water and other resources required for construction and operation, as well as potential emissions resulting from use. This should include the degree of recycling and re-use practiced and their effects (e.g. returning water, nutrients and organic material to agriculture), and the protection of other non-renewable resources (e.g. production of renewable energy, like biogas);
(3) Technology: maximizing functionality, and ease with which the entire system can be constructed, operated and monitored by local utilities. Its robustness and vulnerability towards power cuts, water shortages, floods, etc., and flexibility/adaptability to existing infrastructure and demographic or socio-economic developments are also important aspects;
(4) Financial and economic issues: relating to the capacity of households/communities to pay for the system, including construction, operation, maintenance and necessary reinvestments;
(5) Socio-cultural and institutional aspects: socio-cultural acceptance, convenience, perception, impact on human dignity, compliance with the legal framework and institutional settings must be considered.

From the purely economic viewpoint, any affordable technology could find application almost anywhere; however, for a system to be environmentally sustainable, it must ensure protection of environmental quality, conservation of resources, and allow reuse of water as well as recycling of nutrients and resources. Understanding the receiving environment is crucial for technology selection and should be accomplished by conducting comprehensive site evaluation processes, with determination of the carrying capacity of the receiving environment. Generally speaking, decentralized treatment schemes would allow tighter, more natural-like water-use cycles without

long-distance flow transfer, less water bodies depletion and minimizing effluent-domination phenomena, reducing both ecological and hydrological negative impacts of anthropic water use.
Social acceptance is also a critical factor in the selection process. Centralised systems are already accepted as a *de-facto* necessity by the public, who is aware that treatment processes are continuously ongoing "out of sight" under the supervision of an authority in charge of their management. This is not always so clear-cut in decentralized systems. In case of very small systems, it is the end user(s) who is in charge of management, and probably wish not to be. Decentralized systems generally require more awareness, involvement and participation from local residents. Decentralized systems may be however be very well accepted by residents when clearly made aware of their objectives and advantages, including economical ones. In a few EU countries (Germany, The Netherlands) demonstrative decentralized systems serving up to 1000 people have been implemented in urban areas with positive results. As an additional score point, decentralized WWTPs are generally compact, with highly flexible operating conditions, and reduced aesthetic impact.
Sustainable decentralized sanitation strong points are on-site treatment and recycling of resources contained in domestic wastewater. Centralised systems satisfy the demand of highly populated areas, but do not fit with these new expectations (paradigms). At the moment, the new concept of "City-of-the-future" could strongly favour decentralisation.

Decentralized vs. Centralized

In traditional systems, household discharge streams are combined and transported by an extended sewer systems, to a centralised WWTP. Hence, to collect and treat wastewater, centralized wastewater treatment requires more pumps, longer pipes and more energy than decentralized ones, therefore increasing the infrastructure cost of the system. About 80-90% of capital costs in such systems are related to the collection system itself, with some economy of scale in densely populated areas. Wastewater treatment cost per unit volume in centralized systems is competitive compared to decentralisation where a wastewater collection system already exists, however, it is estimated that any collection system (whole or of part of it) needs to be renewed every 50-60 years, besides the required periodic maintenance. Decentralized systems respond well to suburban areas, rural centres, industrial, commercial and residential areas development changes, as well as to population growth in rural areas and developing countries, since infrastructure investments can be gradual and put in place as needed. Decentralization may be quite helpful in the case of large block redevelopment in metropolitan areas with sewage collection systems, since local treatment and reuse of wastewater can limit the strain of additional discharges into the existing sewer, that may disrupt or overwhelm or service during peak load events.
Conventional wastewater management is also based on a disadvantageous approach, depending on high water flows, and thus waste dilution, for its continued operation. This not only increases the cost of treatment diluted wastewater requires more expensive (due to larger volumes) and less energy-efficient treatment approaches, but also increases operational costs for users, since relatively large volumes of drinking water, requiring significant pumping effort, are usually employed for transporting waste and flushing the system periodically. It has been estimated that by enacting source control and differential water usage, new decentralized technologies could manage wastewater systems with just around 20% of the current drinking water demand (Otterpohl et al, 2002).
Further diseconomies of scale are possible where long distances have to be covered by the collection system, or as a consequence of ground/rainwater infiltration, or both, requiring considerable additional pumping energy. Strong dependency on electrical energy supply for pumping might put these systems at risk in economic/political crisis times, making the system poorly resilient in such instances. In addition, heavy rainfall events or contamination by industrial

wastewater may generate overflow phenomena, impairing ecological status. to water resources transfer and creation of effluent-dominated water bodies, eutrophication phenomena may occur in receiving water body due to the large volumes of treated wastewater discharged at centralized WWTP outlet points. Decentralized system, on the other hand, tend to lessen degradation effects of surface water quality and reduce eutrophication events (Brown et al., 2010).

The cost of the more advanced process technologies in DWTs is rapidly becoming comparable to that of centralisation per unit of treated organic load (this is usually lower if low-tech, low-impact technologies are selected), also considering that small WWTPs can now be easily remotely controlled, facilitating their O&M. In the past, the lack of reliable monitoring technology constituted a serious obstacle to the adoption of DWT systems, often resulting in intensive personnel requirements and unreliable treatment results. The now common availability of reliable remote monitoring technology, dramatically reduces such requirements, allowing remote-control of distant facilities and demand-actuated on-site maintenance when needed (Capodaglio et al., 2016d).

Decentralization separates domestic wastewater and rainwater, avoiding dilution phenomena, and could allow additional solutions such as source separation, extremely difficult to implement in centralized systems, reducing dispersion of micropollutants such as metals, and other emerging compounds (e.g. pharmaceuticals and personal care products) in the environment. Also, potential contamination of reusable nutrients and sludge by these compounds could be greatly reduced (Libralato et al., 2011). Separation of contaminants eases their treatment efficiency, saves energy and enhances potential reuse.

It is evident that adoption of DWT strategies is not in direct contrast with centralised ones, in fact, highly dense populated areas in developed countries are historically served by extended sewage collection systems and centralised WWTPs. In these cases, decentralisation would not represent an immediately suitable and viable economic alternative, and a balanced approach would consist of supporting the coexistence between centralised and satellite decentralised systems, especially in the case of new large developments such as residential and commercial complexes, hospitals, where treated wastewater reuse could be effectively planned.

Decentralized technological options

Some of the most common decentralized technologies have been illustrated in the previous sections. Table 2 summarizes sustainability-related considerations for each of these.

Furthermore, from a technological point of view, while introducing DWTs, concomitant separation of black water (possibly jointly with kitchen waste), and grey water would maximize the total recycling potential of the local system: these wastes, representing a small volume of the overall flow, contain the largest fraction of COD and nutrients of domestic wastewater, and also the almost totality of pathogens and micropollutants. It is an established principle that concentrating treatment needs to a smaller volume with higher loads enables better and more efficient control, and can limits negative environmental effects. A high concentration of black water would make anaerobic treatment with subsequent nutrient recovery a very attractive option. Sewage concentrations in these cases could be as high as 10000 mg/l COD (if using vacuum toilets technology) and reach easily 3000 mg/l using extremely low-flush devices. With these concentrations, UASB technology would generate enough biogas to warrant its recovery. Post-treatment will be still required for anaerobic effluent to fulfil standards for reuse or discharge (especially pathogens).

DWT implementation barriers

Besides factors such as land availability (in particular, for constructed wetlands), costs and environmental requirements, that can be overcome with the choice of a more suitable DWT, several non-technological barriers stand before a wider implementation of DWT systems in developed countries. Somewhat unsurprisingly, DWTs are more readily accepted in developing countries, since no technological pre-existence, favourable economics and the influence of younger, more novelty-prone engineers (local or from ONGs) all favour that choice.

In developed countries, mostly pre-existing centralized settings and traditional engineering approaches favoured by senior public-system water technologists are the main obstacles to a more general diffusion of DWT systems. Often, economics "*it would cost too much to change the entire system*", of lack of specific consolidated experience "*it is not feasible/acceptable by the users, it won't work*, *it cannot possibly be done*" and fear of unknown/undetermined problems are brought up as irrefutable reasons as why system design must go on unchanged. The promoters of decentralized wastewater treatment systems are mainly among progressive young professionals, who have difficulty getting these concepts accepted by decision makers and traditional wastewater professionals with a "Business as Usual" mentality. It is also possible that the odd, old decentralized system had been either inappropriately dimensioned, was born technologically obsolete, or had been hampered by ineffective operation and maintenance, and is still pointed as an example of a bad idea, regardless of the number of existing successful examples reported nowadays.

Table 2. Sustainability-related issues with most common DWT technologies

DWT	Health & Hygiene	Environment & Resources	Technology	Financial	Socio-cultural & Institutional
Constructed Wetlands	May be set up for solar disinfection (post-treatment)	Natural engineered systems. Energetically almost neutral. Good compatibility with sparsely populated locations. No resources recovery (but possible vegetation harvesting)	Easy to operate. High robustness and low vulnerability to crises. High adaptability if physically possible to expand. High water loss in hot climates.	Investment cost mostly for land plot. Operation close to free if gravity flow possible.	Acceptance good if "out of the way" and not causing nuisance. Possible poor institutional understanding (non standard practice)
Aerobic Conventional	Require post-treatment	Energy intensive. Current mainstream technology. Possibility of tertiary recovery of nutrients (struvite) and energy from sludge	Relatively easy to operate with remote control. Medium robustness and vulnerability (power cuts, discharge toxicity). Expandability possible at medium-high costs. Suitable for cheaper "package" construction for smaller facilities.	High investment and O&M costs (energy and sludge management).	Acceptance depending on location and past experience. Possible nuisance from odours. Well accepted institutionally.
MBR Aerobic	May be suitable for reuse without post-treatment	Very energy intensive. Smaller footprint than aerobic conventional. Higher efficiency. Possibility of tertiary recovery of nutrients.	More complex operation, with fouling problems in time. Robust towards flow and load variations, vulnerable to power cuts (medium), less to toxicity. Expansion requires high investments. Suitable for cheaper "package" construction for smaller facilities.	Highest investments and O&M (increased energy, but less sludge to manage)	Acceptance depending on location and past experience. Possible nuisance from odours. Accepted with cost-concerns institutionally
Aerobic Filtration	Will likely require post-treatment	Energy intensive (aeration). Footprint comparable to MBRs, similar efficiency.	Operation simpler than MBRs. Other conditions similar, lower investment for expansion. Suitable for cheaper "package" construction for smaller facilities.	Higher investment but O&M lower than MBRs. (less energy and sludge to manage)	Acceptance depending on location and past experience. Possible nuisance from odours. Accepted with cost-concerns institutionally
UASB	Require post-treatment	Anaerobic technology can be energy neutral or positive (biogas generation in the presence of strong wastes). Possibility of post-recovery of nutrients.	Relatively easy to operate at optimal conditions. Robust towards flow/load variations, vulnerability low. Expansion at medium cost. Suitable for cheaper "package" construction for smaller facilities.	Medium investment, Low O&M, sludge and effluent management. Possible high revenue from biogas recovery.	Acceptance depending on location and past experience, considering likely nuisance from odours. Cost-recovery (energy) enhances institutional support.

CONCLUSIONS

Decentralized or cluster wastewater treatment systems designed to operate at small scale, not only can reduce the effects of wastewater disposal on the environment and public health, but may also increase the ultimate reuse of wastewater, depending on community type, technical options and local settings. However, when both centralized and decentralized systems are viable, the “most appropriate technology” should be selected, case-by-case, as the one that is economically affordable, environmentally sustainable and socially acceptable; management strategies should also be site specific.

Implementing decentralised technologies could give planners a chance to consider whether to also introduce source separation (urine/black water, and possibly grey water) systems toilet or other extreme water saving systems (very low flush/vacuum) in order enhance resources and energy recovery. Furthermore, in view of the necessity to reconstruct/refurbish/upgrade current centralised systems due to ageing, planners could find of interest to speculate upon alternatives to traditional wastewater treatment modes, possibly supporting the coexistence of various degrees of centralisation/decentralisation (satellite systems).

Currently, there is a good level of knowledge regarding implementation and performance of DWTs at the experts’ and scientific levels, however, technological transfer into practice is still insufficient, and low awareness and recognition of DWTs benefits and a “business as usual” mentality still persist at the institutional and administrative levels.

REFERENCES

Abegglen Ch., Ospelt M., Siegrist H. (2008) Biological nutrient removal in a small-scale MBR treating household wastewater, *Wat Res.* 42 (1), pp. 338-346.

Alvarez J.A., Ruiz I., Gomez R., Presas J., Soto M. (2006) Start-up alternatives and performance of an UASB pilot plant treating diluted municipal wastewater at low temperature. *Biores Tech*, 97(14), pp. 1640–1649

Atasoy E., Murat S., Baban A., Tiris M. (2007) Membrane Bioreactor (MBR) Treatment of Segregated Household Wastewater for Reuse. *Clean*, 35 (5), pp. 465 – 472

Boguniewicz J., Capodaglio, A.G. (2016) On-Site Decentralized Wastewater Treatment in Poland: Current Status and Perspectives. Submitted to Polish Journal of Environmental Studies

Behling E., Diaz A., Colina G.a, Herrera M., Gutierrez E., Chacin E., Fernandez N., Forster C.F. (1997) Domestic wastewater treatment using a UASB reactor. *Biores Tech*, 61(3), pp. 239-245

Behrends L. L. , Bailey E., Jansen P, Houke L. Smith S. (2006) Integrated constructed wetland systems: design, operation, and performance of low-cost decentralized wastewater treatment systems. *Proceedings, 7th IWA Specialty Conference on Small Water and Wastewater Systems, Mexico City*, Mexico March 7-10, 2006

Blstakova A., I. Bodík, Dancova L., Jakubcova Z. (2009) Domestic wastewater treatment with membrane filtration - two years’ experience. *Desalination* 240, pp. 160-169

Brown, V., Jackson, D.W., Khalifé, M. (2010) 2009 Melbourne metropolitan sewerage strategy: a portfolio of decentralised and on-site concept designs. *Wat Sci Tech*. 62, pp. 510-517.

Capodaglio A. (2002). Wet-weather transient impacts on wastewater treatment. *In:* R. Arsov (Ed.), *Urban Water Management*. Kluwer Academic Publishers B.V. , DORDRECHT

Capodaglio A.G., A. Callegari (2009). A new reactor for biological treatment of compounds from hydrocarbon sources in groundwater. *Proceedings, IWA MTC 2009 5th Specialized Conference on Membrane Technology for Water and Wastewater IWA*. 1-3 September, Beijing, Cina,

Capodaglio A.G., Suidan M, Venosa AD, Callegari A. (2010) Efficient degradation of MtBE and other gasoline-originated compounds by means of a biological reactor of novel conception: two case studies in Italy and the USA. *Wat Sci Tech*. 61(3), pp. 807-12

Capodaglio A.G. and Callegari A. (2015) Onsite Management of Tanker ships' Rinse Water by Means of a Compact Bioreactor. *Wat Prac Tech*, 10(3)
Capodaglio A.G., Callegari A, Lopez M.V. (2016a) European Framework for the Diffusion of Biogas Uses: Emerging Technologies, Acceptance, Incentive Strategies, and Institutional-Regulatory Support. Sustainability, 8(4), pp. 298-315
Capodaglio A.G., P. Ghilardi, J. Boguniewicz-Zablocka (2016b) New paradigms in urban water management for conservation and sustainability. *Wat Prac Tech*, Vol 11(1), pp.176-186
Capodaglio A.G. and Callegari A. (2016c) Domestic Wastewater Treatment with a Decentralized, Simple Technology Biomass Concentrator Reactor. *Journal WaSH*, Vol. 6(2) (Available Online 8 July 2016, washdev2016042)
Capodaglio A.G., Callegari A., Molognoni D, (2016d) Online monitoring of priority and dangerous pollutants in natural and urban waters: A state-of-the-art review. *Manag Envir Qual Int Jou*, 27(5), pp. 507-536
Chong M.N., A. N. M. Ho, T. Gardner, A. K. Sharma and B. Hood (2013) Assessing decentralised wastewater treatment technologies: correlating technology selection to system robustness, energy consumption and GHG emission. *Jou Wat Clim Ch*, 04(4), pp. 338-347
Gajewska M., Jóźwiakowski K., Ghrabi A., Masi F. (2015) Impact of influent wastewater quality on nitrogen removal rates in multistage treatment wetlands. *Env Sci Poll Res*, 22(17), pp 12840-12848
Khan A.A., Mehrotra I., Kazmi A.A. (2015) Sludge profiling at varied organic loadings and performance evaluation of UASB reactor treating sewage. *Biosys Eng*, 131, pp 32–40
Kalogo, Y. and Verstraete, W. (2000). Technical feasibility of the treatment of domestic wastewater by a CEPS-UASB system. *Env. Tech.*, 21, pp. 55–65.
Istenic D., Bodík I., Bulc T. (2015) Status of decentralised wastewater treatment systems and barriers for implementation of nature-based systems in central and eastern Europe. *Env Sci Poll Res*, 22, pp. 12879–12884
Jamal W., Mahmoud N. (2009) Community onsite treatment of cold strong sewage in a UASB-septic tank. *Biores Tech*, 100, pp. 1061–1068
Lettinga, G., Roersma, R. and Grin, P. (1983). Anaerobic treatment of raw domestic sewage at ambient temperatures using a granular bed UASB reactor. *Biotech. Bioeng.*, 25, pp.1701-1723
Lew B., Tarre S., Belavski M., Green M. (2004) UASB reactor for domestic wastewater treatment at low temperatures: a comparison between a classical UASB and hybrid UASB-filter reactor. *Wat. Sci. Tech.*, Vol 49(11–12), pp 295–301
Lew B., Lustig I., Beliavski M., Tarre S., Green M. (2011) An integrated UASB-sludge digester system for raw domestic wastewater treatment in temperate climates. *Biores Tech*, 102(7), pp. 4921–4924
Libralato G., Volpi Ghirardini A., Avezzù F, (2011) To centralise or to decentralise: An overview of the most recent trends in wastewater treatment management. *Jou Env Manag*, 94, pp. 61-68
Mahmoud N. (2008) High strength sewage treatment in a UASB reactor and an integrated UASB-digester system. *Biores Tech*, 99, pp. 7531–7538
Mander U., Kuusemets V., Öövel M., Mauring T., Ihme R., Pieterse A.J. (2001) Wastewater purification efficiency in experimental treatment wetlands in Estonia. *In:* Vymazal J. (ed.) *Transformations of nutrients in natural and constructed wetlands*. Backhuys Publishers, Leiden, pp. 201–224
Masi F., Caffaz S., Ghrabi A. (2013) Multi-stage constructed wetland systems for municipal wastewater treatment. *Wat Sci Tech*, 67(7), pp. 1590-1598
Matulova, Z.; Hlavinek, P.; Drtil, M. (2010) One-year operation of single household membrane bioreactor plant. *Wat Sci, Tech.*, 61(1) pp. 217-226
Meuler S., Paris S., Hackner T. (2008) Membrane bio-reactors for decentralized wastewater treatment and reuse. *Wat Sci Tech*, 58(2)

Molinos-Senante M., M. Garrido-Baserba, R. Reif, F. Hernández-Sancho, M. Poch (2012) Assessment of wastewater treatment plant design for small communities: Environmental and economic aspects. *Sci Tot Env*, 427–428, pp.11–18

Novotny V. and Brown P. (Eds) (2007) *Cities of the Future: towards integrated sustainable water and landscape management.* IWA Publishing, London

Otterpohl R., Braun U., Oldenburg M. (2002) Innovative technologies for decentralised wastewater management in urban and peri-urban areas. *Proceedings, 5th Specialised Conference on Small Water and Wastewater Treatment Systems* Istanbul-Turkey, 24-26 September

Parkinson, J., Tayler, K. (2003) Decentralized wastewater management in peri-urban areas in low-income countries. *Envir Urbaniz*, 15 (1), pp. 75–90

Pikorova T., Matulova Z., Hlavinek P., Drtil M. (2009) Operation of household MBR WWTP - operational failures. *In:* P. Hlavinek et al. (eds.), *Risk Management of Water Supply and Sanitation Systems,* Springer Science+Business Media B.V.

Rizvi H., Ahmad N., Abbas F., Bukhari I.H., Yasar A., Ali S., Yasmeen T., Riaz M. (2015) Start-up of UASB reactors treating municipal wastewater and effect of temperature/sludge age and hydraulic retention time (HRT) on its performance. *Arabian Jou Chem*, 8, pp. 780–786

Scott D., Hidaka T, Campo P, Kleiner E, Suidan MT, Venosa AD. (2013) Biological nitrogen and carbon removal in a gravity flow biomass concentrator reactor for municipal sewage treatment. *Chemosphere*. 90(4), pp.1412-8.

Shayah M. Mahmoud N. (2008) Start-up of an UASB-septic tank for community on-site treatment of strong domestic sewage. *Biores Tech*, 99(16), pp. 7758-66

Singh K.S. and Viraravaghan T. (1998) Start-up and operation of UASB reactors at 20C for municipal wastewater treatment. *J. Ferment Bioeng*, 85, pp. 609-614

Vymazal J. (2013) The use of hybrid constructed wetlands for wastewater treatment with special attention to nitrogen removal: A review of a recent development. *Wat Res*, 47(14-15)

UNEP (2002) *Environmentally Sound Technologies for Wastewater and Stormwater Management: an International Source Book.* IWA Publishing and UNEP - International Environmental Technology Centre, London and Osaka. http://www.unep.or.jp

U.S. EPA (2015) http://water.epa.gov/infrastructure/septic/upload/MOU-Intro-Paper-081712-pdf-Adobe-Acrobat-Pro.pdf. Accessed June 2015

Van Haandel, A.C. and Lettinga, G. (1994). *Anaerobic sewage treatment. A practical guide for regions with hot climate*. John Wiley and Sons Ltd., Chichester, England., 226 p.

Uemura S, Harada H. (2000) Treatment of sewage by a UASB reactor under moderate to low temperature conditions. *Biores Tech*, 72, pp. 275-282

Wang B., S. He, L. Wang and L. Shuo (2005) Simultaneous nitrification and de-nitrification in MBR. *Wat Sci Tech*, 52(10-11), pp 435–442

Wu H., Zhang J., Ngo H.H., Guo W., Hu Z., Liang S., Fan J., Liu H. (2015) A review on the sustainability of constructed wetlands for wastewater treatment: Design and operation. *Biores Tech*, 175, pp 594–601

Zhang Q., Suidan M.T., Zhang K., Oerther D.B.,Venosa A.D. (2006) Comparison of biomass selection between a novel membrane bioreactor and activated sludge process. *WEFTEC Proceedings*, Dallas, TX, pp. 5030-5037