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D22.1 GUIDELINES FOR PACKAGED PLANT SELECTION AND OPTIMISATION

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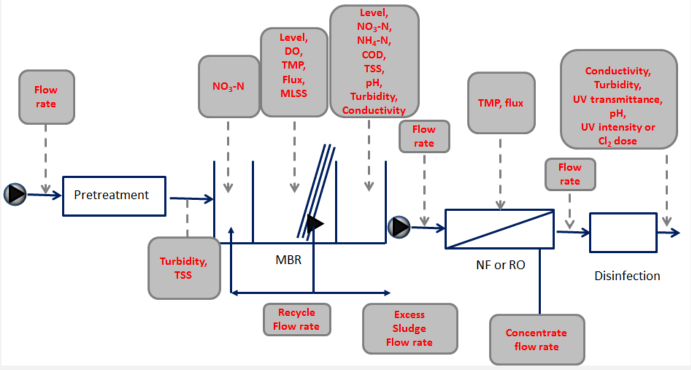
TITLE OF THE REPORT

D22.1: GUIDELINES FOR PACKAGED PLANT SELECTION AND OPTIMISATION

SUMMARY

Deliverable D22.1 is part of Task 22.1 of DESSIN Project which is related to Distributed Reuse in large urban areas. More specifically, D22.1 focuses on new membrane solutions and technologies in the form of modular packaged treatment solutions (MPTS). The treatment level required is determined by the specific quality objectives for unrestricted urban wastewater reuse, identified in the relevant national legal framework, whereas different capacities of MPTS are designed at preliminary level accompanied by technical and operational considerations.



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List of Acronyms and Abbreviations

DALYs	Disability adjusted life years
EDCs	Endocrine – disrupting compounds
EPS	extracellular polymeric substances
JMD	Joint Ministerial Decree
MBR	Membrane Biological Reactor
MF	Microfiltration
NF	Nanofiltration
PhACs	Pharmaceutically active compounds
QMRA	Quantitative microbial risk
RO	Reverse Osmosis
TMP	Trans-membrane pressure
UF	Ultrafiltration
US EPA	Environmental Protection Agency
UV	Ultraviolet radiation
WHO	World Health Organisation

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Executive summary

Deliverable D22.1 is part of Task 22.1 of DESSIN Project which is related to Distributed Reuse in large urban areas. More specifically D22.1 focuses on new membrane solutions and technologies in the form of modular packaged treatment solutions (MPTS). The treatment level required is determined by the specific quality objectives for unrestricted urban wastewater reuse, identified in the relevant national legal framework, whereas different capacities of MPTS are designed at preliminary level accompanied by technical and operational considerations.

More specifically in chapter 1, Water reuse considerations in an urban environment are discussed with main focus on the water reuse criteria established by different organisations including WHO, US EPA, California State and the Greek Ministry of Environment. These criteria are related to urban water reuse which is distinguished to unrestricted and restricted, according to the relevant provisions in regulations in force. In general water reuse guidelines and regulations are directed principally at public health protection. For non-potable reclaimed water applications, criteria generally address only microbiological and environmental concerns, whereas health risks associated with both pathogenic microorganisms and chemical constituents need to be addressed where reclaimed water is to be used for potable water supply augmentation. Chapter 2 deals with small scale membrane wastewater treatment systems with emphasis on the criteria for the selection of appropriate treatment train. For the needs of DESSIN project, compact wastewater treatment solutions are investigated that relate to the fact that the water reclamation plant is located close to potential applications such as agricultural irrigation and recreational enhancement. These solutions include biological treatment with subsequent filtration through the use of Membrane Biological Reactors, followed by and advanced membrane treatment with reverse osmosis and disinfection. In this chapter the principles of MBR, NF and RO are also discussed under the prism of the applicability in relation to the effluent requirements. The process design calculations for the selected treatment scheme and for two typical design flows are presented in chapter 3. The design assumptions considered include design influent data (flows and typical concentrations), treatment performances, design criteria, technical description and process calculations. Chapter 4 presents the operational considerations related to membrane systems where the issues of fouling, maintenance and monitoring of operation are discussed. Chapter 5 highlights the results of a benchmark analysis which aimed to provide rules for the optimization of the operation of the proposed membrane wastewater treatment system. Finally the more important conclusions are summarised in Chapter 6.

1 Water reuse considerations in an urban environment

BOX 1: WORKING TERMINOLOGY as per Metcalf & Eddy, 2007

The terminology frequently used in the field of wastewater reuse is mainly derived from sanitary and environmental engineering practice. The terms used are mentioned below:

Beneficial uses: *The many ways that water can be used, either directly by people or for their overall benefit.*

Potable reuse, direct*: The introduction of highly treated reclaimed water either directly Into the potable water supply distribution system downstream of a water treatment plant, or into the raw water supply immediately upstream of a water treatment plan.*

Potable reuse, indirect*: The planned incorporation of reclaimed water into a raw water supply such as in potable water storage reservoirs or a groundwater aquifer, resulting in mixing and assimilation, thus providing an environmental buffer.*

Non-potable reuse: *All water applications that do not involve either direct or indirect potable reuse.*

Planned water reuse: *Deliberate direct or indirect use of reclaimed water, without relinquishing control over the water during its delivery.*

Potable reuse, direct: *The introduction of highly treated reclaimed water either directly into the potable water supply distribution system downstream of a water treatment plant, or into the raw water supply immediately upstream of a water treatment plant.*

Potable reuse, indirect: *The planned incorporation of reclaimed water into a raw water supply such as in potable water storage reservoirs or a groundwater aquifer, resulting in mixing and assimilation thus providing an environmental buffer.*

Sewer mining: *The process of tapping into a sewer main and extracting wastewater locally, which can then be treated in a satellite treatment and reused for beneficial purposes.*

Urban water reuse: *Types of water reuse applications include landscape irrigation in urban settings, air conditioning, fire protection, toilet and urinal flushing, water features, commercial car washing and laundries and dust control at construction sites.*

Water reclamation: *Treatment or processing of wastewater to make it reusable with definable treatment reliability and meeting appropriate water quality criteria.*

Water recycling: *The use of water that is captured and redirected back into the same water use scheme such as in industry.*

Water reuse: *The use of treated wastewater for a beneficial use.*

Emerging contaminants*: Constituents, which have been identified in water, that are being considered for regulatory action pending the development of additional information on health and the environmental impacts.*

Endocrine – disrupting compounds (EDCs)*: Synthetic and natural compounds that mimic, block, stimulate, OR inhibit natural hormones in the endocrine systems of animals, including humans. The origins of EDCs include pesticides, pharmaceutically active chemicals (PhACs), personal care products (PCPS), herbicides, industrial chemicals, and disinfection by-products.*

Pharmaceutically active compounds (PhACs)*: Chemicals synthesized for medical purposes (e.g. antibiotics).*

Pathogens*: Disease-causing organisms capable of inflicting damage on a host it infects.*

Public health*: The science and practice of protecting and improving the health of a community through preventive medicine, health education, control of communicable diseases, application of sanitary measures, and monitoring of environmental hazards.*

1.1 Rationale and possibilities

As environmental pressures increase and many communities throughout the world are approaching or reaching the limits of their available water supplies it is not surprising that in addition to conventional water and wastewater treatment processes, water reclamation and reuse has become an attractive option for conserving and extending available water supplies. Today, technically proven wastewater treatment or water purification processes exist to provide water of high quality that can meet the stricter quality standards. Irrigation, water for industrial use, urban non-potable and potable water and groundwater recharge, are some example applications of reclaimed wastewater use.

The concept of deriving beneficial uses from reclaimed municipal and industrial wastewater, has inherent benefits associated with the preservation of higher quality water resources, environmental protection, and economic advantages. Nevertheless, to optimize these benefits from implementation of wastewater reuse, a well – designed, integrated planning is essential. Therefore, effort should be given in sectors such as: rational water quality and economics management; public health; environmental and ecological aspects; socio - cultural aspects; water storage; conjunctive use of surface water and groundwater; public involvement; conflict in decisions and in daily practice; flexibility to cope with climatic or other changes in water supply; regional rather than local approaches; sustainability.

Reclaimed water may be used for non-potable purposes, substituting for the high quality water that otherwise would be used for the same purpose; offering a potential for exploiting a new source of water. The quantity of pollutants in wastewater is only a few hundreds ppm's, thus making it "more than 99,9% pure" (Hermanowicz and Asano, 1998). Taking also into account that the large majority of water supplied to urban population is ending up as a wastewater stream, makes the water recycling and reuse within urban environment a feasible opportunity.

Reclaimed water is a "water resource substitute" developed within the limits of the urban environment where water resources are needed the most and priced the highest. The idea of "Source substitution" was initially derived from the main concept of the United Nations Social and Economic Council policy (1958) (Hermanowicz and Asano, 1998): *"No higher quality water, unless there is a surplus of it, should be used for a purpose that can tolerate a lower grade."* Inasmuch as only about 15% of water used in urban areas is required to be of potable water quality, a policy of wastewater reclamation for non-potable use makes sense. This policy is now beginning to see a rapid growth throughout the world.

In the planning and implementation of water reclamation and reuse, the reuse application will usually govern the wastewater treatment needed and the degree of reliability required for the treatment processes and operations. The reuse applications can be distinguished in two main categories: non-potable and potable, each one having subcategories:

Non-potable reuse: Urban • Industrial • Agricultural • Habitat restoration/enhancement and recreational • Groundwater recharge

Potable reuse: Direct • Indirect

Within the framework of DESSIN project **urban** is the water reuse option under consideration that can be distinguished to unrestricted and restricted, according to the relevant provisions in regulations in force. The use of reclaimed water for various non-potable purposes within an urban area commonly includes landscape irrigation and urban non-irrigation uses.

Landscape irrigation is being used for various locations including golf courses, parks, residential areas, roadway medians and roadside plantings and cemeteries. Reclaimed water for landscape irrigation has to meet higher water quality levels for suspended solids and microbial concentrations, as compared to some agricultural applications, whereas many of physical and chemical characteristics of the reclaimed water in landscape applications are similar to those for agricultural use. The main constraints during application include controlling of residual disinfectants, public acceptance, public health concerns, runoff and aerosol control.

Urban non irrigation uses cover a wide variety of applications including air conditioning cooling water, fire protection, toilet and urinal flushing, ornamental water features, and road care and maintenance. Commercial uses of reclaimed water such as a car washing and commercial laundries are practiced typically in urban areas and they are considered as non-irrigation uses. Water needs for most urban non-irrigation water reuse applications are small and generally multiple water reuse applications are implemented including landscape irrigation. High quality and well disinfected reclaimed water must also be maintained to ensure public health protection. The main constraints during application include cross connection with potable water, public acceptance, public health concerns, scaling, corrosion, fouling and biological growths.

1.2 Environmental and public health considerations

Water reuse guidelines and regulations are directed principally at public health protection. For non-potable reclaimed water applications, criteria generally address only microbiological and environmental concerns, whereas health risks associated with both pathogenic microorganisms and chemical constituents need to be addressed where reclaimed water is to be used for potable water supply augmentation.

Regarding landscape irrigation, water quality requirements and operational controls may differ depending on the area being irrigated, its location relative to populated areas and the extent of public access or use of grounds. Irrigation of areas not subject to public access have limited potential for creating public health problems, while the need to reduce the level of pathogens becomes more important as the expected level of direct or indirect human contact with reclaimed water increases. Trace constituents such as PhACs and EDCs may be present in the irrigation water, resulting to increased concerns mainly due to their accumulation potential in turf and soil to health significant levels and possibility of being ingested inadvertently or contacted by children.

The use of area controls need to be imposed at open access landscape irrigation sites as an added safety precaution to protect the public who visits the irrigation sites. Useful controls may include signs warning the public that the area is irrigated with reclaimed water, protecting drinking water fountains from direct contact with the irrigation water, eliminating the potential for ponding of reclaimed water, confining the reclaimed water and spraying and irrigating only during off-hours.

Less common uses of reclaimed water include street cleaning, dust control, soil compaction, making concrete, decorative fountains, commercial car washes, fire protection systems, etc. It is advisable that each application is evaluated on a case-by-case basis, however there are some common regulatory considerations including the level of human contact and the potential environmental impacts. In these cases the expected degree of human contact determines the appropriate level of disinfection. Minimal disinfection is needed for uses where there is little or no expected human contact with the water, whereas uses such as vehicle washing are likely to result in contact, thus a higher level of disinfection is required.

The environmental considerations of a proposed water reuse project are sometimes more important than cost considerations, while public participation and support is an important ingredient in the successful implementation.

1.3 Regulations and Guidelines

1.3.1 WHO

Over the years the World Health Organization (WHO) has provided guidance for the safe use of water, starting with a 1973 report recommending health criteria and treatment processes for various wastewater applications. The 1973 criteria were revised in 1989 and more recent a third edition of the WHO Guidelines has been published in 2006 (WHO 2006).

In general the WHO guidelines are significantly less restrictive than water reuse regulations or earth-based target guidelines adopted by various states in the US. The intention of WHO to encourage the reuse of wastewater in agriculture should be regarded in relation to the significance and applicability of the agricultural use of reclaimed wastewater in developing countries compared to other reuse applications. In its first effort to stipulate guidelines for wastewater reuse (1973), WHO covered a much wider range of reuse applications. For non-potable urban reuse and contact recreation, secondary treatment followed by sand filtration and disinfection were recommended. However, the health criteria differed in that for the urban reuse only a general requirement for effective bacteria removal and some removal of viruses was specified, while for contact recreation a bacterial standard of not more than 100 coliform/100mL in 80% of samples and the absence of skin-irritating chemicals were specified. It is however interesting to view these precedent recommendations in relation to the 1989 guidelines which although referring exclusively to irrigation uses of wastewater they are based on a restricted-unrestricted type of reuse concept and are considerably less restrictive (1000 fecal coliform/100mL for unrestricted irrigation and 200 fecal coliform/100mL for irrigation of parks). For indirect portable reuse, secondary treatment followed by filtration nitrification, denitrification, chemical clarification, carbon adsorption, ion exchange or membranes and disinfection were recommended. However, based on actual filed experience at some existing full-scale and demonstration stabilisation pond systems, it has been found that the desired reductions of helminths and fecal coliform organisms may be difficult to achieve in practice (Metclaf and Eddy, 2007).

The 2006 Guidelines was an extensive update of the previous two editions expanded to include new scientific evidence and contemporary approaches to risk management. The WHO Guidelines are intended to be used as the basis for the development of international and national approaches (including standards and regulations) to managing the health risks from hazards associated with wastewater use in agriculture and aquaculture as well as providing a framework for national and local decision making.

In the 2006 Guidelines, three types of evaluations were used to assess risk: microbial and chemical laboratory analysis, epidemiological studies and quantitative microbial risk assessment (QMRA). Health based targets define a level of health protection that is relevant to each hazard and may be based on a standard metric of disease such as a disability adjusted life years (DALYs) (e.g. 10^{-6} DALYs). Usually a health based target can be achieved through a combination of health protection measures targeted at different components of the system to achieve the tolerable risk of 10^{-6} DALYs. The WHO's health-based target for wastewater reuse in agriculture is shown in Table 1.

Table 1: **Health-based targets for wastewater use in agriculture**
Source: WHO (2006)

Exposure scenario	Health-based target (DALY per person per year)	Log pathogen reduction needed	Number of helminth eggs/L
Unrestricted irrigation	≤10^{-6}		
Lettuce		6	≤1
Onion		7	≤1
Restricted irrigation	≤10^{-6}		
Highly mechanized		3	≤1
Labor intensive		4	≤1
Localised (drip) irrigation	≤10^{-6}		
High growing crops		2	No recommendation
Low growing crops		4	≤1

The health based targets for rotavirus are based on QMRA conclusions to the pathogen reduction required to achieve 10^{-6} DALY for different exposures. For helminth infections epidemiological evidence was used, showing that infections could not be demonstrated at wastewater used in irrigation with less than 1 helminth egg/L. Figure 1 shows pathogen reductions achieved by several option for combining wastewater treatment and other health protection measures to achieve ≤10^{-6} DALY per person per year.

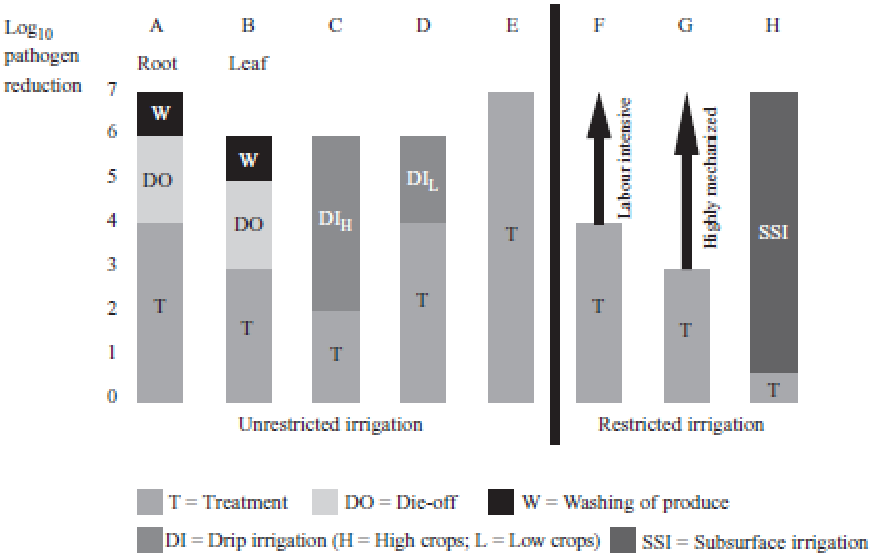

Figure 1: Examples of options for the reduction of viral, bacterial and protozoan pathogens by different combinations of health protection measures (WHO, 2006)

The options in Figure 1 represent examples of combinations of health protection measures that can achieve the health based target in practice, whereas other combinations are also possible since planners and designers of wastewater use schemes may wish to explore and/or use a variety of health protection measure combinations that are locally feasible to implement.

1.3.2 US EPA

In 1992 the US EPA published Guidelines for water reuse, holding the position that national water reuse standards were not necessary and comprehensive guidelines with flexible state regulations would foster increased considerations and implementation of water reuse projects. The guidelines were updated in 2004 to include technological advances and recent research data. The guidelines address various aspects of water reuse and include recommended treatment processes, reclaimed water quality limits, monitoring frequencies and other information depending on the water reuse application.

For non-potable uses of reclaimed water, two different levels of treatment are recommended. Reclaimed water used for applications where no direct public or worker contact with the water is expected should receive at least secondary treatment and should be disinfected to achieve a fecal coliform concentration not exceeding 200/100 mL. The reasoning for this limit is based on the fact that most bacterial pathogens will be destroyed or reduced to low or insignificant levels in the water; the concentration of viable viruses and parasites will be reduced somewhat; disinfection of secondary effluent to this coliform level is readily achievable at minimal cost; and significant health-related benefits associated with disinfection to lower, but not pathogen-free, levels are not obvious.

It is noted however that for reuse applications such as surface irrigation of orchards and vineyards or restricted irrigation of non-edible crops that even California regulation prescribes primary treatment as the minimum accepted level of treatment, EPA suggests that some level of disinfection should be provided to avoid adverse health consequences from inadvertent contact or accidental or intentional misuse of reclaimed water. On the other hand the same level of treatment and quality requirements (200/100mL and secondary treatment-disinfection) refers to reuse applications (food crop spray irrigation and non-food crop irrigation) that in California regulation fall under far more stringent requirements (2.2/100mL or 23/100 ml total coliforms).

For uses where direct or indirect contact with reclaimed water is likely or expected, and for dual water systems where there is potential for cross-connections with potable water lines, high level disinfection to produce reclaimed water having no detectable fecal coliform organisms/100mL is recommended. This more restrictive disinfection level is intended to be used in conjunction with tertiary treatment (secondary treatment, filtration, disinfection) and other water quality limits such as turbidity less than 2 NTU in the wastewater prior to disinfection, considering the close association of pathogens with the particulate matter that can shield both viruses and bacteria from disinfectants, in order to ensure adequate level of particulate matter removal and consequently effective distraction of viruses during disinfection.

US EPA recommends both reclaimed water quality limits and wastewater treatment unit processes for the following reasons: water quality criteria involving surrogate parameters alone do not adequately characterize reclaimed water quality; a combination of treatment and quality requirements known to produce reclaimed water acceptable quality obviate the need to monitor the finished water for certain constituents; expensive, time-consuming, and in some cases, questionable monitoring for pathogenic microorganisms is eliminated without compromising health protection; and treatment reliability is enhanced.

The guidelines include limits for fecal coliform organisms, but do not include parasites (such as helminths) or virus limits. Parasites have not been shown to be a problem at reuse operations in the U.S. at the treatment levels and reclaimed water limits recommended in the guidelines, although there has been considerable interest regarding the occurrence and significance of *Giardia* and *Cryptosporidium* in reclaimed water. Where filtration and a high level of disinfection are recommended, the guidelines indicate that it may be necessary to provide chemical addition prior to filtration to assure removal or inactivation of parasites and viruses.

While viruses are a concern in reclaimed water, virus limits are not recommended in the guidelines for the following reasons (US EPA, 1992): a significant body of information exists indicated that viruses are inactivated or removed to low or immeasurable levels via appropriate wastewater treatment; the type of concentration of viruses in wastewater are difficult to determine accurately because of low virus recovery rates; there are limited number of facilities having the personnel and equipment necessary to perform the analyses; the laboratory analyses can take as long as 4 weeks to complete; there is no consensus among public health experts regarding the health significance of low level of viruses in reclaimed water; and there have not been any documented cases of viral disease resulting from the reuse of wastewater in the US.

For non-potable urban uses of reclaimed water, the guidelines recommendations include *inter alia* clear, colourless, odourless product water and maintenance of a minimum residual chlorine concentration of 0.5 mg/L in the distribution system, as well as treatment reliability and emergency storage or disposal of inadequate treated water and colour coded or tapped reclaimed water lines and appurtenances.

The suggested guidelines for wastewater treatment and reclaimed water quality are presented in Table 2.

Table 2: US EPA Suggested guidelines for reuse of municipal wastewater – Urban reuse Source: Metcalf & Eddy (2007)

Types of reuse	Reclaimed water quality	Treatment
Landscape irrigation, vehicle washing, use in fire protection and other uses with similar access or exposure to the water.	pH = 6-9 $BOD_5 \leq 10$ mg/L Turbidity ≤ 2NTU Fecal coliform/100 mL – not detectable Residual chlorine ≥ 1 mg/L	Secondary Filtration Disinfection
Soil compaction, dust control, washing aggregate, making concrete	$BOD_5 \leq 30$ mg/L TSS ≤ 30 mg/L Fecal coliform – 200/100mL Residual chlorine ≥ 1 mg/L	Secondary Disinfection
Landscape impoundments	$BOD_5 \leq 30$ mg/L TSS ≤ 30 mg/L Fecal coliform – 200/100mL Residual chlorine ≥ 1 mg/L	Secondary Disinfection

According to these guidelines, secondary treatment processes include activated sludge, trickling filters, rotating biological reactors, and may include stabilization pond systems. In any case secondary treatment should produce effluent in which both BOD and SS do not exceed 30 mg/L. Filtration in conventional filters is acceptable (sand and/or anthracite), as well as microfilters and membrane technology. Regarding disinfection, this may be accomplished by chlorination, ozonation, other chemical disinfectants, UV radiation, membrane processes or other processes. It is clearly stated in the guidelines, that the use of chlorine as defining the level of disinfection does not preclude the use of other disinfection processes as acceptable means of providing disinfection for reclaimed water. Total chlorine residual should be met after a minimum contact time of 30 min.

It is also notable that the turbidity limit should be met prior to disinfection and should not exceed 5 NTU at any time, whereas as previously noted chemical (coagulant and/or polymer) addition prior to filtration may be necessary to meet water quality recommendations. The recommended coliform limit is median value, whereas the number of fecal coliform organisms should not exceed 14/100mL in any sample, in order to increase safety when contact with reclaimed water is likely.

1.3.3 State of California

The state of California has a long history in wastewater reuse and was the first to issue the relevant regulations in 1918. Since then the regulation has undergone modifications and has been extended to its basic form, as from 1978, and is the basis for the criteria for reuse not only for this state but for the whole USA and other countries in the world. The microbiological criteria and the related treatment schemes (Table 3) are not based so much on epidemiological studies, but relate to an effort to minimise the theoretical dangers arising from wastewater reuse. The basic parameter considered is the possibility of human exposure to the reused wastewater, a parameter that regulates the degree of danger. Thus, in an indirect way there is recognition of the difference between restricted and unrestricted reuse.

Table 3: Criteria for non-potable uses of reclaimed wastewater in the state of California Source: Crook (1998)

Type of water use	Total Coliform limits	Treatment required
Irrigation of fodder, fibre, and seed crops orchards and vineyards, and processed food crops; flushing sanitary sewers	None required	Secondary
Irrigation of pasture for milking animals, landscape areas (cemeteries, freeway landscaping, restricted access golf courses, and other controlled access irrigation area), ornamental nursery stock, and sod farms; landscape impoundments; industrial or commercial cooling water where no mist is created; non-structural fire fighting; industrial boiler feed; soil compaction; dust control; cleaning roads, sidewalks, and outdoor	23/100 mL (7-day median) 240/100 mL (30-day max)	Secondary Disinfection
Surface irrigation of food crops; restricted landscape impoundments	2.2/100 mL (7-day median) 23/100 mL (30-day max)	Secondary Disinfection
Irrigation of food crops and open access landscape areas (parks, playgrounds, schoolyards, residential landscaping, unrestricted access golf courses, etc.); non restricted recreational impoundments, toilet and urinal flushing; industrial process water; decorative fountains; commercial laundries; snow-making; structural fire fighting; industrial or commercial cooling where mist is created	2.2/100 mL (7-day median) 23/100 mL (30-day max)	Secondary Coagulation Filtration Disinfection

During the restricted irrigation of non-edible crops, animal feed and in cases of orchards and vineyards, there are no microbiological criteria imposed, whereas the minimum treatment requirement is secondary treatment (without disinfection). In the California regulation and for the category of restricted irrigation there is more differentiation referring to pastures, irrigation of edible crops, irrigation of stadiums, golf courses, cemeteries etc., and for certain categories of artificial lakes, where an even small possibility of contact with pathogens is recognised. In these cases, the microbiological criteria expressed in terms of average values of total coliforms, range from 2.2/100 mL to 23/100 mL and the suggested treatment is based on biological treatment with greater or less intense disinfection (usually with chlorine). In the case of unrestricted reuse (including unrestricted irrigation) with the expected possibility of direct contact, the regulation requires that wastewater is practically free of pathogens limiting the average value of total coliforms to 2.2/100 mL and to 23/100 mL as the maximum value. On first observation, these limits do not seem to differ much from those of the previous category (2.2/100 mL as an average value), however, the recommended scheme of treatment (which includes apart from biological treatment additional tertiary treatment with flocculation, sedimentation, filtration and disinfection) clearly suggests advanced treatment that aims to remove almost all types of viruses.

Due to the close associations of pathogens with the particulate matter which can shield both viruses and bacteria from disinfectants, turbidity standard is induced to ensure adequate level of particulate matter and consequently effective destruction of viruses during the disinfection process. For uses when direct human contact is likely (unrestricted urban use, spray irrigation) turbidity should not exceed 2 NTU on a continuous monitoring base. This target value is not required if the turbidity of the influent to the filters does not exceed 5 NTU more than 15 minutes and never exceeds 10 NTU and there is capability to automatically activate chemical addition.

The reclamation criteria apart from water quality standards and treatment process requirements include treatment reliability requirements. The reliability requirements address standby power supplies, alarm systems, multiple or standby treatment process units, emergency storage or disposal of inadequately treated wastewater elimination of treatment process bypassing, monitoring devices and automatic controls and flexibility design.

1.3.4 Australia & New Zealand

Since 1992, National Water Quality Management Strategy (NWQMS) is applied on Australian and New Zealand waterways, as a joint national approach to improve their water quality. In the context of NWQMS, a number of documents are released to provide guidelines for use of reclaimed water.

According to Guidelines for Sewerage System and water recycling, the treatment process used and the resulting water quality, combined with on-site controls, determine the range of acceptable uses available for recycled water (NWQMS, 2000; NWQMS, 2006; RMCG, 2012). Thermotolerant coliforms are recommended as general indicators of microbiological reclaimed water quality (NWQMS, 2000), and depending on the quality and water reuse alternative, treatment options are prescribed. In Table 4 a brief summary of the Guidelines is provided.

Table 4: Criteria for uses of reclaimed wastewater according to Australian National Recycling Guidelines (Radcliffe, 2004).

Type of water use	Thermotolerant Coliform limits	Other parameters	Treatment required
• Indirect potable groundwater recharge by spreading or injection. • Municipal with uncontrolled public access. • Residential non- potable. • Raw human food crops in direct contact with reclaimed water eg via sprays, irrigation of salad vegetables.	<10 org/100 ml (median)	Turbidity: ≤2NTU (mean), 5NTU (max) pH 6.5-8.5 (90 percentile). Cl_2 residual:>1mg/1 after at least 30 minutes contact time or equivalent level of pathogen destruction. Consider salinity controls.	Tertiary with pathogen reduction. May need nutrient reduction for groundwater recharge.

Type of water use	Thermotolerant Coliform limits	Other parameters	Treatment required
• Indirect potable (surface water). • Crops to be consumed raw but no in direct contact with reclaimed water (edible product separated from contact with effluent e.g. by peel or use of trickle irrigation or crops sold to consumers cooked or processed. • Pasture and fodder for dairy animals without withholding period. • Drinking water for all stock except pigs.	<100 org/100 ml (median)	PH: 6.5-8.5 (90 percentile)	Secondary With pathogen reduction. Indirect potable (surface water) should comply with raw drinking water standards.
• Raw human food crops not in direct contact with reclaimed water, or crops sold to consumers peeled, cooked or processed. • Pasture and fodder for grazing animals (except pigs and dairy animals) with 4 hr. withholding period. • Pasture and fodder for dairy animals with 5 day withholding period. • Municipal with controlled public access (4 hr. withholding period). • Ornamental water with no contact and restricts access. • Mines, dust suppression.	<1000 org/100 ml (median)	PH: 6.5-8.5 (90 percentile)	Secondary Treatment and pathogen reduction
• Silviculture, turf, cotton etc. with 4 hour withholding period. • Aquaculture- non- human food chain. • Stream augmentation.	<10.000 org/100 ml (median)	PH: 6.5-8.5 (90 percentile) For aquaculture, salinity TDS < 1.000 mg/L, <10% change in turbidity (seasonal mean conc.), May need dissolved oxygen controls for fish, zooplankton.	Secondary Treatment and pathogen reduction (Pathogen reduction is site-specific for streams as required)

1.3.5 Europe

One of the most important parameters that restrict the reuse of wastewater within the European Union is the absence of a common legal framework, while the only general reference is made in the Directive 91/271 of the European Union (EU) stating (Article 12, paragraph 1): “Treated wastewater shall be reused, whenever appropriate.”

The main difficulty in regulating a uniform statutory scheme lies with the uneven distribution of the available water resources. At the beginning of 1990, a series of droughts that occurred throughout Europe, the most severe experienced in Spain during 1991-95, affected the agriculture and the population significantly. In 1995, serious drought occurred in England with problems in agriculture and the water supply network. Moreover, various long-term climate change models predict an increase in rainfall in wetter areas and a decrease in drier areas together with changes in weather patterns. The Mediterranean countries are characterised as areas of high risk, this giving an early warning for the necessity of improving the management of the water resources in these areas. In that context, wastewater reuse appears as an attractive solution mainly in southern Europe, but also in France and even in the UK.

The Communication "Blueprint to safeguard Europe's water resources" highlighted water reuse “as a concrete and valid alternative supply option to address water scarcity issues”. With maximisation of water reuse as a specific objective, the Commission identified the opportunity to develop a legislative instrument for water reuse. (E.C., 2017b).

Supporting this policy development, an impact assessment study was prepared and published in 2015. The report includes a description of the problem definition and of the baseline situation regarding water reuse in the EU, and elaborates on policy options. Another support study is currently on-going in order to refine these initial findings.

To inform this impact assessment, the European Commission organized a Public Consultation on Policy Options to optimise Water Reuse in the EU in autumn 2014. As well as, an on-line consultation, a stakeholders meeting was organised in December 2014 in Brussels. (E.C., 2017b).

Also, a technical workshop on possible minimum quality requirements on water reuse at EU level was organised by DG ENV and JRC in June 2015.

A dedicated activity on water reuse is now included in the CIS work programme for 2016 - 2018 to accompany the development of related actions by Member States and the Commission (E.C., 2016b).

At the moment, Commision is committed to develop a number of actions to promote further uptake of water reuse at EU level. According to Action Plan:

Guidelines on Integrating Water Reuse into Water Planning and Management in the context of the WFD have already published, contaning recommendations on how to better integrate water reuse in water planning and management within the EU policy framework and taking into account underlying environmental and socio-economic benefits (E.C., 2016a).

An Inception Impact Assessment has been already published which sets out in greater detail the background, the policy objectives and options as well as their likely impacts (E.C., 2017a).

Establishment of water reuse criteria at European Union level is going to be in full compliance with the requirements of EU legislation, as: the Water Framework Directive (2000/60/EC), the Urban Wastewater Treatment Directive (91/271/EEC), the Sewage Sludge Directive (86/278/EEC), the Nitrates Directive (91/676/EEC), the Groundwater Directive (2006/118/EC), the Thematic Strategy for Soil Protection (Com(2006) 231), the Drinking Water Directive (98/83/EC), the Bathing Water Directive (2006/7/EC), the Freshwaters Fish Directive (2006/44/EC), the Shellfish Waters Directive (2006/113/EC), the Habitat Directive (92/43/EEC), the Birds Directive (2009/147/EC), the Industrial Emissions Directive (2010/75/EU), the Environmental Quality Standards Directive (2008/105/EC) and the EU food safety regulations (Alcalde, 2014).

However, several Member States have produced their own frameworks in their national legislation. These are: Cyprus, France, Greece, Italy, Portugal and Spain (Alcalde, 2014). Below, there is a short description of the applied standards in Cyprus, France, Greece and Spain.

1.3.5.1 Cyprus

The relative national legislation of Cyprus is consisted by Law 106/2002 for “Water and Soil pollution control“ and its associated regulations and by the General Administrative Orders: KDP 772/2003 and KDP 269/2005[1].

The table below presents the required quality objectives, for different irrigation products (Table 5).

Table 5: Example of criteria for uses of reclaimed wastewater for irrigation according to KDP 269/2005 in Cyprus

Type of irrigation	BOD$_5$	SS (mg/L)	E.Coli (/100mL)	Eggs of intestinal warms	Treatment required (Kamizoulis et al, 2005)
All crops and green public zones (unrestricted) (c)	10[a]	10[a]	5[a] -15[b]	0	Secondary- tertiary and disinfection
Vegetables[d]	10[a] -15[b]	10[a] -15[b]	50[a] -100[b]	0	Secondary- tertiary and disinfection
Crops for human, green public zones (restricted)	20[a] -30[b]	30[a] -45[b]	200[a] - 1000[b]	0	Secondary, storage >1 week and disinfection or tertiary and disinfection. Stabilization maturation ponds total reten tion time >30 d or secondary and storage >30 d
Fodder crops	20[a] -30[b]	30[a] -45[b]	1000[a] - 5000[b]	0	Secondary and storage >1 week or tertiary and disinfection. Stabilization maturation ponds total retention time >30 d or secondary and storage >30 d or secondary and storage > 30 d
Industrial crops	50[a] -70[b]	-	3000[a] - 10.000[b]	-	Secondary and disinfection. Stabilization maturation ponds with total retention time >30 d or secondary and storage >30 d

[a] These values must not be exceeded in 80% of samples per month.
[b] Maximum value allowed.
[c] Irrigation of leaved vegetables, bulbs, and corns eaten uncooked is not allowed.
[d] e.g potatoes.

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[1] http://www.psb.org.cy/index.php/en/file/rZyoDPlArnihGYAsl9Rd6A==/

1.3.5.2 France

The standards of France are included as regulation in the national legislation through JORF num. 0153/4.07.2014, an Order related to the use of water from treated urban wastewater for irrigation of crops and green areas (exclude industrial uses, urban uses and aquifer recharging).

JORF 0153/2014 lays down the required quality objectives, establishing 4 levels of treatment which are defined by a set of maximum acceptable values for a series of parameters relevant to different water uses (Table 6).

Table 6: Example of criteria for uses of reclaimed wastewater according to Annex II & Annex III of JORF 0153/2014.

Type of irrigation	TSS	COD	E.Coli (/100mL)	F.enterococci (log)	Sulphate-reducing bacteria (log)	F- Specific bacteriophages (log)
vegetable crops, fruit and vegetable without industrial heat treatment, green public zones	<15	<60	≤ 250	≥ 4		
vegetable crops, fruit and vegetable with industrial heat treatmentFresh fodder, flowers for sell, pasture	Depends on the end use		≤ 10.000	≥ 3		
Irrigation to tree crops, Other cereal crops and forage, Nurseries, other shrubs and flower crops			≤ 100.000	≥2		
Irrigation to brush areas						

1.3.5.3 Greece

One of the most important parameters that restrict the reuse of wastewater within the European Union is the absence of a common legal framework, while the only general reference is made in the Directive 91/271 of the European Union (EU) stating (Article 12, paragraph 1): "Treated wastewater shall be reused, whenever appropriate."

The difficulties in regulating a uniform statutory scheme could be noted in the significant differences between the WHO guidelines and the California regulation. More specifically, an important parameter for the absence of a European legislation lies with the uneven distribution of the available water resources. At the beginning of 1990, a series of droughts that occurred throughout Europe, the most severe experienced in Spain during 1991-95, affected the agriculture and the population significantly. In 1995, serious drought occurred in England with problems in agriculture and the water supply network. Moreover, various long-term climate change models predict an increase in rainfall in wetter areas and a decrease in drier areas together with changes in weather patterns. The Mediterranean countries are characterised as areas of high risk, this giving an early warning for the necessity of improving the management of the water resources in these areas. In that context, wastewater reuse appears as an attractive solution mainly in southern Europe, but also in France and even in the UK.

In 2011 Greece adopted a comprehensive legal framework for wastewater reuse through the Greek Joint Ministerial Decree 145116/2011 on "Establishment of measures, conditions and procedures for the reuse of treated wastewater and other provisions". This relatively new framework aims to a) promote the use of treated wastewater and through this saving water resources, which will contribute significantly to addressing the impact of: i) the increasing scarcity and drought in the Mediterranean region and the expected worsening of the problem due to the climate change, ii) the deterioration and / or sea water intrusion to groundwater aquifers of certain areas that experience overexploitation, are affected by the on-going drought, and b) improve the water balance through groundwater recharge. A prerequisite for the reuse of treated wastewater is to protect public health.

Regarding urban water reuse, specific provisions are included in article 6, and refer to urban green areas, forest areas, recreation, restoring the natural environment, fire protection, cleaning roads, excluding uses for drinking, bathing and domestic activities. More specifically, reuse possibilities include landscape irrigation, irrigation of forests, cemeteries, roadway medians and roadside plantings, golf courses, public parks, residential courtyards, green areas at hotels and leisure facilities, water for fire protection, on soil compaction, for cleaning of roads and pavements, for decorative fountains, to create artificial or conserve lakes or wetlands and to enhance flow in surface streams.

Table 7 presents the specific quality objectives for microbiological and conventional parameters and the respective treatment required in the case of urban reuse of treated wastewater. These limits are supplemented by target values for metals (Table 8) and priority and toxic substances (Table 9). The latter are only obligatory for reclaimed wastewater from wastewater treatment plants with population equivalent greater than 100.000 or industrial facilities size independent.

Table 7: Water reuse criteria for urban reuse of reclaimed wastewater
Source: Greek JMD (2011)

Parameter	Quality level	
Total Coliforms (TC/100 ml)	≤ 2 *for 80% of the samples and* ≤ 20 *for 95 % of the samples*	Secondary biological treatment followed by advanced treatment and disinfection
BOD_5 (mg/l)	≤ 10 *for 80% of the samples*	
SS (mg/l)	≤ 2 *for 80% of the samples*	
Turbidity (NTU)	≤ 2 *for 50% of the samples*	

Secondary biological treatment includes of activated sludge systems, trickling filters and rotating biological reactors. Other configurations, for which adequate justification is provided, are also acceptable as long as the produced effluent quality is equivalent to the requirements of the Directive 91/271/EEC for BOD and SS. Nitrogen removal through nitrification-denitrification is necessary for the achievement of ammoniacal and total nitrogen concentrations lower than 2 mg/L and 15 mg/L, respectively.

Advanced treatment is related to the adoption of appropriate membrane system (at least at the level of ultrafiltration) or equivalent treatment system that achieves the quality objectives specified in

Table 11 for BOD_5, SS and turbidity. In the case of membrane bioreactors (MBR) secondary and advanced treatment are joined in one single treatment stage.

Disinfection refers to chlorination, ozonation and ultraviolet radiation (UV) or any other method of destruction or retaining pathogens, ensuring the required effluent quality for 80% of samples. When chlorination is applied design criteria include: minimum residual chlorine concentration of 2 mg/L, plug flow configuration of the contact tank (flow ratio of length / width greater than or equal to 40) and minimum contact time of 60 min, while dechlorination before reuse should be examined on a case by case basis. UV disinfection must ensure a minimum dose of 60 mWsec/cm^2 at end of lamp life, whereas for the design of the UV system UV transmittance may not exceed 70%.

Table 8: Maximum permissible metal concentrations
Source: Greek JMD (2011)

Metal	Maximum concentration (mg/L)
Al (aluminum)	5
As (arsenic)	0.1
Be (beryllium)	0.1
Cd (cadmium)	0.01
Co (cobalt)	0.05
Cr (chromium)	0.1
Cu (copper)	0.2
F (fluorine)	1.0
Fe (iron)	3.0
Li (lithium)	2.5
Mn (manganese)	0.2
Mo (molybdenum)	0.01
Ni (nickel)	0.2
Pb (lead)	0.1
Se (selenium)	0.02
V (vanadium)	0.1
Zn (zinc)	2.0
Hg (mercury)	0.002
B (boron)	2

Table 9: Maximum permissible concentrations for priority and toxic substances
Source: Greek JMD (2011)

Parameter	CAS	Maximum concentration (μg/L)
Alachlor	15972-60-8	0.7
Anthracene	120-12-7	1
Atrazine	1912-24-9	2
Benzene	71-43-2	5
Brominated	32534-81-9	0.025
Carbon-tetrachloride	56-23-5	ND

Parameter	CAS	Maximum concentration (µg/L)
C10-13 Chloroalkanes	85535-84-8	1.4
Chlorfenvinphos	470-90-6	0.3
Chlorpyrifos	2921-88-2	0.1
Aldrin	309-00-2	ND
Dieldrin	60-57-1	ND
Endrin	72-20-8	ND
Isodrin	465-73-6	0.01
DDT total	Not applicable	ND
para-para-DDT	50-29-3	ND
1,2-Dichloroethane	107-06-2	20
Dichloromethane	75-09-2	50
Di(2-ethylhexyl)-phthalate(DEHP)	117-81-7	10
Diuron	330-54-1	1.0
Endosulfan	115-29-7	0.01
Fluoranthene	206-44-0	1
Hexachloro-benzene	118-74-1	ND
Hexachloro-butadiene	87-68-3	0.6
Hexachloro-cyclohexane	608-73-1	ND
Isoproturon	34123-59-6	1
Naphthalene	91-20-3	2.4
Nonylphenol(4-Nonylphenol)	104-40-5	2
Octylphenol((4-(1,1',3,3'-tetramethylbutyl)-phenol))	140-66-9	1
Pentachloro-benzene	608-93-5	0.1
Pentachloro-phenol	87-86-5	1
Benzo(a)pyrene	50-32-8	0.1
Benzo(b)fluor-anthene **Benzo(k)fluor-anthene**	205-99-2 207-08-9	sum=0.03
Benzo(g,h,i)-perylene **Indeno(1,2,3-cd)-pyrene**	191-24-2 193-39-5	sum=0.02
Simazine	122-34-9	1
Tetrachloro-ethylene	127-18-4	10
Trichloro-ethylene	79-01-6	10
Tributyltincompounds(Tributhyltin-cation)	36643-28-4	0.003
Trichloro-benzenes	12002-48-1	0.4
Trichloro-methane	67-66-3	2.5
Trifluralin	1582-09-8	0.03
Acute toxicity for indicator organism *Daphnia Magna* (prior to disinfection)	-	1 toxicity unit (TU 50 ≤1)

ND: no detectable

1.3.5.4 Spain

Spain has adopted a comprehensive legal framework for wastewater reuse based on the Royal Decree (RD) No 1620/2007. The main target of RD 1620/2007 is to establish:

- All appropriate definitions in order to facilitate the comprehension of water reuse and,
- The required conditions of reclaimed wastewater quality accordingly the type of use (MARM, 2010).

As a result, Royal Decree 1620/2007, based on the WHO guidelines from 1989, establishes 24 uses for reclaimed water that are grouped into five broad categories: urban, agricultural, industrial, recreational, and environmental. RD lays down the required quality objectives, which are defined by a set of maximum acceptable values for a series of parameters relevant to different water uses (Table 10). In addition, in order to assess compliance with quality requirements, it establishes a self - monitoring programme to be carried out at the outlet point of the reuse system (BIO by Deloitte, 2015).

Table 10: Example of criteria for uses of reclaimed wastewater according to Annex I.A of RD 1620/2007.

Type of water use	Nematode intestinal	E. Coli	Suspension solid	Turbidity
Urban use- residential level: • Irrigation of private gardens, • Discharge of sanitary equipment.	1 egg/10 L	0/100 mL	≤10 mg/L	≤2 UNT
Urban use- services level: • Irrigation of urban zones, • Road washing- down, • Fire fighting systems, • Industrial wash of vehicles.	1 egg/10 L	≤200/100 mL	≤20 mg/L	≤10 UNT
Agriculture use: Raw human food crops in direct contact with reclaimed water.	1 egg/10 L	≤100/100 mL	≤20 mg/L	≤10 UNT
Agriculture use: • Crops to be consumed raw but no in direct contact with reclaimed water. • Drinking water for all stock. • Aquaculture.	1 egg/10 L	≤1.000/100 mL	≤35 mg/L	-
Agriculture use: • Lenticular crops no in direct contact with reclaimed water. • Ornamental water no in direct contact with reclaimed water. • Industrial crops	1 egg/10 L	≤10.000/100 mL	≤35 mg/L	-
Industrial use: process or cleaning water or other industrial use (except food industry)	-	≤10.000/100 mL	≤35 mg/L	≤15 UNT
Industrial use: process or cleaning water for food industry	1 egg/10 L	≤1.000/100 mL	≤35 mg/L	-

Industrial use: Cooling towers and evaporating condensers	1 egg/10 L	no	≤5 mg/L	≤1 UNT
Recreational use: golf course irrigation	1 egg/10 L	≤200/100 mL	≤20 mg/L	≤10 UNT
Recreational use: ponds	-	≤10.000/100 mL	≤35 mg/L	-
Environmental use: Indirect recharge of aquifers.	-	≤1.000/100 mL	≤35 mg/L	-
Environmental use: Direct recharge of aquifers.	1 egg/10 L	no	≤10 mg/L	≤2 UNT
Environmental use: Silviculture, Irrigation of forest etc.	-	-	≤35 mg/L	-

Table 11 summarises the provisions of the previously presented regulations/guidelines with respect to microbiological organisms, while in Box 2 the water reuse objectives within DESSIN project are presented.

Table 11: Suggested guidelines/regulations from different institutions for urban reuse of municipal wastewater with reference to the microbiological organisms

Regulations/ Guidelines	TC/100ml	FC/100ml	Treatment
WHO			In the 2006 guidelines health based targets define a level of health protection that is relevant to each hazard and respective log pathogen reduction needed
US EPA		No detectable (landscape irrigation)	Secondary treatment Advanced Treatment Disinfection
US EPA		14 max value (control access irrigation sites)	Secondary treatment Disinfection
US EPA		200/100 mL (other urban uses)	Secondary treatment Disinfection
California	23/100 mL (7-day median) 240/100 mL (30-day max) Limited contact expected Restricted use		Secondary Disinfection
California	2.2/100 mL (7-day median) 23/100 mL (30-day max) Restricted landscape impoundments		Secondary Disinfection
California	2.2/100 mL (7-day median) 23/100 mL (30-day max) Unrestricted use		Secondary Coagulation Filtration Disinfection

Regulations/ Guidelines	TC/100ml	FC/100ml	Treatment
Australia	10/100 mL (median)		Tertiary with pathogen reduction. May need nutrient reduction for groundwater recharge.
Australia	100/100 mL (median)		Secondary With pathogen reduction. Indirect potable (surface water) should comply with raw drinking water standards.
Australia	1000/100 mL (median)		Secondary Treatment and pathogen reduction
Australia	10.000/100 mL (median)		Secondary Treatment and pathogen reduction (Pathogen reduction is site- specific for streams as required)
Cyprus		5 [a] -15 [b] ([c])	Secondary- tertiary and disinfection
Cyprus		50[a]-100[b] ([c])	Secondary- tertiary and disinfection
Cyprus		200[a]-1000[b] ([c])	Secondary, storage >1 week and disinfection or tertiary and disinfection. Stabilization maturation ponds total retention time >30 d or secondary and storage >30 d
Cyprus		1000[a]-5000[b] ([c])	Secondary and storage >1 week or tertiary and disinfection. Stabilization maturation ponds total retention time >30 d or secondary and storage >30 d or secondary and storage > 30 d
Cyprus		3000[a]-10.000[b] ([c])	Secondary and disinfection. Stabilization maturation ponds with total retention time >30 d or secondary and storage >30 d
Greece	2 for 80% of the samples 20 for 95% of the samples		Secondary treatment Advanced Treatment Disinfection

[a] These values must not be exceeded in 80% of samples per month.

[b] Maximum value allowed.

[c] expressed as E. coli

BOX 2: Water reuse objectives within DESSIN project

Type of water reuse: ***Unrestricted urban reuse*** *as specified in the Greek National legal framework and specifically article 6 of the JMD 145116/2011. These include: large green areas (cemeteries, roadway medians and roadside plantings, golf courses, public parks), recreation, fire protection, soil compaction, cleaning of roads and pavements, decorative fountains.*

Quality Levels: These derive from the Greek National legal framework and correspond to the specific use of unrestricted reuse as described in JMD 145116/2011, Annexes I, II and IV.

Tables 4 and 5: Obligatory quality standards

Table 6 Guideline limits for the needs of DESSIN project

Minimum treatment Level Required: Secondary biological treatment - Advanced treatment - Disinfection

2 Small scale membrane wastewater treatment systems

BOX 3: WORKING TERMINOLOGY as per Metcalf & Eddy, 2007

Conventional secondary treatment*: Activated sludge treatment, commonly with nitrification, used for the removal of soluble organic matter and particulate constituents.*

Decentralised wastewater management: *Collection, treatment, and discharge/reuse of wastewater from individual homes, clusters of homes, isolated communities, industries, or institutional facilities, as well as from portions of existing communities at or near the point of wastewater generation*

Flux*: The mass or volume rate of transfer through the membrane surface, usually expressed as m^3/m^2-h or L/m^2-h (gal/ft^2-d). Flux is the prevalent term for referring to the rate of water production from a membrane system.*

Fouling*: The accumulation of material on the membrane surface resulting in the loss of performance.*

Membrane bioreactor: *A process that combines a suspended growth biological reactor with a membrane separation system; membrane separation is accomplished by either microfiltration or ultrafiltration membranes.*

Multiple barrier concept*: The provision of multiple safeguards to maintain reliably the finished water quality examples include source control, redundant systems, and treatment processes arranged sequentially.*

Nanofiltration*: A pressure-driven membrane separation process that typically operates at pressures in the range of 5 to 10 bar and removes particle and dissolved material as small as approximately 0.001 pm.*

Pilot scale testing*: The testing of unit operations or processes at a small-scale to establish the sustainability of the treatment method in the treatment of a specific wastewater under specific environmental conditions and to obtain necessary data on which to base full scale design.*

Pore size*: The nominal size of a membrane's pores (typically measured in microns) that allows passage of permeate through the membrane wall while retaining selected contaminants on the membrane surface. Pore size is a classification system used typically to distinguish between types of membranes.*

Process reliability*: The level of assurance that a process will achieve consistently the needed degree of constituent removal over the expected range of operating conditions.*

Reverse Osmosis*: A high pressure [over 10 bar (1000 kPa)] membrane separation process used primarily for the removal of organic matter and salts from wastewater and for desalting brackish water and seawater.*

Satellite treatment systems*: Systems where wastewater in an upstream portion of the collection system is intercepted and diverted for treatment in a water reclamation facility located close to the point of reuse. Satellite treatment systems generally do not have solids-processing facilities; solids removed during treatment are returned to the collection system for processing in a central treatment plant located downstream.*

In selecting appropriate treatment operations and processes for water reuse applications the provision of multiple barriers is an important consideration. This concept is commonly used in potable water treatment and is based on the principle of establishing a series of barriers to preclude the passage of pathogens and harmful organic and inorganic contaminants into the water system. For water reuse, barriers may take the form of (1) source control programmes, in order to prevent the entrance of substances into the wastewater collection system that may inhibit treatment and prevent water reuse, (2) a combination of treatment processes where each provides a specific level of treatment and (3) and environmental buffer (retention ponds, dilution with fresh water, soil aquifer treatment). The advantages of this concept are related to the provision of a degree of public and environmental protection even in the event one of the barriers should fail, the reduced probability that multiple processes will fail simultaneously and the robustness to potential process upsets because a greater number of barriers is used.

The principle treatment operations and processes along with the constituents categories for which they are used are presented in Figure 2.

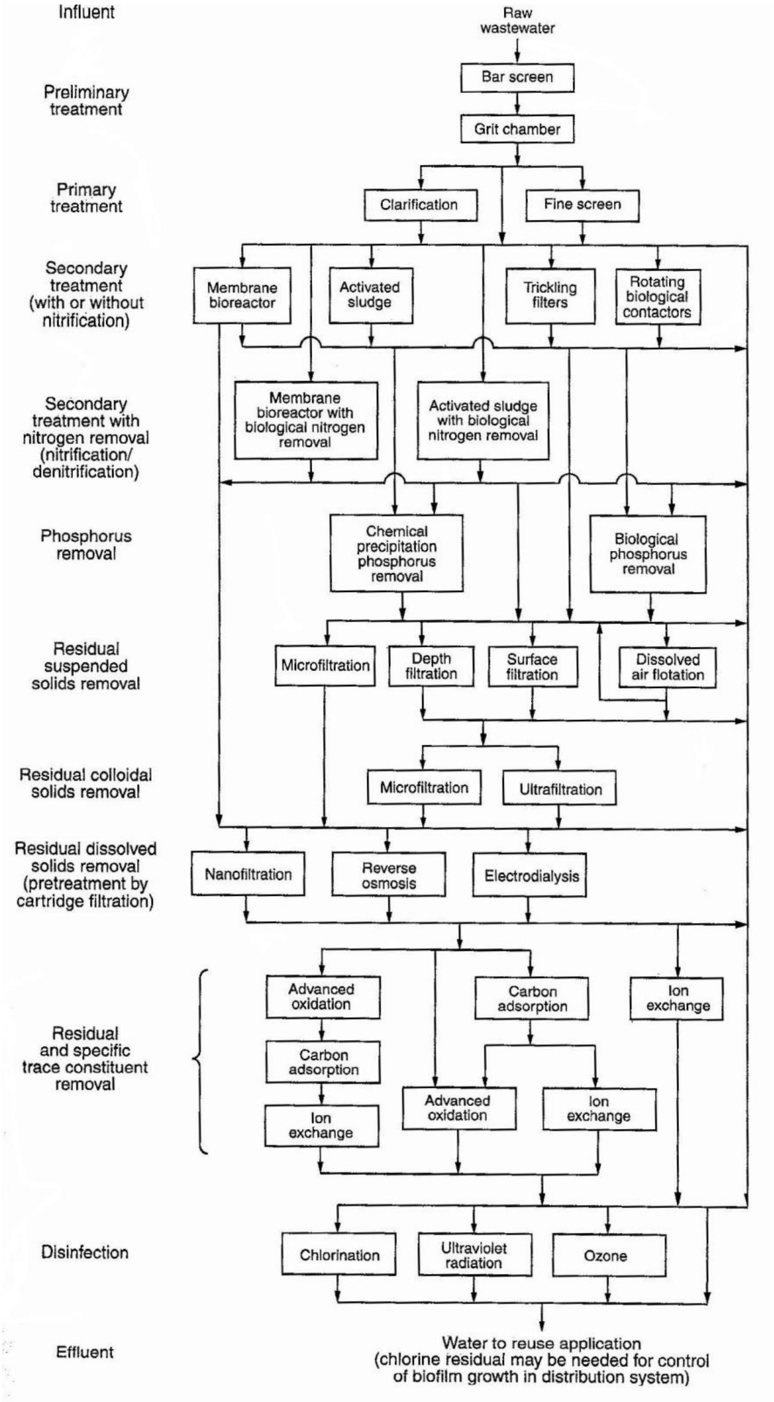


Figure 2: **Alternative treatment processes in wastewater reclamation and reuse** (Metcalf & Eddy, 2007)

The various membrane processes differ in their molecular separation size and the driving force that has to be expended. Figure 3 indicates the molecular weight and the size of the materials which can be separated by microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). With respect to the driving force needed MF requires a pressure difference at the range of 0.1 – 3 bar, UF at the range 0.5 – 10 bar, NF at the range 2 – 40 bar and RO at the range 5 – 70 bar, while in special cases pressure may rise up to 120 bar (ISA, 203).

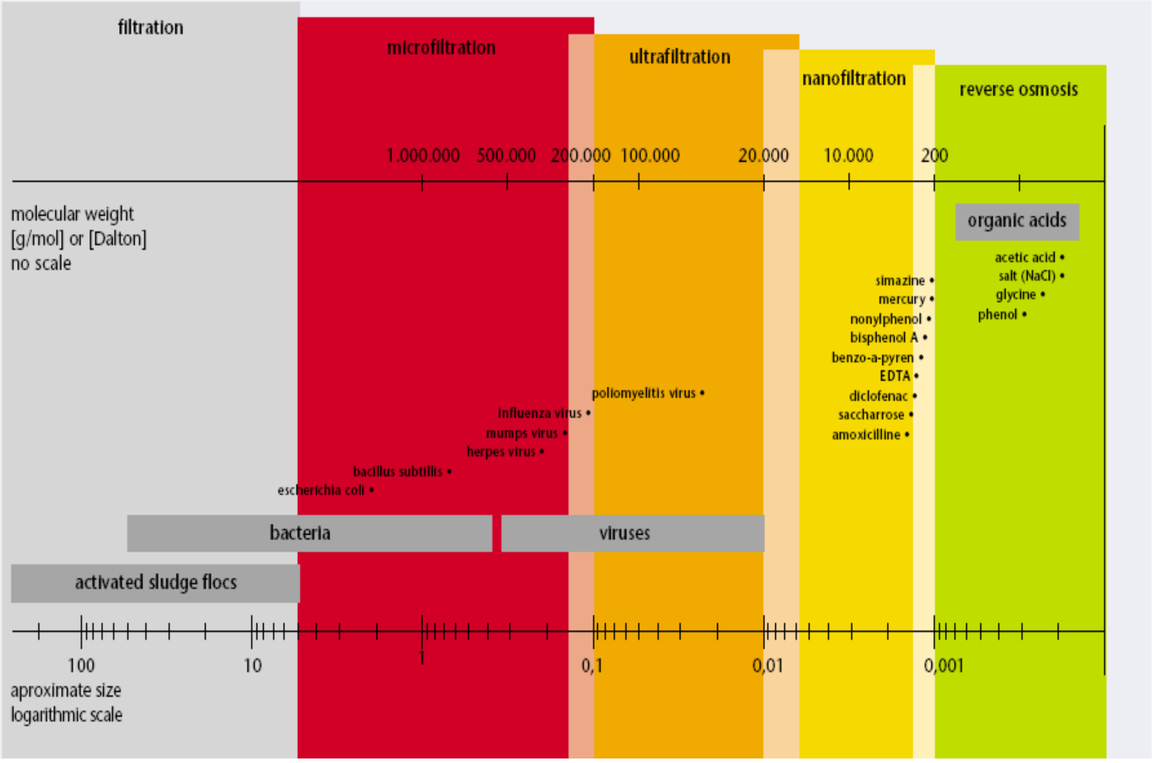


Figure 3: Fields of application of membrane processes (ISA, 2003)

In the field of wastewater purification synthetic solids membranes are used, from materials that can be either organic (e.g. cellulose, polymer membranes-polypropylene PP, polyvinylidene fluoride PVDF, polyamide PA) or inorganic (e.g. ceramic), the former being predominately used at present. Depending on the manufacturing process membranes are distinguished in tubular membranes and flat membranes, which are formed in modules. Table 12 presents the characteristic values of module types. The different module forms can be characterised by the arrangement of the separation layer, the component density and operation mode.

Table 12: Membrane modules characteristics
Source: ISA, 2003

	Tubular membranes		
	Tube module	Capillary module	Hollow-fibre module
Arrangement of the separation layer	inside	outside/inside	outside/inside
Inside diameter	5,5-25 mm	0,25-5.5 mm	0,04-0,25 mm

	Tubular membranes		
	Tube module	**Capillary module**	**Hollow-fibre module**
Component density	<80 m^2/m^3	<1.000 m^2/m^3	<10.000 m^2/m^3
Operating mode	cross-flow	dead-end/cross-flow	dead-end
Advantages	Hardly susceptible to blockage Low pressure loss operation controlled by covering layer is possible	High component density Cheap production Backwashing possible on the permeate side	Extremely high component density Favourable specific membrane costs High pressure resistance
Disadvantages	Low component density	Low pressure resistance	Susceptible to blockage pressure loss
	Flat membranes		
	Plate module	**Spiral-wound module**	**Cushion module**
Arrangement of the separation layer	outside	outside	outside
Component density	40-100 m^2/m^3	<1.000 m^2/m^3	ca. 400 m^2/m^3
Operating mode	cross-flow	dead-end/cross-flow	dead-end/cross-flow
Advantages	Membranes can be changed separately Hardly susceptible to blockage	Cheap production of seals High component density	Little pressure losses on the permeate side Hardly susceptible to fouling
Disadvantages	Many seals Low component density	Long flow path on the permeate side Mechanical cleaning not possible Risk of blockages	Low component density Many seals

A prerequisite for module selection is in each case the selection of the membrane process and/or the membrane which is suitable for the separation problem (Table 13).

Table 13: Characteristic features of different membrane processes
Source: ISA (2003)

	Microfiltration (MF)	Ultrafiltraton (UF)	Nanofiltration (NF)	Reverse osmosis (RO)
Operation mode	cross-flow/dead-end	cross-flow/dead-end	cross-flow	cross-flow
Operation pressure (transmembrane)	0.1-3 bar	0.5-10 bar	2-40 bar	5-70 bar (up to 120 bar)
Separating mechanism	screening controlled by covering layer, if necessary	screening controlled by covering layer, if necessary	solubility/diffusion/ charge (ion selectivity)	solubility/diffusion
Molecular separation size	solids>0.1 µm	colloids:20.000 to	dissolved matter:200 to	dissolved matter<200

	Microfiltration (MF)	**Ultrafiltraton (UF)**	**Nanofiltration (NF)**	**Reverse osmosis (RO)**
		200.000 Dalton solids>0.005 µm	200.000 Dalton solids>0.001 µm	Dalton
Membrane types	symmetric polymer or ceramic membranes	asymmetric polymer composit or ceramic membranes	asymmetric polymer or composit membranes	asymmetric polymer or composit membranes
Module types	spiral-wound, hollow-fibre and tube modules, plate or cushion modules	spiral-wound, hollow-fibre and tube modules, plate or cushion modules	spiral-wound, tube and cushion modules	spiral-wound, tube, plate, cushion or disc-tube modules

In principle, there are two filtration operating modes: dead-end or static filtration and cross-flow or dynamic filtration. Cross-flow operation is used in nanofiltration and reverse osmosis, while in ultra- and microfiltration both operating modes are possible. In the cross-flow mode (cross-current filtration) the feed is pumped parallel to the membrane surface and the permeate is withdrawn diagonally to it. In dead-end operation the membrane is fed orthogonally, comparable to a "coffee filter".

Due to the retention of suspended material, a covering layer develops on the feed side, which diminishes the filtration capacity. As a result, the permeate flow decreases with progressive process duration. As preventive measure, the entire module is submitted in intervals to backwashing.

Based on the analysis of Section 1 and the specifications in BOX 2 for unrestricted urban wastewater reuse which is the selected water reuse application in the framework of DESSIN Project, the following treatment options are identified:

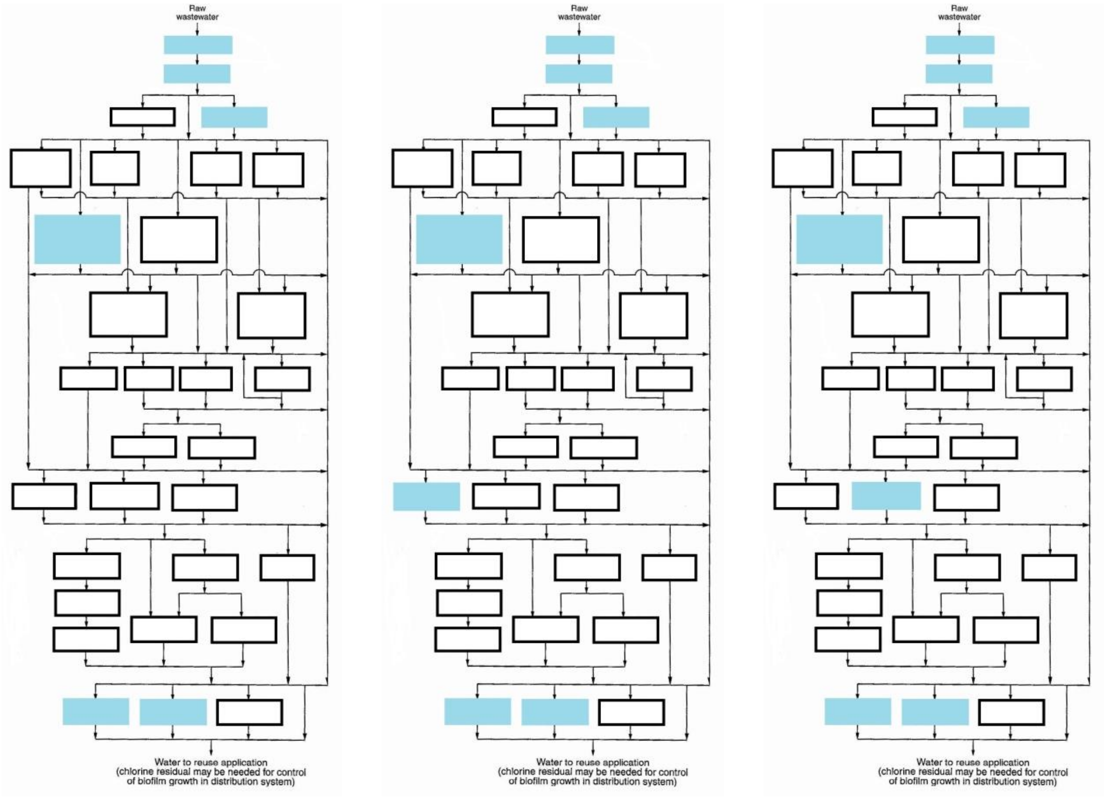
- Membrane bioreactor with biological nitrogen removal and disinfection (chlorination or UV) (Figure 4a)
- Membrane bioreactor with biological nitrogen removal, nanofiltration and disinfection (chlorination or UV) (Figure 4b)
- Membrane bioreactor with biological nitrogen removal, reverse osmosis and disinfection (chlorination or UV) (Figure 4c)

In all cases secondary treatment with biological nitrogen removal is desirable, where most of the organic matter and the suspended solids are removed at high levels of efficiency. Removal of residual particulate matter requires further tertiary treatment through a filtration process, and it is notable that the membrane biological reactors (MBR) offer the advantage to incorporate both stages of treatment.

When dissolved constituents are present in treated wastewater in amounts that limit water use, advanced membrane treatment could be incorporated either by nanofiltration or reverse osmosis.

A major goal of water reclamation and reuse is to reduce the pathogen content, thus decrease the public health risks associated with exposure to reclaimed water. Disinfection is the final stage of treatment and is accomplished most commonly by the use of chlorine or UV. When UV is used as the principle disinfectant chlorine is often added to maintain a residual concentration in the distribution system to control regrowth of microorganisms.

Further to the above, for the needs of DESSIN project, compact wastewater treatment solutions are investigated that relate to the fact that the water reclamation plant is located close to potential applications such as agricultural irrigation and recreational enhancement. The so called satellite plant as well decentralised systems are expected to be used increasingly as urban growth continues. These plants may use processes similar to those used at a centralised treatment plant however the development of compact treatment facilities has made satellite applications more feasible. The advantages of such application include relatively reduced costs as compared to centralised system and greater potential for having reuse applications adjacent to treatment system, which minimise transmission costs.



(a) (b) (c)

Figure 4: Alternative treatment processes in wastewater reclamation and reuse within the DESSIN Project

In the following sections the main principles and the technical characteristics of the core treatment processes of MBR, NF and RO and their combinations are described.

2.1 MBR Technology

Membrane biological reactors (MBR) combine biological treatment with an integrated low pressure membrane system (e.g. MF or UF) to provide enhanced organic and suspended solids removal, thus eliminating the need for secondary clarification facilities and media filtration. Membrane bioreactors require less space than traditional activated sludge systems because of the shorter hydraulic retention time in the bioreactor and the smaller footprint of the membrane separation unit and this is one of the reasons that they are particularly adaptable to satellite decentralised wastewater management systems. Membrane reactors come in different configurations that may include:

(i) external pressure driven membrane
(ii) integrated submerged

(iii) with external membrane tank submerged

In the various MBR systems, the key component is the MF or UF membrane either hollow fibre or fixed plate. The membranes may be pressure driven or vacuum driven. Pressure driven membranes are installed external to the bioreactor and the mixed liquor from the bioreactor is pumped to the membranes. To maintain permeability and improve performance pretreatment with fine screens is installed ahead of the membrane unit. Vacuum driven membranes may be immersed directly into the activated sludge reactor or in a separate membrane separation tank. The membranes are subjected to a vacuum that draws permeate through the membrane while retaining solids in the reactor. To clean the exterior of the membranes air is introduced below the membranes, while as the air bubbles rise to the surface scouring of the membrane surface occurs and rejected material is returned to the mixed liquor.

As compared to conventional suspended growth systems MBRs have the following advantages: (1) because MBRs operate with higher suspended solids concentrations the hydraulic retention times are shorter, thus reducing the reactor size, (2) longer SRTs on the order of two to three times those of conventional processes result in less sludge production and more stable operation, (3) simultaneous nitrification-denitrification can be achieved through process control when longer SRTs are combined with lower DO concentrations in the bioreactor. Disadvantages include high capital costs for the membrane modules, limited data on membrane life that may result in a potential high recurring cost of periodic membrane replacement, high energy costs, and potential membrane fouling that affect the treatment ability, and the fact that waste sludge from the membrane process may be difficult to dewater (Metcalf & Eddy, 2007).

Wastewater characteristics are important in the design of activated sludge systems, particularly for biological nutrient-removal processes and for evaluating the capacity of an existing system. Influent quality characterisation is important to identify the constituents that need to be removed and contaminants that inhibit performance of the membranes. Typical constituents that affect membrane performance are presented in Table 14.

Table 14: Wastewater constituents that affect performance of membrane bioreactors Source: Metcalf & Eddy, (2007), Malamis S. (2009)

Type of constituent	Specific constituent	Effect on MBR
Physical	High concentration of TSS (>30 mg/L), hair, fibrous material and other inert solids	Buildup on membrane surfaces that may cause reduced membrane efficiency, physical damage to membranes and ability to maintain cleaning. May increase permeate quality.
	Temperature variations	Affects water viscosity and flux rate.
Chemical	High alkalinity Soluble iron	Membrane fouling that may require acid cleaning to remove chemical foulants
	Oil and grease	Membrane fouling causing diminished performance and more frequent cleaning.
	Sufractants	Foaming that requires cleanup
	Oxidants, e.g. ozone and chlorine	Attacks certain types of membrane material.
Biological	Dissolved and colloidal organic matter	Membrane fouling causing diminished performance and more frequent cleaning.
	Extracellular polymeric substances (EPS)	Clogs membrane pores resulting in diminished membrane performance and more frequent cleaning; also affects viscosity of sludge

MF and UF membranes are effective in producing product low in BOD, COD, TSS and turbidity, thus focus is given in other effluent water quality issues such as nutrients, viruses and total dissolved solids concentrations. In each case the treatment train must consider which types of constituents must be removed, thus disinfection stage and post treatment with NF or RO may be applied.

The principle process variables in the design and operation of MBR systems include the temperature, prose size, membrane flux rate, membrane life, bioreactor suspended solids concentration and solids and hydraulic retention times. Design considerations include:

- pretreatment to prevent macro-fouling which can be accomplished by the installation of fine screens of 1mm opening
- air supply for the MBR, to sustain the biological process and cleaning of the membranes
- membrane fouling control and cleaning, to maintain membrane integrity
- peak flow management, to enable for an economically sound technical solution
- biosolids production and management where the balance between SRT and solids in the bioreactor should be maintained
- nutrient removal where additional zones or compartments are added ahead of the aerobic zone of the MBR to establish anoxic and/or anaerobic conditions conducive of nutrient removal
- biosolids processing and handling constraints.

During the selection of appropriate treatment systems different issues should be considered including the final use of the effluent, type of disinfection process, future water quality requirements, energy considerations, site constraints and economic considerations.

MBR is a best fit solution when high quality effluent with greater reuse potential is required, satellite plants are considered, land limitations are expected, thus reduced footprint is required, potential reduction of sludge volume due to high SRT values is desirable.

In cases where increased removal of dissolved constituents is desirable advanced processes such as nanofiltration and reverse osmosis are engaged. NF and RO unlike MF and UF are capable of separating dissolved ions from the feed stream. The former use pressure to provide convective flow of the liquid through the membrane and NF and RO require hydrostatic pressure to overcome the osmotic pressure of the feed stream.

2.2 Nanofiltration (NF) Technology

NF technology is used to remove particles in the 200 to 1000 molecular weight range, rejecting selected salts and most organic and microorganisms operating at higher recovery rates and at lower pressures than RO systems. As previously discussed, spiral wound and hollow fibre are the two membrane configurations commonly used. The performance of NF with respect to the removal of specific organic constituents is site specific related to the characteristics of the water to be treated, the type of membrane and the operational strategies. The main issues that are related to process performance with respect to the removal of dissolved constituents are rejection rate (up to 60% for dissolved solids and 5 log removal for microorganisms) and the degree of variability.

When unrestricted urban water reuse is required and quality standards of Table 4, 5 and 6 should be met, NF technology is not adequate for the removal of substances of molecular weight less than 200, as presented graphically in Figure 5.

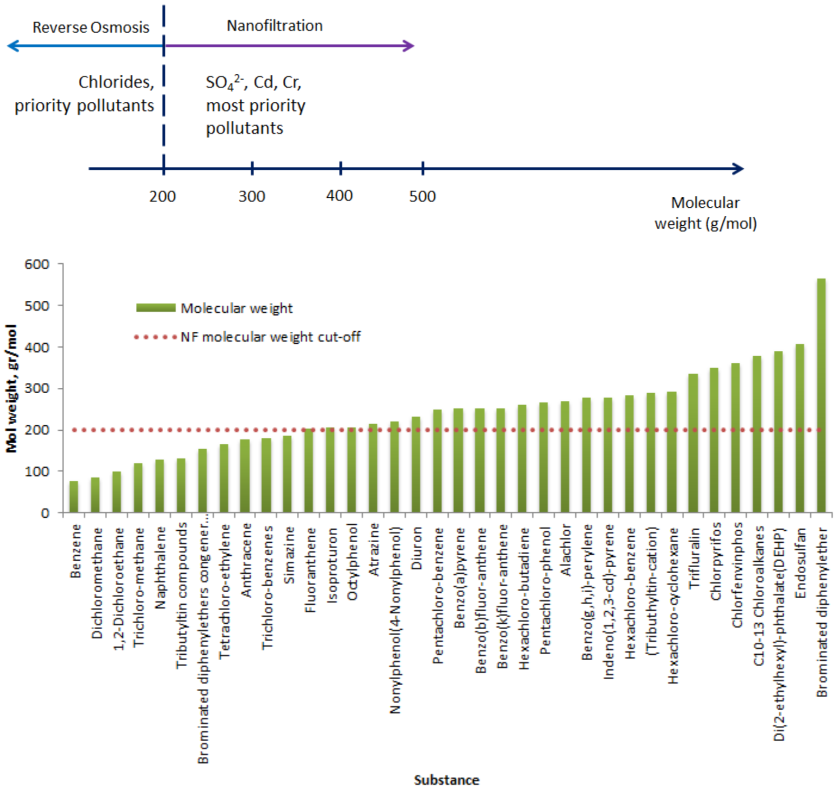


Figure 5: Nanofiltration vs Reverse Osmosis removal capacity

2.3 Reverse Osmosis (RO) Technology

Reverse osmosis is used to remove dissolved materials, commonly salts, under pressures ranging from 5 to 70 bar (and up to 120 bar) and at flux rates varying from about 12 to 2000 L/m^2-h. RO membranes are typically thin film composite membranes in a spiral wound configuration or hollow fibre with a pore size of approximately 0,0005 µm. Characteristics of commonly used RO membrane configurations are presented in Table 15.

Table 15: Characteristics of commonly used RO membrane configurations
Source: Metcalf & Eddy, (2007)

Performance characteristics	hollow fibre	spiral wound
Resistance to chemical cleaning	Good	Poor
Plugging potential	High	High
Mechanical cleaning	Poor	Poor
Area to volume ratio	High	Moderate
Power consumption	Good	Good
Membrane replacement costs	High	Low

In water reuse applications RO is used for the removal of dissolved constituents remaining in wastewater after MBR biological treatment in order to obtain quality characteristics appropriate for groundwater recharge, surface water augmentation or industrial use (e.g. cooling tower). Dissolved solids rejection rate could reach 98% and 7 log removal for microorganisms.

Process design considerations for NF and RO systems include:

- Feedwater characterisation, in order to identify the constituents that are related to high potential for membrane fouling
- Pretreatment, that should be considered to extent membrane life
- Flux rate, that influences system costs and membrane life
- Recovery that affects solute rejection and membrane performance
- Membrane fouling, for the establishment of cleaning procedures
- Membrane life, which is the principle economic consideration that governs successful application of membrane technology
- Operating and maintenance costs
- Recycle flows to control membrane velocity, influent concentration and flow variations
- Retentate and backwash disposal, especially when chemicals are used for membrane cleaning and large volumes of waste require disposal.

3 Process design

3.1 Design data

Water reuse objective within DESSIN project is related to unrestricted urban reuse as specified in the Greek National legal framework and specifically article 6 of the JMD 145116/2011 and quality levels and treatment processes identified in relevant Annexes I, II and IV. The design is performed for two different inflow scenarios with the same quality characteristics.

3.1.1 Influent characteristics

The process design calculations of the proposed plant are based in the data given in Table 16.

Table 16: Design flows and loads for selected scenarios

Parameter	Units	Scenario 1	Scenario 2
Daily flow	m^3/d	100	300
Hourly peak flow	m^3/h	6.3	18.9
	l/s	1.75	5.25
COD	kg/d	30.0	90.0
BOD	kg/d	75.0	225.0
SS	kg/d	37.5	112.5
TKN	kg/d	6.0	18.0
TP	kg/d	1.25	3.75
COD	mg/L	300.00	
BOD	mg/L	750.00	
SS	mg/L	375.00	
TKN	mg/L	60.00	
TP	mg/L	12.50	

The design loads correspond to the anticipated maximum average weekly loads entering the treatment plant during the year. The design flow corresponds to the maximum daily flow.

The process design of the plant will be performed for wastewater temperatures equal to 12°C winter and 23°C for winter and summer, respectively. The Total Coliform concentration at the inflow is equal to 30×10^6 TC/100ml, and the percentage of volatile solids to total suspended solids is considered 70%.

3.1.2 Treatment Performance

The treated wastewater will comply with the following requirements (Table 17):

Table 17: Requirements for treated wastewater after MBR

Parameter	Units	Effluent characteristics
Total Coliforms	TC/100 ml	*≤ 2 for 80% of the samples and* *≤ 20 for 95 % of the samples*
BOD$_5$	mg/L	*≤ 10 for 80% of the samples*
SS	mg/L	*≤ 2 for 80% of the samples*
Turbidity	mg/L	*≤ 2 for 50% of the samples*

Parameter	Units	Effluent characteristics
Total nitrogen	mg/L	15
Ammoniacal nitrogen	mg/L	2

Further to the above minimum requirements, the quality objectives of Tables 5 and 6 should also be met.

3.2 Design criteria and assumptions

Table 18 presents for each treatment phase the proposed design criteria.

Table 18: Design criteria and assumptions

Treatment stage	Design Criteria	Comments
Preliminary treatment / Compact system **Screen unit** **Grit unit**	opening 6 mm 95% removal of inorganic material of greater than 0.2mm diameter	The unit is designed for peak flow.
Equalisation tank	Mixing providing air ≤ 0,8m^3/m^3-h	The unit is designed in order to provide for constant flow to the downstream units.
Fine screen	opening 1 mm	The unit is designed for daily flow.
MBR with biological nitrogen removal **Anoxic tank** **Aerobic tank** **MBR unit**	• Minimum sludge age for total (aerobic and anoxic) volume 18 d • Separate anoxic tank for needs of the of the denitrification process • MLSS ≤ 15.000 mg/L – selected value 10.000 mg/L • Volumetric load ≤0,6 $KgBOD_5/m^3$.d • Design flux 30L/m^2-h	Winter temperature: 12^oC Summer temperature: 23^oC
Disinfection with chlorine	• plug flow configuration of the contact tank (flow ratio of length / width greater than or equal to 40) • minimum contact time of 60 min	The Total Coliform concentration after MBR is equal to 10^5 TC/100ml The unit is designed for peak flow.
UV disinfection	• minimum dose of 60 $mWsec/cm^2$ at end of lamp life • UV system transmittance may not exceed 70%.	The Total Coliform concentration after MBR is equal to 10^5 TC/100ml The unit is designed for peak flow.
Residual chlorine	2 mg/L	
Reverse osmosis	• Minimum recovery 75%	

3.3 Process design

3.3.1 Preliminary treatment

Feedwater is pumped from the local sewerage network to the satellite wastewater treatment plant. The capacity of the inlet pumping station is capable to pump the maximum hour flow to the preliminary treatment units that include a coarse screen with 20mm openings and a compact fine screen-grit system. The capacity of the preliminary treatment will adequately treat the peak hour flow. The screens with opening of 6 mm allow for the retention of solids and the grit-grease unit for the protection of the downstream equipment from sand particles and grease and oil. The system combines the benefits of both aerated grit traps by using a highperformance grit trap with a small overall plan area. The wastewater flows firstly through an inlet screen that retains, washes, compacts and dewaters the solids contained within the flow. The screened wastewater then passes into an aerated grit trap that reduces the settlement of organics within the flow by the action of an aeration system within the grit trap. Grease along with other greasy material are collected in a separate integrated grease trap chamber from where the grease is automatically discharged. Whilst the separated particles are removed from the grit trap by classifying screws, they are simultaneously being statically dewatered prior to being discharged into a container.

The preliminary treatment unit will have a capacity of 2 l/s and 6 l/s for scenarios 1 and 2 respectively in order to adequately treat the peak wastewater flows. The pretreatment constists of a coars sceen (2mm), and a compact screen – grit and grease removal system of the aforementioned capacity.

The outlet flow from the pretreatment unit enters the equalisation tank from where sewage is pumped to the main treatment units. The main treatment units consist of a fine 1mm screen, biological treatment with MBR, an RO unit and a UV disinfection stage (Figure 6).

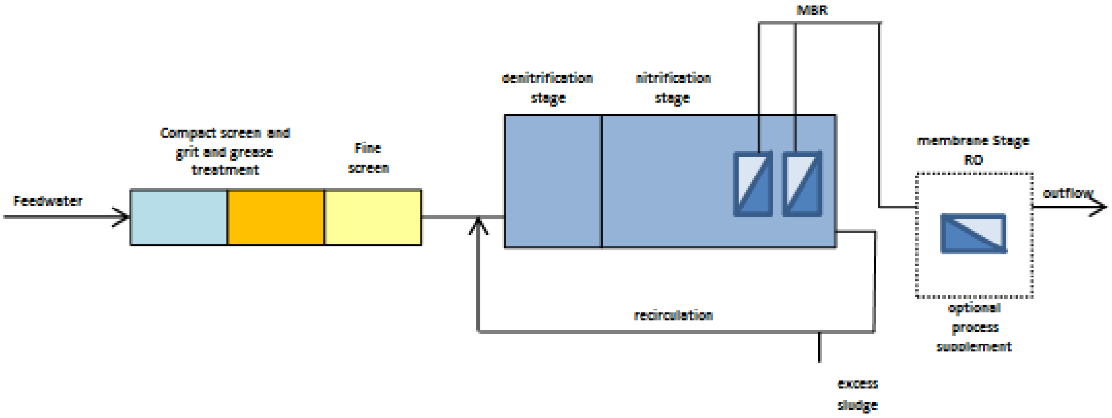


Figure 6: Typical treatment scheme for wastewater reclamation

The screen is a crucial pretreatment stage when MBR technology is selected. With an opening of 1 mm the fine screen is capable to treat the maximum design flow of the treatment plan and is automatically backwashed. The system consists of a cylindrical drum screen which allows a complete separation of solids larger size and fibrous materials.

The biological treatment applied is activated sludge with simultaneous stabilization of sludge and advanced nitrification and denitrification. Sludge separation is performed through the membrane system (MBR), while the supply of oxygen is conducted through an aeration system that consists of a blower and fine-bubble diffusers.

3.3.2 Biological treatment

The denitrification stage consists of an anoxic tank equipped with a proper mixing device that ensures mixing of the liquor. The mixed liquor from the denitrification tank enters the aeration tank where the biological processes of oxidation of the organic load, nitrification and stabilization of sludge take place.

The method chosen is the separation of the mixed liquor from the treated effluent by a system with ultrafiltration membranes. The installation of modules is selected each with active filtration of 280 m^2. The submerged membrane modules are installed in separate tank which is fed by gravity after the aerobic tank. The filtration can be performed with using a natural water head differential pressure generated from a vertical distance between the liquid level of the membrane submerged tank and the level of the permeate water outlet.

Cleaning of the membranes with air (air scouring) is performed thorough an aeration system that consists of blowers and coarse bubble diffusers. For chemical cleaning of membrane systems a complete system must be installed consisting of NaClO (Sodium hypochloride) and Citric acid dosage systems. Chemical cleaning should be an automated procedure with contact time of the membranes to the chemical solution of 2-3 hours.

The sludge from the MBR tank flows to the recirculation and excess sludge pumping station. The recirculation sludge is then returned to the inlet of the biological treatment. Excess sludge returns to sewage network.

3.3.2.1 Denitrification tank and aeration tank

BOD$_5$ removal

The rate biokinetics determine the loading rate (the rate at which organic matter is introduced into the reactor, kgBOD/m^3), as determined by Monod kinetics. Accordingly, the rate of reaction is first order with respect to a limiting substrate up to a maximum specific growth rate, after which growth is unaffected by any increase in substrate concentration:

Monod Kinetic:
$$\mu_{\mathrm{H}} = \mu_{\mathrm{H}\mu\mathrm{T}} \frac{F}{K_{SH} + F} \qquad (1)$$

where

F = effluent BOD$_5$ soluble (mg/l)

μ_{HmT} = maximum growth rate for temperature T ($\mu_{\mathrm{H}m\mathrm{T}} = \mu_{\mathrm{H}m20} e^{\{kh(T-20)\}}$)

K_{SH} = Monod Constant for Substrate (120 mg/l)

Based on the fact that $\frac{1}{\theta_c} = \mu_{\mathrm{H}} - b_{\mathrm{H}}$ the operation function for the estimation of solids retention time (SRT) as a function of soluble BOD concentration at the effluent of the biological treatment is the following:

$$\frac{1}{\theta_c} = \mu_{\mathrm{H}\mu\mathrm{T}} \frac{F}{K_{SH} + F} - b_H \qquad (2)$$

where θc = sludge age (d)

b_H = heterotrophic biomass decay coefficient (0,06 d^{-1})

For a given SRT and in order to estimate the required aerobic volume the following equation is employed, which results from the mass balance in the aerobic tank:

$$S = \frac{1}{\lambda}\left[\frac{1+\beta b_H \theta_c}{1+b_H\theta_c} Y_H E_H F_o + aS_{vo} + S_{fo} + \frac{Y_n E_n S_{NH0}}{1+b_n\theta_c}\right] \quad (3)$$

where

λ	= θ/θc
θ	= V/Q= hydraulic retention time (d)
F_0	= BOD concentration at the inlet of the biological treatment
E_H	= BOD removal efficiency
Y_H	= heterotrophic biomass yield
b_H	= heterotrophic biomass decay coefficient
Y_n	= nitrifying bacteria biomass yield
b_n	= nitrifying bacteria biomass decay coefficient
S_{NH0}	= ammoniaclal nitrogen at the influent (mg/L)
E_n	= ammoniacal nitrogen removal efficiency
β	= inert matter generating rate from the deterioration of biomass
α	= percentage of non-biodegradable organic solids
S_{v0}	= concentration of organic solids
S_{f0}	= concentration of inorganic solids
S	= MLSS (mg/l)

For the determination of the recirculation rate the following equation is applied:

$$r_A^{des} = \frac{MLSS}{S_U^* - MLSS} \quad (4)$$

where

MLSS =suspended solids in the anoxic - aeration tanks.

Su* = suspended solids in the MBR tanks.

Nitrification

The specific growth rate of nitrifying bacteria is adequately described by the Monod kinetic:

$$\mu_n = \mu_{nmT}\left(\frac{S_{NH}}{K_{Sn}+S_{NH}}\right)\cdot\left(\frac{DO}{K_{DO}+DO}\right) \quad (5)$$

where

μ_n : specific growth rate of nitrifying bacteria (d^{-1})

μ_{nmT} : maximum specific growth rate of nitrifying bacteria (d^{-1})

S_{NH} : ammoniacal nitrogen concentration at the effluent (mg/L)

K_{Sn} : half saturation coefficient for nitrification (0,5 mg/l)

DO : desired concentration of dissolved oxygen in the aeration tank (2 mg/l)

K_{DO} : half saturation coefficient for DO (0,5 mg/l)

The specific growth rate of nitrifying bacteria depends on environmental conditions and mainly the temperature, the pH, the DO concentration and the presence of toxic substances. The variation of the specific growth rate of nitrifying bacteria with temperature is described by equation (6) and as a result during the design different operation conditions must be assessed, although winter conditions are less favourable and provide for a safe design.

$$\mu_{nmT} = 0.60 \exp 0.116\,(T-20) \qquad (6)$$

where

μ_{nmT} : maximum specific growth rate of nitrifying bacteria at temperature T °C

Regarding the pH impact, the optimum value of pH is 8.5, while for pH values below 7 nitrification rate decreases significantly.

The required retention time for nitrification can be estimated with equations (5) to (7) based on the desired ammoniacal concentration in the effluent.

$$\theta_{CN} = \frac{1}{\mu_n - b_n} \qquad (7)$$

Dentrification

The removal of total nitrogen by biochemical means demands that oxidation of ammonia to nitrate takes place under aerobic conditions, and that nitrate reduction to nitrogen gas takes place under anoxic conditions. The micro-organisms responsible for denitrification are autotrophic and thus rather slow growing, they demand relatively long SRTs to accumulate and provide close to complete nitrification (i.e. above 90% ammonia removal). This presents another advantage of MBRs where long SRTs are readily attainable.

The relevant chemical reaction is the following:

$2NO_3^- + 2H^+ \rightarrow N_2 + H_2O + 2{,}5O_2$

A large amount of oxygen (64%) that was consumed during nitrification can be recovered during denitrification (2,8g O_2/g(NO_3 -N), whereas during the denitrificaton process half of the hydrogen ions released during nitrification are bound. As a result under controlled denitrification nitrogen removal can be achieved, reduction of oxygen demand and avoidance of biological reaction disturbances due to pH reduction.

Denitrification requires a sufficient carbon source for the heterotrophic bacteria. This can be provided by the raw wastewater, which is why the nitrate-rich waste from the aerobic zone is recycled to mix with the raw wastewater. Complete nitrification is common in fullscale MBR municipal installations, although, since it is temperature-sensitive, ammonia removal generally decreases below 10°C.

In contrast to the nitrification process, which can be carried by only one category of microorganisms (nitrifiers), large numbers of bacteria are able to use the oxygen contained in the nitrates, rather than the dissolved oxygen. Growth in denitrifiers and nitrates removal at steady state (steady-state), can be described by procedures similar to nitrification. Because the denitrification reaction can be regarded as zero-order for NO3-N concentrations higher than 1 mg/L, the design based on the rate of denitrification (qDN) is a reliable alternative approach compared with that of the aged sludge (Θc).

Denitrification rates vary significantly, due to factors such as the adequacy of the organic carbon and the ease with which they can be uptaken by denitrifiers, sludge age, temperature, etc.

The estimation of the denitrification rate is based on the following equation:

$$q_{DN} = \frac{dN}{X_{DN}dt} = 6{,}4 \times 10^{10} e^{-15880/RT} \qquad (8)$$

where

X_{DN} : mixed liquor solids concentration (mg/L)

R : constant value 1,987

T : mixed liquor temperature (°K)

The required anoxic volume for denitrification is estimated by equation (9).

$$V_{DN} = \frac{N}{q_{DN} \times S_V} \qquad (9)$$

where

N : the mass of nitrogen that has to be removed (kg/d)

Sv : volatile solids (MLVSS) in the anoxic tank (kg/m^3).

The quantity of nitrogen to be denitrified is related to the incoming mass of nitrogen (under the assumption of complete nitrification) from which the mass of nitrogen at the effluent and the mass of nitrogen in the sludge are extracted.

Excess sludge

Excess sludge (m^3/d) is calculated by the following equation:

$$W = \frac{(\lambda \times S - Sout)}{(mS - Sout)} \times Q_{des}$$

where

W = excess sludge (m^3/d)

Qdes = design flow (m^3/d)

Sout = effluent suspended solids concentration (mg/L)

S = MLSS (Kg/m^3)

Nitrates recirculation

Nitrates recirculation from the aerobic zone to the anoxic is calculated by the applicaton of equation (10):

$$R = \frac{N_D}{(NO_3 - N)_{EFF}}, \qquad (10)$$

where:

ND	daily mass of denitrified nitrogen (kg/d)
$(NO3\text{-}N)_{EFF}$	effluent mass of nitrates (kg/d)

Oxygen demand

In conventional aerobic biological wastewater treatment processes, oxygen is usually supplied as atmospheric air, either via immersed air-bubble diffusers or surface aeration. At the present design immersed air-bubble diffusers are employed for the supply of the required oxygen. The oxygen requirement to maintain a community of micro-organisms and degrade BOD and ammonia and nitrite to nitrate can be found by a mass balance on the system.

The terms in Equation (11) refer to substrate oxidation, biomass respiration, nitrification and denitrification.

$$R = 0.59(B) + 4.34(NH) - 2.86(NT) + 0.024\,(V*X*R\varepsilon) \qquad (11)$$

where

R = oxygen demand (Kg/d)

B = organic load expressed as BOD_5 (Kg/d)

NH = oxidised ammoniacal load (Kg/d)

NT = denitrified oxidised nitrogen (Kg/d)

X = MLSS (Kg/m^3)

V = anoxic and aerobic volume (m^3)

Rε = specific oxygen demand rate due to endogenous respiration (grO_2/Kg MLSS.)

The specific oxygen demand rate ranges between 2-5 grO_2/KgMLSS. A typical value is $R\varepsilon = 5$ grO_2/Kg MLVSS, for T=20°C. For Για lower temperatures Rε is estimated by the following equation:

$$R\varepsilon_t = R\varepsilon_{20} \times 1.07^{(T-20} \qquad (12)$$

The denitrification-nitrification process calculations are presented in Table 19 and Table 20.

Table 19: Process calculations of the biological treatment process – Scenario 1 – 100 m^3/d

DESING DATA			KINETICS		
POPULATION	500	p	**b***	0,05	1/day
FLOW	0,200	m3/day/p	**μHmax20**	7,0	1/day
BOD*	60	g/day/p	**μHmaxT**	4,0	1/day
SS*	75	g/day/p	**Y***	0,65	
HOURS	24	hr	**β**	0,2	
BODsol_efffl	4,20	mg/l	**α**	0,1	
			bb*	0,05	
Nex	0,840	mg/l	**Yn***	0,15	
Nex	0,840	mg/l	**μn**	0,216	
T*	12	oC	**Kn**	0,500	
NH4 effl	1	mg/l	**Sf**	1,101	
NH4εξ	0,840	mg/l	**TAC***	500	
MLSS*	8000	mg/l	**NH4effl real**	0,840	mg/l
N*	12,00	g/day/p			
Su*	12000	mg/l			
			peak*	1,500	
N aer.	1		**aox***	0,590	
N c*	0		**box***	0,120	kg/kgSS/day
Edif.*	0,1		**Ret**	5	gr/kgVSS/hr
P*	2,5	g/day/p			
Synt	0,85				
bn*	0,05		**Eden**	0,847	
θθc	0,135				
1/θθc	7,396		**Rmax**	6,250	
			tai*	1	
θ nitrification	10,663	days			
DO	2	mg/l			
KDO	0,5	mg/l			

DIMENSIONING					
BODin	300,00	mg/l	**Nin**	60,000	mg/l
SSin	375,00	mg/l	**m**	1,500	
SSiv	262,50	mg/l	**r**	1,930	
SSif	112,50	mg/l	**w**	2,315	m3/day
E	0,986	(-)	**w*Su**	27,778	kg/day
EReal	0,989	(-)	**Yo**	0,939	
Θc aer	11,74	d	**O**	2,241	Kg/h
Z1	135,391	mg/l	**Omax**	2,090	Kg/h
Z2	26,250	mg/l	**P in.**	12,500	mg/l
EnReal	0,986	(-)	**P effl**	4,375	mg/l
En	0,983	(-)	**NO3 effl real**	7,00	mg/l
Zn	5,593	mg/l	**NO3 effl**	7,00	mg/l
%nitrifiers	1,999		**Nmic/gr***	80	mg N/g micro

DIMENSIONING					
TAC εξ.	216,381		**NO3 den**	3,9	mg/l
N org effl	0,092	mg/l	**NO3 den**	45,87	mg/l
Z3	112,500	mg/l	**Air**	79,47	m3/h
Z	279,734	mg/l	**Airm**	74,12	m3/h
λ aer	0,035	(-)	**SS effl**	2	mg/l
Θ aer	0,410	day	**Rmax/Q**	1,5	
V aer	41,034	m3			
Tot.V	41,034	m3			
Θ tot	0,636	day			
qpar	5,44				
qan	0,0361	gNO3/gVSS/day			
M anox	107775	g VSS			
V anox απαιτ	22,535	m3			
Vtot	63,569	m3			
Θc anox	6,445	day			

INLET			OUTLET		
Flow	100	m3/d	**Qmax**	150	m3/d
BOD5	300	mg/l	**BOD5**	4,20	mg/l
SS	375	mg/l	**SS**	2,00	mg/l
SVS	263	mg/l	**N org**	0,09	mg/l
Norg.	21,00	mg/l	**NH4 req**	1,00	mg/l
NH4	39,00	mg/l	**NH4**	0,84	mg/l
NO3	0	mg/l	**NO3**	7,00	mg/l
TAC	500	mg/l	**TAC**	216	mg/l
P	12,50	mg/l	**P**	4,38	mg/l

	RESULTS – EFFLUENT CHARACTERISTICS				
MCRTa	11,74	d	**Va**	41	m3
MCRTan	6,44	d	**Van**	23	m3
MCRT	18,18	d	**Vtot**	64	m3
T	12,00	oC	**Qr**	8	m3/hr
E	0,986		**Sludge**	26	Kg/d
En	0,986		**O2**	2,24	Kg/hr
Edn	0,847		**O2max**	2,09	Kg/hr
MLSS	8000	mg/l	**NVtot**	1	
Su	12000	mg/l			
F/Ma	0,091	Kg/kg			
F/M	0,059	Kg/kg			
F/V	0,472	Kg/m3			
Θ tot	15,26	hr			
MLVSS	4583	mg/l			

Table 20: Process calculations of the biological treatment process – Scenario 2 – 300 m^3/d

DESING DATA			KINETICS		
POPULATION	1500	p	b*	0,05	1/day
FLOW	0,200	m3/day/p	μHmax20	7,0	1/day
BOD*	60	g/day/p	μHmaxT	4,0	1/day
SS*	75	g/day/p	Y*	0,65	
HOURS	24	hr	β	0,2	
BODsol_efffl	4,20	mg/l	α	0,1	
	0		bb*	0,05	
Nex	0,840	mg/l	Yn*	0,15	
Nex	0,840	mg/l	μn	0,216	
T*	12	oC	Kn	0,500	
NH4 effl	1	mg/l	Sf	1,101	
NH4εξ	0,840	mg/l	TAC*	500	
MLSS*	8000	mg/l	NH4effl real	0,840	mg/l
N*	12,00	g/day/p			
Su*	12000	mg/l			
	20		peak*	1,500	
N aer.	1		aox*	0,590	
N c*	0		box*	0,120	kg/kgSS/day
Edif.*	0,1		Ret	5	gr/kgVSS/hr
P*	2,5	g/day/p			
Synt	0,85				
bn*	0,05		Eden	0,847	
θθc	0,135				
1/θθc	7,396		Rmax	18,750	
			tai*	1	
θ nitrification	10,663	days			
DO	2	mg/l			
KDO	0,5	mg/l			

DIMENSIONING					
BODin	300,00	mg/l	Nin	60,000	mg/l
SSin	375,00	mg/l	m	1,500	
SSiv	262,50	mg/l	r	1,930	
SSif	112,50	mg/l	w	6,944	m3/day
E	0,986	(-)	w*Su	83,334	kg/day
EReal	0,989	(-)	Yo	0,939	
Θc aer	11,74	d	O	6,723	Kg/h
Z1	135,391	mg/l	Omax	6,270	Kg/h
Z2	26,250	mg/l	P in.	12,500	mg/l
EnReal	0,986	(-)	P effl	4,375	mg/l
En	0,983	(-)	NO3 effl real	7,00	mg/l
Zn	5,593	mg/l	NO3 effl	7,00	mg/l
%nitrifiers	1,999		Nmic/gr*	80	mg N/g micro
TAC εξ.	216,381		NO3 den	11,7	mg/l
N org effl	0,092	mg/l	NO3 den	45,87	mg/l

DIMENSIONING					
Z3	112,500	mg/l	**Air**	238,40	m3/h
Z	279,734	mg/l	**Airm**	222,35	m3/h
λ aer	0,035	(-)	**SS effl**	2	mg/l
Θ aer	0,410	day	**Rmax/Q**	1,5	
V aer	41,034	m3			
Tot.V	41,034	m3			
Θ tot	0,636	day			
qpar	5,44				
qan	0,0361	gNO3/gVSS/day			
M anox	107775	g VSS			
V anox απαιτ	22,535	m3			
Vtot	63,569	m3			
Θc anox	6,445	day			

INLET			OUTLET		
Flow	300	m3/d	**Qmax**	450	m3/d
BOD5	300	mg/l	**BOD5**	4,20	mg/l
SS	375	mg/l	**SS**	2,00	mg/l
SVS	263	mg/l	**N org**	0,09	mg/l
Norg.	21,00	mg/l	**NH4 req**	1,00	mg/l
NH4	39,00	mg/l	**NH4**	0,84	mg/l
NO3	0	mg/l	**NO3**	7,00	mg/l
TAC	500	mg/l	**TAC**	216	mg/l
P	12,50	mg/l	**P**	4,38	mg/l

	RESULTS – EFFLUENT CHARACTERISTICS				
MCRTa	11,74	d	**Va**	123	m3
MCRTan	6,44	d	**Van**	68	m3
MCRT	18,18	d	**Vtot**	191	m3
T	12,00	oC	**Qr**	24	m3/hr
E	0,986		**Sludge**	78	Kg/d
En	0,986		**O2**	6,72	Kg/hr
Edn	0,847		**O2max**	6,27	Kg/hr
MLSS	8000	mg/l	**NVtot**	1	
Su	12000	mg/l			
F/Ma	0,091	Kg/kg			
F/M	0,059	Kg/kg			
F/V	0,472	Kg/m3			
Θ tot	15,26	hr			
MLVSS	4583	mg/l			

3.3.2.2 MBR

MBR modules

The design of the MBR is directly related to the membrane flux rate with typical values between 20-30 L/m^2-h. The membranes are installed in a separate tank where they are submerged in an external separtion vessel. This configuration allows for fine bubble areation in the areation tank and coarse bubble diffusers in the membrane compartment for membrane scourig and fouling control.

Airscouring

For cleaning of the membranes and to avoid deposits which could lead to clogging of the pores at the bottom of the membranes air is supplied in the form of coarse bubbles, which both ascending and contacting the surface of the membranes, on the other to create upwelling, achieves the continuous cleaning of the membranes. The dimensioning of the required air is performed with the assumption of 0,5 Nm^3/h per m^3/d of inflow.

The supplied air is regarded as providing part of the required oxygen for life processes (oxidation of organic and nitrification). Because this is provided by diffusion medium - coarse bubble, efficiency of diffusion is small, is obtained equal to 2% under normal conditions.

Chemical cleaning

Membrane chemical cleaning depends on the operating conditions and is usually limited to two to four times a year. Sodium hypochlorite solution (NaClO) is applied to remove organic coating and solution of citric acid to remove inorganic coating. The required quantity of chemical solution per sheet membrane is to the order of 5lt / sheet.

The MBR process calculations are presented in Table 21, Table 22 and Table 23.

Table 21: Process calculations of the MBR

	Scenario 1	Scenario 2
Maximum design flow m^3/d	150	450
Maximum design flow m^3/h	6,25	18,75
Actual design flow m^3/h (the real operation time is considered with assumption that for every 10 min operation 1 min is rest time)	6,94	20,83
Maximum membrane flux lit/m^2/h	30	30
Required membrane surface m^2	231	694
Elements per module	200	200
Surface /module m^2/module	280	280
Required number of modules	0.83	2,48
Installed modules	1	3
Surface/module m^2/module	280,00	280,00
Total membrane surface m^2	280,00	840,00
Real membrane Flux lit/m^2/h	24,80	24,80

Table 22: Air scouring

	Scenario 1	Scenario 2
Air/design flow Nm^3/h per m^3/d	0.5	0.5
Air flow total Nm^3/h	85	250

Table 23: Chemical cleaning

	Scenario 1	Scenario 2
Chemical solution required/ element lit/element	5	5
Chemical solution required / module lit/module	1000	1000
Chemical solution required / line lit/line	1000	3000
Number of cleaning procedures	2	2
NaClO solution tank lt	2000	6000
Citric acid tank lt	2000	6000
Chemical solution feeding time to modules h	0,5	0,5
Chemical dosing pumps capacity m^3/h	2	6

3.3.3 RO

The need for RO as a post treatment level derives from the necessity to treat wastewater with a high salinity content. The treatability of RO membranes is mainly assessed by the slit density index (SDI) and the modified fouling index (MFI). The SDI is a static measurement of resistance and varies between 0-3, while the MFI index is 0-2s/L^2. The critical design parameter as in the case of UF membranes is the flux rate which varies from 12-20 L/m^2-h. Two key variables that affect flux are temperature and operating pressure. Flux increases with higher temperature because fluid viscosity decreases. The flux through membranes increases by about 3% per degree Celsius (Metcalf& Eddy, 2007), whereas as the pressure increases the flux increases linearly and the product quality increases.

Discharge to wastewater collection system is a viable consideration where the retentate comes from a satellite treatment facility and the volume of the retentate is relatively small compared to the total flow of the central wastewater treatment plant. It is evident that in these cases site specific regulations for disposal in the sewerage network must be followed.

3.3.4 Disinfection with UV

Disinfection is required to ensure the microbial integrity of the product water and to prevent bacterial regrowth in storage and distribution systems. A number of low and medium pressure high intensity UV disinfection systems are designed to operate in closed channels. In most design configurations the direction of the flow is perpendicular to the placement of the lamps, while design configurations in which direction of flow is parallel to the UV lamps also exist.

The effectiveness of the UV disinfection process depends on a number of factors such as the chemical characteristics of the reclaimed water, the presence of particles, the characteristics of the microorganisms and the physical characteristics of the UV disinfection system and is based on the UV dose to which the microorganisms are exposed and is expressed as

$D = I_{avg} \times t$

where D=UV dose, mWsec/cm^2

I_{avg} = average UV intensity, mW/cm^2

t = exposure time, s

The design of the UV disinfection unit should meet the minimum requirements of Table 14 and the effluent standards of Table 13.

4 Operational considerations

4.1 Fouling

Municipal and industrial waste waters contain organic and inorganic matter. During wastewater treatment by membranes, the constituents of the feed concentrate and a separation of particles at the membrane surface occurs due to the selective effect of the membrane. With increasing operating time, this results in the development of a covering layer. Covering layers can be used to a certain extent in a beneficial way for filtration (e. g. in order to increase the purification degree), but often they are undesirable because they diminish the permeate flow and thus the performance of the membrane.

The reducing performance of the membrane is based on an increase in the filtration resistance, which increases the output membrane resistance. Concerning the micro- and ultrafiltration membranes, the increased covering layer resistance results from adsorption, pore blockage and the covering layer formation itself. However, the increase of the filtration resistance of the tight nanofiltration and reverse osmosis membranes is due to a concentration polarisation of dissolved matter, the concentration of which rises with increasing filtration duration. Increased resistances due to adsorption and pore blockage normally cannot be reduced by measures such as backwashing, so that during severe pore blockage another membrane material should be used. On the other hand covering layer formation can be decreased or undone by increasing the overflow velocity or backwashing the membrane with permeate in intervals.

The formation of covering layers can have different causes, which also determine the composition of the layer, and more specifically biological fouling, colloidal fouling and scaling.

Biofilm formation on the membrane surface is caused by adhesion and the growth of microorganisms. Biofouling means that the biofilm causes a reduction of the performance of the membrane system by decreasing the specific membrane flow. Plant shut-downs should be treated with caution, since under these conditions the number of bacteria on the membrane surface may increase dramatically.

From the accumulation of colloids results a kind of film or mucus on the membrane surface, which leads to a reduction of the filtration capacity.

Scaling can be described as coatings on the membrane formed by inorganic precipitations (crystallization). Usually they only occur with NF and RO membranes if, for example, the solubility limit of dissolved salts is exceeded by excessive concentration on the membrane surface.

The parameters that affect membrane fouling vary significantly thus increasing the difficulty entailed in the examination of this phenomenon. These parameters can be grouped into four main categories: (a) the properties of the biomass, (b) the characteristics of the membrane, (c) the operational conditions and (d) the characteristics of the feedwater. The properties of the biomass and the characteristics of the membranes directly influence the phenomenon, while and the characteristics of the wastewater and the operating conditions indirectly through their impact to the biomass characteristics. Table 24 summarises the parameters that influence fouling (Malamis, 2009).

Table 24: Parameters that influence membrane fouling

Source: Malamis, (2009)

Biomass	Membrane	Operational conditions	Feedwater characteristics
EPS	Material	SRT	Organic load fractions
Organic colloids	Porosity	Organic load	Inorganic substances
Biofloc size	Module configuration	HRT	
Biofloc structure	Hydrophobic/Hydrophilic	Aeration conditions	
Permeability	Porous size	Flux	
MLSS	Porous distribution	Crossflow velocity	
DO			
Temperature			
Viscosity			
Settling properties			

4.2 Maintenance

Conrol of the membrane fouling is achieved by applying a combination of purification techniques. The usual techniques applied in almost all MBR systems combine air scouring and periodic chemical cleaning. Furthermore, the optimization of operating parameters of the system and especially the SRT significantly reduces memrbrane fouling, while the addition of chemicals or other additives with adsorptive or flocculant properties, in system biomass contributes significantly to the improvement of sludge filtration characteristics (Malamis, 2009). Operation and maintenance protocols for specific technologies are normally recommended by the membrane and/or process suppliers and sometimes further adapted for specific applications. Fundamental relationships between cleaning requirements and operating conditions, usually flux and aeration for submerged systems, have been generated from scientific studies of fouling (Judd, 2006).

Key design parameters relating to membrane cleaning are: period between physical cleans, where the physical clean may be either back-flushing or relaxation; duration of the physical clean; period between chemical cleans; duration of the chemical clean; back flush flux; cleaning reagent concentration and volume normalised to membrane area.

The course of the flow over time at a constant transmembrane pressure with and without chemical cleaning is represented in Figure X. Despite the significant improvement of the flow capacity by the chemical cleanings, the flow decreases with increasing filtration time. This phenomenon is explained by irreversible fouling, which cannot be eliminated by cleaning. For membrane cleaning, chemical cleaning agents are used in combination with backwashing (permeate side) or flushing (feed side). In principle, we distinguish three types of cleaning: backwashing/flushing of the membrane, interim cleaning using chemicals in lower concentration, e. g. weekly and intensive cleaning using chemicals in higher concentration, e. g. biannually. The cleaning agents used for intensive cleaning have a higher concentration than those used for interim cleaning. The cleaning agent is chosen depending on the substances in the covering layer (Table 25).

The effectiveness of cleaning does not only depend on the cleaning agents applied and their chemical activity, but is also determined by factors such as temperature, pH value, contact or reaction time, concentration of the active substance, and mechanical forces. The cleaning result improves with higher temperatures or longer cleaning times. At higher temperatures the cleaning time can be reduced, or the temperature can be lower with a longer cleaning time. In order to adjust the pH value, it is necessary to consider not only the compatibility with the membrane- or the module material, but also the specific effectiveness of the cleaning agent in dependence on the pH.

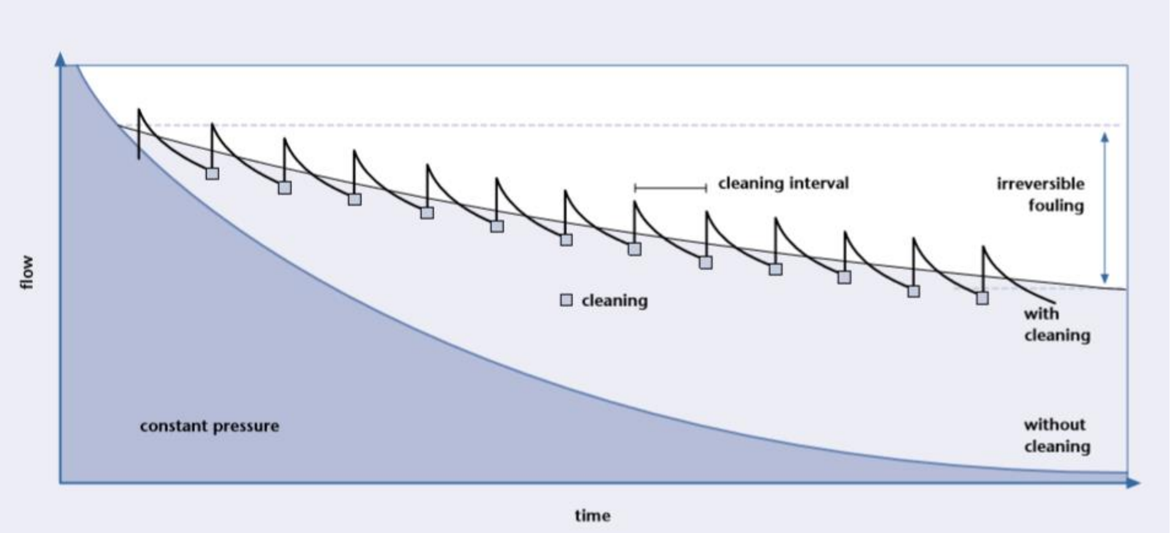


Figure 7: Effect of membrane cleaning on the flow at constant pressure (ISA, 2003)

Table 25: Examples of cleaning chemicals and their applications
Source: ISA, (2003)

	Operational conditions
Calcium-, magnesium scaling	Acids, e.g. citric acid, acetic acid
Metal hydroxide, inorganic colloids	Acids, e. g. citric acid
Organic substances	Anionic surfactants, oxidants, e. g. hypochlorite, hydrogen peroxide, alkaline cleaning agents, e. g. caustic soda solution
Bacteria, germs	Disinfectants, hypochlorite; biocides

For handling the cleaning chemicals, the references on possible hazards of the respective safety data sheets must be considered. This is of special importance in cases where the personnel are not familiar (or only to a limited extent) with the use of hazardous materials, e. g. at wastewater treatment plants. Moreover it has to be considered that some cleaning chemicals, after having been used for cleaning, may have undesirable effects on the permeate quality. After cleaning these cleaning solutions have to be collected, if necessary, and disposed of separately.

It is necessary to aerate the membrane unit in an MBR to scour solids from the membrane surface. In practice the membrane aeration value is not defined theoretically since the relationship between aeration and flux decline is not well understood at present. Membrane aeration values are based on previous experience, and in many cases the suppliers recommend an appropriate aeration rate.

There are two main types of aeration used in MBR plants: coarse bubble aeration, fine bubble aeration and, less commonly, jet aeration. The principal differences between the two main aerator types are given in Table 22. Traditionally, fine bubble diffusion has been used for biomass aeration and a separate coarse bubble aeration system applied for membrane scouring. In many proprietary systems separate tanks are provided for the membrane to simplify membrane cleaning operations. During the process of scouring the membrane, if air is used, there is some transfer of oxygen into the biomass which raises its DO level in the biomass. Membrane aeration is usually carried out using coarse bubble aeration because of the increased turbulence and hence shear forces created, whilst biomass aeration is usually performed using fine bubble devices because of the enhanced oxygen transfer (Table 26) (Judd, 2006).

Table 26: Main features of aeration systems, Source: Judd, (2006)

	Fine bubble	Coarse bubble
Bubble size	2-5 mm	6-10 mm
% of oxygen transfer per m of depth	3-10%	1-3%
Mechanical component	Air blower	Air blower
Diffuser type	Ceramic or membrane diffuser disk, dome or tube	Steel or plastic disk or tube
Shear rate (Shear rate is a measure of propensity to ameliorate membrane fouling)	The small bubble sizes provide lower velocity and hence smaller shear forces.	Bubble velocity, and so shear, is higher than fine bubble aeration since the larger bubbles rise faster than small bubbles.

4.3 Personnel

A membrane bioreactor differs from a conventional activated sludge plant with view to operation and process engineering and currently there is still need for training of the operating personnel of membrane installations.

4.4 On-line monitoring and control of treatment system

As with other process plant for water and wastewater treatment, feedback control and alarm triggering relies on monitoring of key parameters such as TMP (for indicating membrane fouling condition and triggering a cleaning cycle), DO (for biological process control) and turbidity (for membrane integrity). The principle impact of added process complexity is on the software and programmable logic controllers (PLCs), and on ancillary hardware such as pumps, valves and actuators. Foaming control and abatement procedures are particularly important in an MBR since aeration is more intense than for an ASP. Sludge wasting for SRT control can be based on on-line MLSS measurement, although instruments have only recently developed for this (Judd, 2006).

The performance of the treatment process is related to the raw water quality and the operating conditions. It is recommended to monitor and record the values of operating parameters in order to achieve the stable operation and the expected performance. These include: (1) Scouring Air Flow rate (2) Diffusion pressure (3) Permeated water flow rate (4) Trans-membrane pressure (TMP) (5) Liquid temperature of membrane submerged tank (6) DO concentration of membrane submerged tank (7) pH of membrane submerged tank (8) MLSS (9) Raw water quality (BOD, COD, TSS, turbidity) (10) Permeated water quality (11) Excess-sludge discharge rate.

In Figure 8, control points are shown and relevant parameters that need to be monitored are indicated. More specifically these include:

Pretreatment	Flow, turbidity, TSS
MBR	

Anoxic	NO3,
Aerobic	DO, TMP, Flux, MLSS, Recycle flow rate, excess sludge
Biological treatment outlet	NO3, NH4, COD, TSS, pH, Turbidity, Conductivity
RO	Flow, TMP, Flux, Concentrate flow rate
UV Disinfection	Flow, Turbidity, Conductivity, UV transmittance, pH, UV intensity

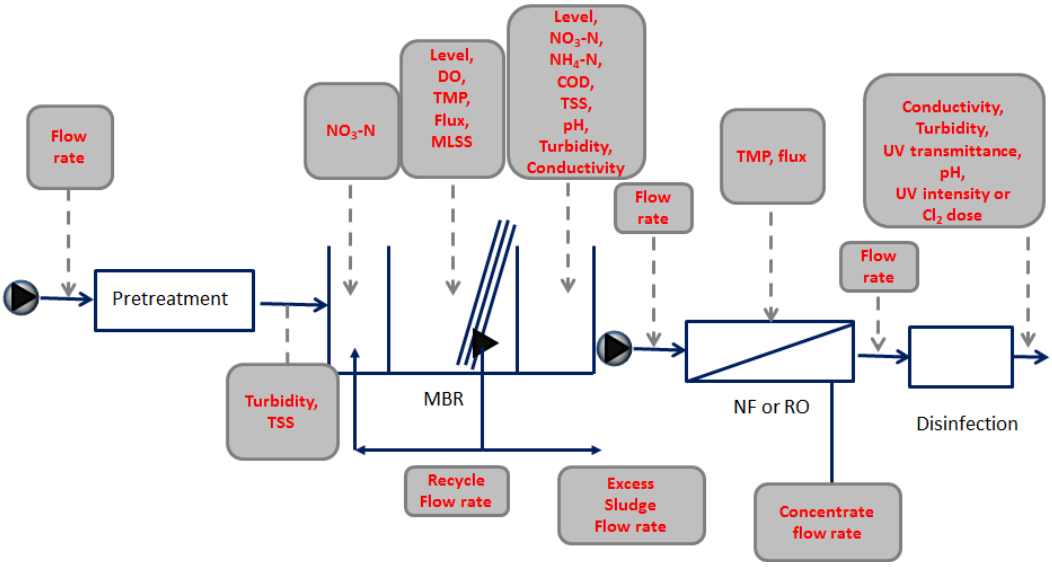


Figure 8: On-line monitoring and control of treatment system

A flow meter combined with an automatic control valve, should be installed on the permeate water line to control the flow rate of permeate water. For trans-membrane pressure (TMP) determination the differential pressure (in the permeate line and water level) has to be measured and calculated, either by installing two pressure sensors and calculating the readings in the PLC or by using a differential pressure device. Level sensor is necessary to be installed in the membrane submerged tank to monitor and control the liquid level of the membrane tank and to calculate the TMP in PLC.

5 Optimization of the plant

5.1 Set-up of the benchmark study

In the context of this deliverable a benchmark study was undertaken in order to provide rules for the optimization of the operation of the proposed membrane wastewater treatment system. This benchmark study was performed through mathematical modelling of the operation of the demonstration system under alternative operational conditions. The optimization process refer to the operation of the MBR unit. A flow diagram of the simulated system is presented in Figure 9.

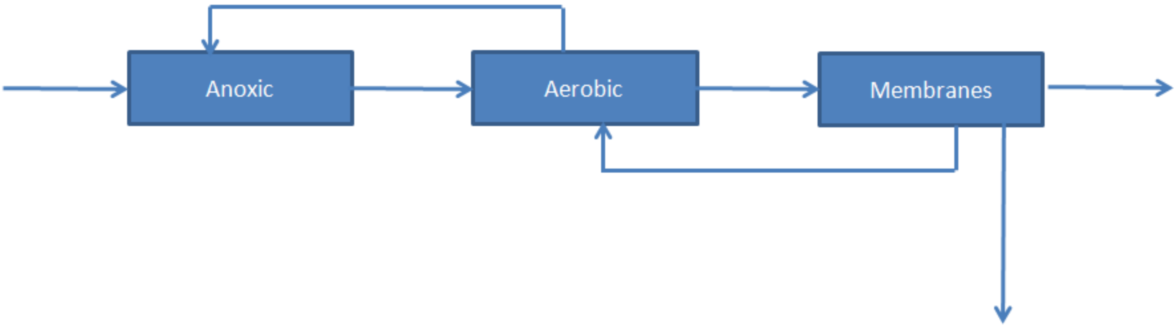


Figure 9: Flow diagram of the simulated system

More specifically an MBR treatment unit consisting of an anoxic, an aerobic and a membrane tank was simulated. The simulation was performed for the reference Scenario 1 of Chapter 3 (influent flow rate of 100 m^3/d) and therefore the characteristics of the raw wastewater are the following (Table 27):

Table 27: Characteristics of the raw wastewater used in the benchmark study.

Parameter	Units	Scenario 1
Daily flow	m^3/d	100
Hourly peak flow	m^3/h	6.3
	l/s	1.75
COD	kg/d	30.0
BOD	kg/d	75.0
SS	kg/d	37.5
TKN	kg/d	6.0
TP	kg/d	1.25
COD	mg/L	750.00
BOD	mg/L	300.00
SS	mg/L	375.00
TKN	mg/L	60.00
TP	mg/L	12.50

According to the analysis of Chapter 3 the MBR effluent for every simulated scenario should comply with the following requirements (Table 17):

Table 28: Effluent quality characteristics used in the benchmark study

Parameter	Units	Effluent characteristics
Total Coliforms	TC/100 ml	≤ 2 *for 80% of the samples and* ≤ 20 *for 95 % of the samples*
BOD_5	mg/L	≤ 10 *for 80% of the samples*
SS	mg/L	≤ 2 *for 80% of the samples*
Turbidity	mg/L	≤ 2 *for 50% of the samples*
Total nitrogen	mg/L	15
Ammoniacal nitrogen	mg/L	2

Based on the results of the process design calculations presented in Chapter 3, the total volume of the MBR system for the treatment of 100 m^3/d of raw wastewater is 64 m^3. The simulated bioreactor is comprised of an anoxic tank with an effective volume of 17 m^3, an aerobic tank with an effective volume of 39 m^3 and a membrane tank with an effective volume of 8 m^3. The simulation of the operation of the MBR system was performed by using an activated sludge mathematical model which is based on ASM1 and has been developed by the Sanitary Engineering Laboratory of the National Technical University of Athens.

According to the methodology followed, the operation of the treatment plant was simulated for seven alternative operating scenarios. The basic operating parameter that was changed in every simulated scenario was the value of the solids retention time (SRT). More specifically the following SRT values were examined: 5.2 d, 5.8 d, 7.2 d, 9 d, 13.7 d, 18 d, 24.4 d. The optimization of the operation of the MBR system was performed by using the following criteria:

- ✓ <u>Final effluent quality</u>: The effluent quality of the MBR permeate was evaluated: a) in terms of the effluent concentrations of organic carbon (in terms of BOD_5 and COD), nitrate-nitrogen (NO_3-N), ammoniacal nitrogen (NH_4-N) and total nitrogen (TN) and b) by using the effluent quality index EQI). EQI is an aggregated weighted index of all pollutional loads of the treated effluent (COD, BOD_5, TKN, NOx, TSS) which has been extensively used in benchmark simulation models (Nopens et al., 2010). The calculation of EQI is based on equations (13)-(14):

$$EQI = \frac{1}{1000(t_f - t_0)} \int_{t_0}^{t_f} PU_{(t)} Q_{e(t)}\, dt \tag{13}$$

$$PU_{(t)} = PU_{TSS(t)} + PU_{COD(t)} + PU_{BOD(t)} + PU_{TKN(t)} + PU_{NO_3(t)} \tag{14}$$

where PU represents the load of each pollutant in kg/d and is calculated by:

$$PU_k = \beta_k C_k \tag{15}$$

The factors β_k are weighting factors that are attributed to each effluent parameter. In this study, the following factors were used: $\beta_{COD} = 1$; $\beta_{BOD} = 2$; $\beta_{TKN} = 30$; $\beta_{NO3} = 10$.

- ✓ Energy demand: In the present study the energy consumption of the aeration system was evaluated. The calculations were based on an average energy efficiency factor of 4 kgO_2/kWh and the energy demand was calculated in kWh/PE/y (annual energy consumption per population equivalent) by assuming that the design flow of 100 m^3/d corresponds to 500 PE.
- ✓ Quantity of sludge produced: The quantity of sludge produced was calculated by the mathematical model for each examined scenario.
- ✓ Membrane fouling: The selection of the optimum conditions to tackle the problem of membrane fouling was based on the extensive experience of the research team and the literature. Based on these, a minimum value of SRT to the order of 15 d is required in order to decrease the production of the precursors that lead to the formation of membrane fouling (Malamis 2009a; Malamis and Andreadakis 2009b).
- ✓ Greenhouse Gas Emissions (GHG): The calculation of GHG emissions (in CO_2^{eq}/PE/y) was performed based on the model proposed by Mamais et al., (2015). The major on site GHG emissions considered were generated from the biological wastewater treatment while off site gas emissions considered were only from the energy consumption. Total on site GHG emissions (kg/d) during biological wastewater treatment were estimated by taking into account the following processes: i) CO_2 production from biomass decay, ii) CO_2 production from BOD_5 removal and biomass production, iii) CO_2 consumption from nitrification, iv) CO_2 production from denitrification and v) N_2O (in equivalent CO_2) production from nitrification and denitrification processes.

5.2 Results of the benchmark study – Optimization rules

The results of the benchmark study for the seven simulated scenarios (SRT between 5.2-24.4 d) are presented in Figures 10-15.

More specifically Figure 10 illustrates the variation of effluent organic carbon concentrations (in terms of BOD_5 and COD) with respect to the operating SRT. Accordingly Figures 11, 12, 13 and 14 present the dependence of effluent nitrate-nitrogen, ammoniacal nitrogen and total nitrogen, oxygen demand and sludge quantity on the operating SRT. Finally Figure 15 illustrates the variation of EQI, GHG emissions and energy consumption with the increase of SRT.

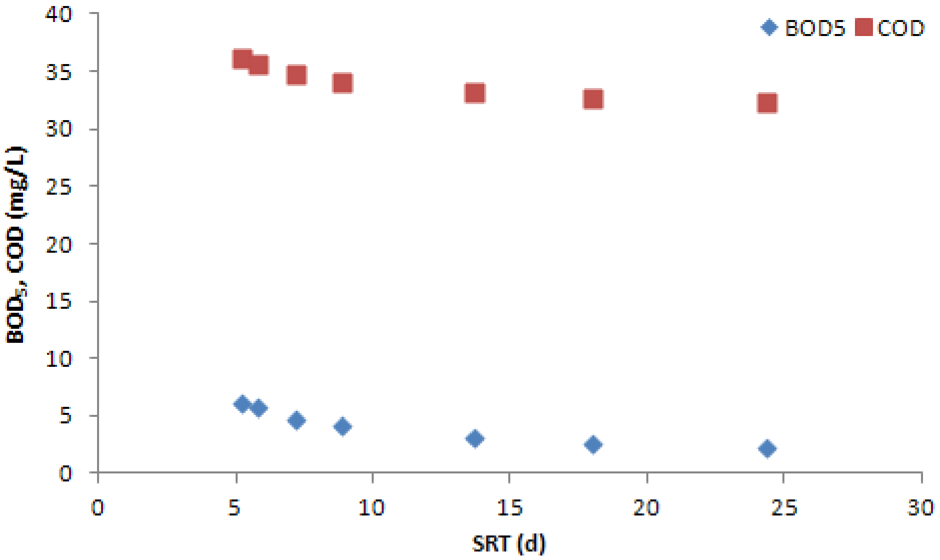


Figure 10: Organic carbon effluent concentrations with respect to SRT

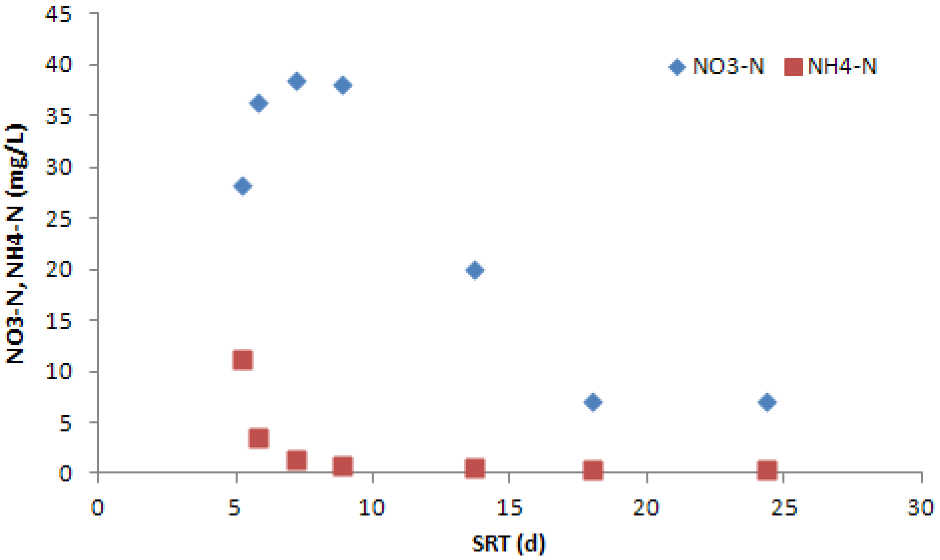


Figure 11: NO_3-N and NH_4-N effluent concentrations with respect to SRT

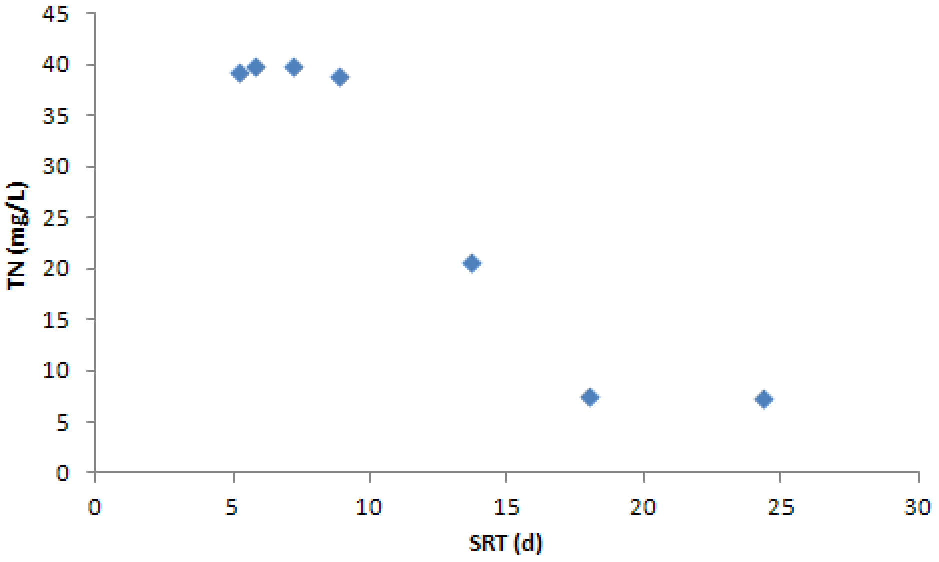


Figure 12: Total nitrogen effluent concentrations with respect to SRT

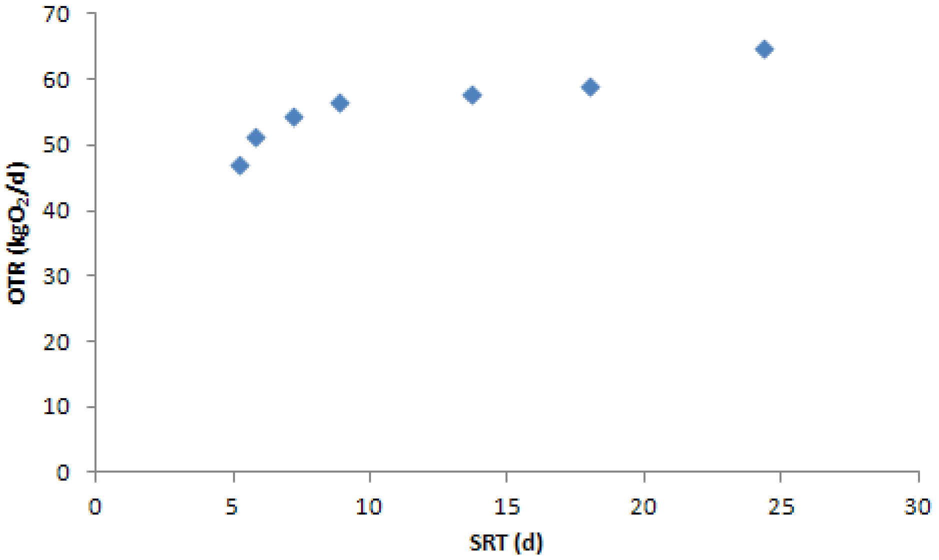


Figure 13: Oxygen transfer rate with respect to SRT

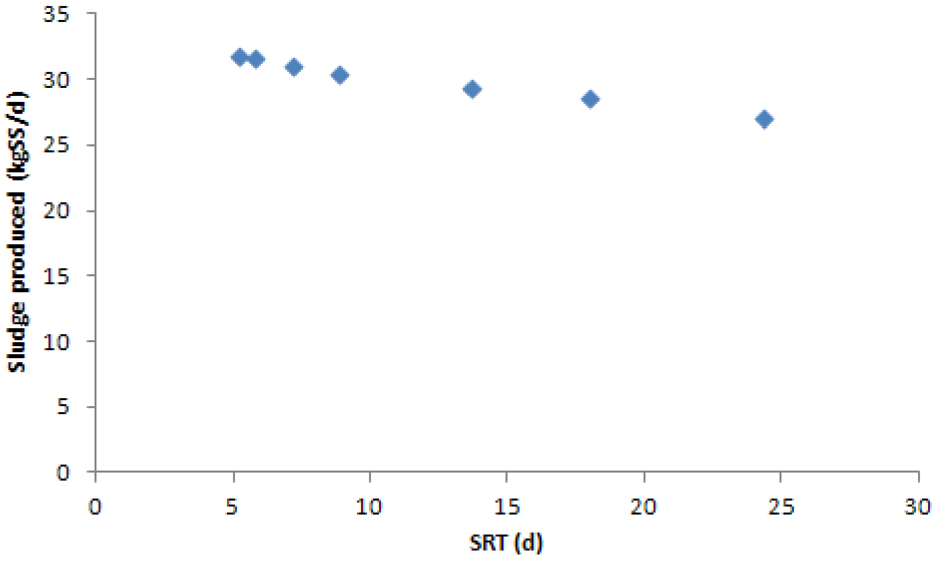


Figure 14: Sludge production with respect to SRT

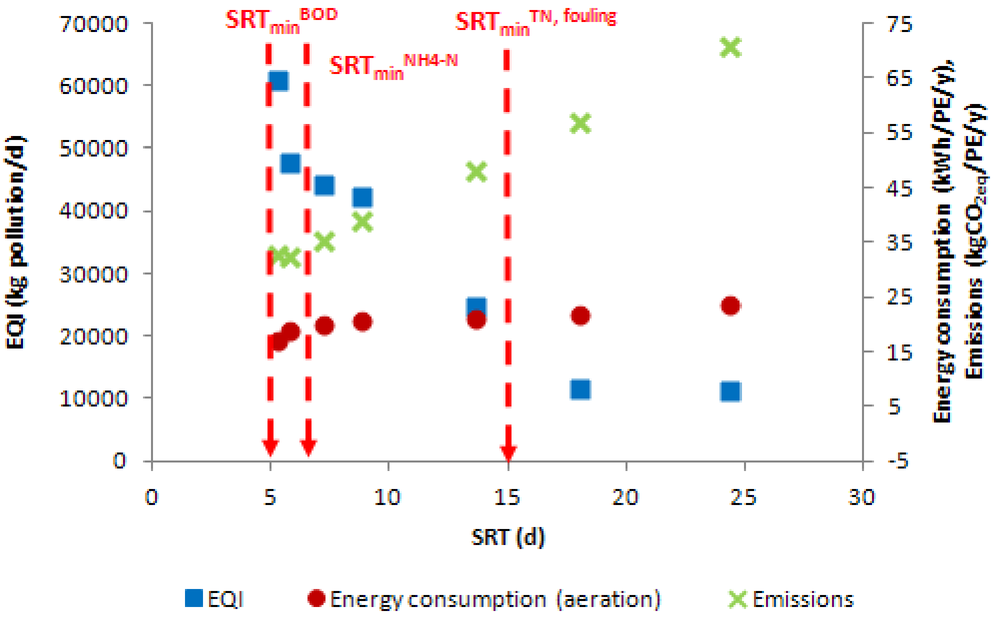


Figure 15: EQI, energy consumption and GHG emissions with respect to SRT

Based on the results of the benchmark study, the effect of SRT on the performance of the treatment system is profound. More specifically the minimum SRT required in order to comply with the effluent limits for BOD_5, NH_4-N and total nitrogen concentrations are 5d, 6.5 d and 15 d respectively (Figures 10-12 and Figure 15). Furthermore it is well documented that a minimum SRT of 15 d is required in order to cope with membrane fouling. Therefore it seems that an optimum range of SRT for the operation of the MBR system is between 15-20d. As depicted in Figure 15, under these conditions low EQI values are achieved, while the increase of the energy consumption for aeration is rather minimal (3-8%). The only disadvantage of this practice is the increase of the direct on site GHG emissions which for SRT between 15-10 d seem to increase by a factor of 50% compared to the operation at lower SRT values. However it should be noted that the calculated absolute values of GHG emissions are rather low for every simulated scenario and therefore the effect is practically very limited.

In view of the above the optimum operating conditions for the MBR system can be summarized to the following:

- Minimum dissolved oxygen concentration in the bioreactor: 2 mg/L
- Minimum internal recirculation ratio: 400%
- Minimum mixed liquor suspended solids concentration in membrane tank 8 g/L
- Minimum solids retention time: 15 d

6 Conclusions

Due to global climate change and rapid population growth, there has been a worldwide effort to reduce the use of natural resources. Turning waste into a resource is an essential part of increasing the efficiency of resources and moving towards a more circular economy. Various EC reports stress the need to encourage European stakeholders to first acknowledge that "water is an essential but limited resource and needs to be carefully allocated and used", and then to endorse and promote circular and green economies. In the context of the urban water cycle, this translates primarily into using treated wastewater (a waste) to supply (as a resource) a non-potable water use. Wastewater reuse can be implemented at several scales, associated with the degree of centralisation of the treatment employed. For example existing centralized wastewater treatment facilities can open up non-potable reuse options, especially in large water non-potable reuse options, especially in large water consumers such as agriculture or industry. However, as centralised wastewater treatment plants are usually not close enough to agricultural or industrial activities the operation and construction of treated effluent conveyance systems is costly and can, in some cases, turn this alternative unattainable.

Within the concept of the DESSIN project another alternative for urban wastewater reuse is evaluated, namely sewer-mining (SM). SM extracts wastewater from local sewers, treats it at the point of water demand and supplies local urban wastewater non-potable uses (such as urban green irrigation) while returning treatment residuals back to the sewer system for eventual treatment in the centralised wastewater treatment plant thus eliminating the need for expensive conveyance systems. Therefore SM is considered a decentralized technology that is closer to the circular economy concept, in that by closing the loop between waste and resource locally, wastewater becomes not 'just' a by-product of the urban wastewater system with some potential for reuse, but a resource per se, also decreasing (or eliminating) the barrier of wastewater conveying costs.

As shown in Chapter 1, according to the wastewater reuse legislations of most developed countries, in selecting appropriate treatment operations and processes for wastewater reuse applications the provision of multiple barriers is an important consideration. The advantages of this concept are related to the provision of a degree of public and environmental protection even in the event one of the barriers should fail, the reduced probability that multiple processes will fail simultaneously and the robustness to potential process upsets because a greater number of barriers is used. This principle is applied also in urban wastewater reuse guidelines that consider urban reuse as an unrestricted wastewater reuse option. Most regulations for urban reuse recommend a combination of strict reclaimed water quality limits and application of advanced wastewater treatment unit processes.

Dual-membrane processes, such as an ultrafiltration (UF) with an RO, are gaining popularity in the process of reclaiming municipal wastewater for urban reuse due to their high treatment efficiency and small footprint. The role of the UF membranes is to perform secondary and tertiary treatment of wastewater and RO, if needed, acts as a final polishing treatment step. A membrane bioreactor (MBR) can carry out the secondary and tertiary treatment of sewage and produces an effluent that following disinfection fulfills the strict quality and treatment criteria of unrestricted urban reuse. The RO unit may be required as a post treatment level in the case of reuse of saline wastewater. Therefore a combination of MBR followed by a nanofiltration or a reverse osmosis unit has a great potential for the treatment of raw sewage to produce reclaimable water and falls very well in the concept of applying multiple barriers to protect public health. Adding to that, the fact that European regulations could evolve in the future with the addition of new compounds and the gradual decrease in EQS values highlights the importance of technologies, such as the MBR-RO, that can meet even stricter future wastewater reuse criteria.

Within the framework of the DESSIN project these two concepts of SM and membrane treatment systems have been joined in an effort to develop an efficient wastewater reuse system. Therefore for unrestricted urban wastewater reuse the following treatment options are identified:

- Membrane bioreactor with biological nitrogen removal and disinfection (chlorination or UV)
- Membrane bioreactor with biological nitrogen removal, nanofiltration and disinfection (chlorination or UV)
- Membrane bioreactor with biological nitrogen removal, reverse osmosis and disinfection (chlorination or UV)

Based on the analysis presented in the previous sections of this report the MBR system provides both secondary and tertiary wastewater treatment. Secondary treatment with biological nitrogen removal is achieved within the membrane biological reactors (MBR) system, where most of the organic matter and the suspended solids are removed. Removal of residual particulate matter requires further tertiary treatment through a filtration process, which is also incorporated within the MBR. It is also notable that the MBR system provides adequate pre-treatment for a nanofitration or a reverse osmosis system. Such advanced membrane treatment systems may be required when dissolved constituents are present in treated wastewater in amounts that limit wastewater reuse.

A benchmark study was undertaken in order to provide rules for the optimization of the operation of the proposed membrane wastewater treatment system. Based on the results of the benchmark study, the most critical parameter on the performance of the treatment is the solids retention time (SRT). According to the benchmark study the optimum operating conditions for the MBR system can be summarized to the following:

- Minimum dissolved oxygen concentration in the bioreactor: 2 mg/L
- Minimum internal recirculation ratio: 400%
- Minimum mixed liquor suspended solids concentration in membrane tank 8 g/L
- Minimum solids retention time: 15 d

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