Treatment Techniques for Combined Sewer Overflows

A literature study of the available techniques

TU Delft

Hoogheemraadschap van Delfland

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Master thesis, August 2006

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Summary

During storm events, the flow in a combined sewer system can exceed the capacity and, as a result, a combined sewer overflow (CSO) will occur. During a CSO raw wastewater is discharged to surface water. This wastewater is a mixture of raw sanitary wastewater, raw industrial wastewater and rainwater. The receiving water will get polluted by dissolved as well as undissolved pollutants. Therefore a CSO can cause damage to the ecological and biological state of the receiving water and besides it can cause public health risks.

Until now the problem, with respect to CSOs in the Netherlands, is dominated by a quantitative approach. CSO flow rates and frequencies were in the past decades the main subject of research. These frequencies were translated into the Wet Verontreiniging Oppervlaktewater (1970). In the year 1998 the Ministry of Transport and Water Management came with a renewed policy, the fourth Memorandum on Water Management, dealing with groundwater, dehydration and water quality, for the protection and the recovery of nature. At the end of 2000 the European Water Framework Directive (WFD) came into force, which charges the European members of the EU to report obligatory. The aim of the WFD is to have an ecological and biological balance for all surface waters and groundwater in Europe effectively working in 2015. Measures are required to push back the pollution by defined dangerous substances.

Measures with regard to the reduction of CSO frequencies alone is not enough to fulfil the legislation. When a CSO occurs an amount of pollutants will enter the surface water. CSO water needs to be treated to prevent pollution and odour annoyances to the surroundings. The goal of this research is to find a suitable treatment technique or a combination of treatment techniques.

Primary and secondary techniques, adsorption and disinfection techniques are described. Primary techniques remove suspended solids and a fraction of the organic material, secondary techniques remove suspended solids and biological degradable material. Adsorption techniques are used to remove for example endocrine disrupting substances and disinfection techniques are used to minimize health risks for the population.

In the Netherlands CSOs occur five to ten times a year per location. Therefore a treatment technique needs to be able to start up in a few minutes even after a long period without feedwater and should be able to handle wide and quick variations in flow without causing any inconveniences to the surroundings.

Primary techniques like sieving, the Netting TrashTrap™ system and sedimentation basins and secondary techniques like membrane filtration, sand filtration and synthetic medium filtration are described. Adsoprtion techniques like activated carbon filtration and ion exchange and disinfection techniques like ozone dosage, chlorine dosage and UV treatment are described.

To select treatment techniques for the treatment of CSO water seven selection criteria are drawn up:

1. the treatment facility must be able to survive long periods without feedwater;
2. the treatment facility must be able to handle wide variations in flow rate and loading rate due to the first flush effect;
3. the treatment facility must be able to start up within a couple of minutes;
4. advanced removal of SS is necessary;
5. chemical dosage needs to be as less as possible;
6. the treatment facility must have a small footprint and cause no annoyance to the surroundings;
7. the maintenance costs need to be as low as possible.

Together with these selection criteria a multi criteria table is made in which every technique is graded per selection criterion between 1 and 10, with 1 as the lowest score and 10 as the highest score. After applying a weight factor, because not all of the selection criteria are equal, a final grade is calculated for deciding a suitable technique for the treatment of CSO water.

Reading the table it becomes clear that the primary techniques wetlands, coarse screens, sieves, the Netting TrashTrap™ system and lamella with or without chemical dosage give the best results. The Fuzzy Filter® (filtration with a synthetic medium) and ultra filtration are good filtration techniques. The best adsorption technique is activated carbon and the best disinfection techniques are chlorine dosage and UV treatment.

For these selected techniques calculations are made with flow rates of 1000m^3/h of CSO water to calculate how large the footprint has to be. Lamella plate clarification is easy to implement in an existing storage basin but removes merely 54% of the suspended solids. The Fuzzy Filter® has the smallest footprint, because of a high surface loading. Ultrafiltration requires a membrane area of 12.500m^2. This is relatively much but ultrafiltration removes besides suspended solids also viruses and bacteria. Activated carbon has a footprint which is comparable with the Fuzzy Filter® which is also because of high surface loadings. UV disinfection is easy to implement and the installation is small. UV disinfection is more effective for the disinfection of viruses than chlorine dosage and no hazardous chemicals need to be added to the water. The conclusion is that UV disinfection has far more advantages than chlorine disinfection. Therefore chlorine disinfection will not be an option for the treatment of CSO water.

A scheme is made to provide a clear overview of the selected techniques of this report. From the scheme can be determined which possibilities there are for the combination of primary, secondary, adsorption and disinfection techniques and which removal rates can be reached. With the help of this scheme process schemes are made for different situations like an urban area with a small or large available area or a rural area.

There is no general solution for the treatment of CSO water. Research is necessary to find the best treatment technique or the best combination of techniques per location. The scheme with possible process schemes can be used to decide which techniques are useful for site specific pollution removal.

Samenvatting

Tijdens hevige regenval kan het debiet in een gemengd rioolstelsel groter zijn dan de afvoercapaciteit met als gevolg dat een overstort plaatsvindt. Tijdens een overstort wordt onbehandeld rioolwater geloosd op het oppervlaktewater. Dit rioolwater is een mengsel van ruw huishoudelijk afvalwater, ruw industrieel afvalwater en regenwater. Zowel opgeloste als onopgeloste vervuiling komt in het oppervlaktewater terecht. Een overstort kan dan ook schadelijk zijn voor de ecologische en biologische staat van het oppervlaktewater en kan bovendien gezondheidsrisico's voor de bevolking met zich mee brengen.

Tot nu toe zijn overstortproblemen in Nederland op een kwantitatieve manier benaderd. In de afgelopen decennia zijn vooral debieten en overstortfrequenties onderwerp van gesprek geweest. Deze debieten en frequenties zijn opgenomen in de Wet Verontreiniging Oppervlaktewater (1970). In 1998 heeft het Ministerie van Verkeer en Waterstaat in de Vierde Nota Waterhuishouding het beleid ten aanzien van grondwater, verdroging en waterkwaliteit vastgelegd, gericht op bescherming en herstel van de natuur. Eind 2000 is de Europese Kaderrichtlijn Water (KRW) van kracht geworden die rapportageverplichtingen oplegt aan de lidstaten van de Europese Unie. De KRW moet er voor zorgen dat de kwaliteit van het oppervlaktewater en grondwater in Europa in 2015 op orde is. Er worden maatregelen vereist met betrekking tot het terugdringen van verontreiniging door bepaalde gevaarlijke stoffen.

Maatregelen met betrekking tot het verlagen van overstortfrequenties alleen is niet genoeg om te kunnen voldoen aan de wettelijk gestelde eisen. Wanneer een overstort plaatsvindt zal een hoeveelheid vuil in het oppervlaktewater terecht komen. Om vervuiling en stankoverlast voor de omgeving te voorkomen moet overstortwater worden gezuiverd. Het vinden van een geschikte zuiveringstechniek of een combinatie van zuiveringstechnieken is het doel van dit onderzoek.

Primaire en secundaire technieken, adsorptietechnieken en desinfectietechnieken worden beschreven. Primaire technieken verwijderen zwevende stof en een fractie van het organisch materiaal, secundaire technieken verwijderen zwevende stof en biologisch afbreekbaar materiaal. Adsorptietechnieken worden toegepast om bijvoorbeeld hormoonverstorende stoffen te verwijderen en desinfectietechnieken worden toegepast om gezondheidsrisico´s voor de bevolking te minimaliseren

In Nederland vinden overstorten gemiddeld vijf tot tien keer per jaar plaats per locatie. Een zuiveringstechniek moet ook na lange perioden zonder voedingswater kunnen opstarten binnen enkele minuten en bovendien een grote en snelle variatie in debiet aankunnen, zonder overlast voor de omgeving te veroorzaken.

Primaire technieken zoals zeven, Netting TrashTrap™ systemen en bergbezinkbasins en secundaire technieken zoals membraanfiltratie, zandfiltratie en filtratie met een synthetisch medium worden beschreven. Adsorptietechnieken zoals koolfiltratie en ionenwisseling en desinfectietechnieken zoals ozondosering, chloordosering en UV bestraling worden behandeld.

Voor de selectie van zuiveringstechnieken voor behandeling van overstortwater zijn zeven selectiecriteria opgesteld:

1. de installatie moet lange perioden zonder voedingswater kunnen overleven;
2. de installatie moet snelle en grote veranderingen in debiet en vuilvracht aankunnen;
3. de installatie moet binnen enkele minuten kunnen opstarten;
4. vergaande verwijdering van zwevende stof moet mogelijk zijn;
5. er moeten zo min mogelijk chemicaliën worden verbruikt;
6. de installatie moet compact zijn en geen overlast veroorzaken voor de omgeving;
7. de onderhoudskosten moeten zo laag mogelijk zijn.

Met behulp van deze selectiecriteria is een multicriteriatabel gemaakt, waarin de betreffende techniek per criterium een cijfer krijgt tussen 1 en 10, met als laagste score een 1 en als hoogste score een 10. Na het toepassen van een wegingsfactor, omdat niet ieder criterium even zwaar weegt, wordt een eindcijfer berekend om te bepalen welke techniek in aanmerking komt voor het zuiveren van overstortwater.

Uit de tabel valt af te lezen dat de primaire technieken wetlands, grove roosters, zeven, het Netting TrashTrap™ systeem en lamellen met of zonder chemicaliëndosering het beste resultaat geven. Het Fuzzy Filter® (filtratie met een synthetisch medium) en ultrafiltratie zijn goede filtratietechnieken. De adsorptietechniek actief koolfiltratie en de desinfectietechnieken chloordosering en UV bestraling geven goede resultaten.

Voor de geselecteerde technieken zijn vervolgens berekeningen gemaakt om het oppervlak van de installatie te bepalen bij 1.000m^3/h overstortwater. Lamellen zijn makkelijk te plaatsen in een bestaand bergbezinkbasin maar verwijderen slechts 54% van de zwevende stof. Het Fuzzy Filter® heeft het kleinste grondoppervlak nodig vanwege de hoge oppervlaktebelasting. Ultrafiltratie vraagt een membraanoppervlak van 12.500m^2. Dit is relatief veel, maar ultrafiltratie verwijdert naast zwevende stof ook virussen en bacteriën. Actief kool heeft een oppervlak nodig dat vergelijkbaar is met het Fuzzy Filter®, eveneens vanwege de hoge oppervlaktebelasting. UV bestraling is makkelijk toe te passen en de installatie is klein. UV desinfectie is effectiever dan chloordosering met betrekking tot desinfectie van virussen en er hoeven geen gevaarlijke chemicaliën aan het water te worden toegevoegd. UV bestraling heeft veel meer voordelen dan chloordosering waardoor chloordosering wordt afgeraden voor behandeling van overstortwater.

Er is een schema gemaakt om een duidelijk overzicht te geven van de zuiveringstechnieken die zijn geselecteerd in het verslag. Aan de hand van het schema kan worden afgeleid welke mogelijkheden er zijn voor het combineren van de primaire en secundaire technieken, adsorptie- en desinfectietechnieken en welke rendementen van vuilverwijdering kunnen worden gehaald. Met behulp van dit schema zijn processchema's gemaakt voor verschillende gebieden, zoals voor stedelijk gebied met veel of weinig beschikbare ruimte en voor landelijk gebied.

Er is voor het behandelen van overstortwater geen algemene oplossing die in alle situaties werkt. Er zal onderzoek op locatie moeten worden gedaan naar de beste zuiveringstechniek of naar een combinatie van technieken. Het schema met de geselecteerde zuiveringstechnieken kan worden gebruikt om te bepalen welke technieken in aanmerking komen voor het verwijderen van vervuiling.

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1 Introduction

1.1 Wastewater and the sewage system

Wastewater is water that has been supplied to support life, maintain a standard of living and satisfy the needs of industry, according to Butler and Davies (2004). When this water is not transported by a sewer system and treated at a waste water treatment plant (WWTP), it will pollute groundwater and surface water and it can cause a risk for the public health. Treatment of wastewater can be divided in preliminary treatment, primary treatment, secondary treatment and advanced treatment. Preliminary treatment is the removal of rocks, sticks etc. During primary treatment a portion of suspended solids and organic matter is removed. Secondary treatment is the removal of biodegradable organic matter (in solution or suspended) and suspended solids. Advanced treatment is the enhanced removal of suspended solids and organic matter from the wastewater (Metcalf & Eddy, 2003).

Combined sewers carry both wastewater and stormwater in the same pipe (Butler and Davies, 2004). During dry weather the system only carries wastewater. During a storm event the flow increases as a result of the stormwater flow. The wastewater will be diluted by the stormwater. In the Netherlands, combined sewers are most frequently used to transport the wastewater to the wastewater treatment plant. After treatment is the water discharged to the surface water, this water is named WWTP-effluent. During storm events the flow in a combined sewer system can exceed the capacity resulting in a combined sewer overflow (CSO). During a CSO untreated wastewater is discharged to surface water as is illustrated in Figure 1-1. This wastewater is a mixture of untreated domestic wastewater, industrial wastewater and run-off water. In the Netherlands CSOs occur on average five to ten times per year per location. These CSOs can cause damage to the ecological and biological state of the receiving (surface) water.

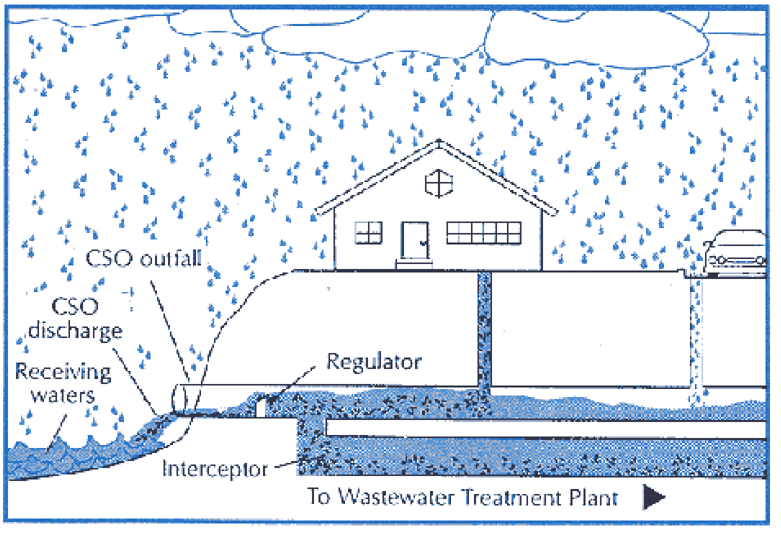

Figure 1-1: Combined Sewer Overflow (The Rouge River Project)

1.2 Impact of CSOs on the receiving water

The untreated wastewater contains different types of solids, which can be divided into three types according to Cigana et al. (1998): floatables, sinkers and swimmers. Floatables are washed to the surface by wind and water currents. Sinkers have a higher density than water and will settle. Swimmers can settle, float or swim; this depends on the turbulence of the flow. According to Field (2002) a significant amount is natural material like leaves, twigs, and other vegetation but in a combined sewer also faecal matter and sanitary items are in the wastewater. Everything, which is flushed down the toilet, like (toilet) paper, rubber and plastic foils, will be in the wastewater. In addition sand and sediments are collected in the sewer system, which originates from ground water intrusion through damaged sewer pipes.

Wastewater does not only contain large solids but also dissolved material. This material is mainly caused by the domestic wastewater and the run-off from rooftops and streets/highways. Heavy metals, for example lead from rooftops, will dissolve in stormwater and run off into the sewer system. On its way to the sewer system the stormwater will take up particles and more pollutants will dissolve. Pollutants are constituents which are added to the water supply by use (Metcalf & Eddy, 2003). All these pollutants will enter the receiving water during a CSO in case no treatment takes place.

According to Butler and Davies (2000) it depends on the self-purification capacity of the receiving water if waste can be assimilated. However when the pollution load exceeds the self-purification capacity, the aquatic ecology will be harmed. Emissions can be divided in direct and indirect pollution. Direct pollution is caused by intermittent discharges from CSOs. The impact of these discharges can only be measured during a spill. Indirect pollution is caused by the wastewater treatment plant emitting continuously effluent.

In general there are three processes occurring in the receiving water: physical, biochemical and microbiological processes. Physical processes are for example transport, mixing, dilution, etc.. Biochemical processes are aerobic and anaerobic oxidation, nitrification, adsorption and desorption of metals and other toxic compounds. Microbiological processes are the growth and die-off, and toxicant accumulation (Butler and Davies, 2000).

Table 1-1: Potential of endangering receiving waters by CSO (Uhl et al., 2005)

period of time	kind of stress	indicator/parameter
short (few hours)	hydraulic	flow, shear stress, erosion, drift
	chemical	ammonia, toxic substances
	physical	suspended matter
	biochemical	oxygen starvation in water and sediment (esp. easily degradable organic solids)
	hygienic	bacteria, viruses
delayed (days, weeks)	hydraulic	erosion, morphology
	chemical	ammonia, toxic substances
	biochemical	oxygen starvation in water and sediment (esp. organic solids)
	hygienic	bacteria, viruses
	aesthetical	floatables, solids, waste, oil
long term (weeks, years)	hydrolocial	hydrolocic regime, morphology
	chemical	heavy metals, persistant organic substances, anorganic/organic solids/sediments
	biochemical	oxygen starvation by eutrophication

The impacts of a CSO on the receiving water are (Butler and Davies, 2000; Uhl et al., 2005) dissolved oxygen depletion, eutrophication, toxic accumulation, public health risks and aesthetics, which are listed in Table 1-1. Dissolved oxygen depletion can cause death to fishes and can also cause odour problems for the surroundings. Eutrophication will cause an excessive growth of weeds and algaes. During a CSO high concentrations of pathogens come into the receiving water which can cause risks for public health.

Figure 1-2: Example of surface water pollution caused by a CSO (Waterforum)

A general and clear relationship between the representative flow or catchment area characteristics and the pollution load has not been identified according to Skipworth et al. (2000). Lau et al. (2002) conclude that the overflow spill frequency or volume can be used as an indicator of receiving water quality, but it must be used with considerable care.

According to Andersen et al. (2005b) three different CSO situations can be distinguished, namely CSOs from small catchment areas to small watercourses, CSOs from large downstream catchment areas to larger watercourses and CSOs to marine coastal waters and bathing waters. Each situation will need a different approach, because the impact of CSOs differs per situation.

1.3 Legislation

Surface water is a resource which plays an important role for the human population and for the worldwide ecosystem. Surface water is used for transport, for commercial fishery, to generate electricity, for tourism, for industry and for the production of drinking water. In Europe including the Netherlands the water quality of surface water is far from satisfactory. Given the increasing pressure on the water resources it is vital that effective legislative instruments address the problem effectively and help secure these resources for future generations (European Commission, 2002).

1.3.1 Dutch Law and policy

In the Netherlands point discharges are restricted by the Wet Verontreiniging Oppervlaktewater (WVO). Permission is needed for every point discharge like the effluent disposal of a WWTP, CSO overflows and industrial discharges (Mostert, 2005). With regard to CSOs this permit can include restrictions of the maximum number of spills per location per year. The municipality needs to ensure that the number of CSOs does not exceed the restrictions.

The former Commission Integraal Waterbeheer (CIW) gave advices about CSOs which was policy and not juridical binding. The CIW advised to permit a limited number of spills and only at non-vulnerable water. The CIW has been abolished on the 12th of February 2004. The tasks were taken over by the Landelijk Bestuurlijk Overleg Water (LBOW). As chairman is the secretary of the Ministry of Transport and Water Management in function.

The LBOW is responsible for the execution of the European Water Framework Directive (FWD) regulations. In the year 2015 all the municipalities need to comply with the basic efforts in which storage requirements are given for new and existing combined sewer systems.

In 1998 the Ministry of Transport and Water Management introduced the fourth Memorandum on Water Management (in Dutch Vierde Nota Waterhuishouding, or NW4). The NW4 contains the water policy for the Netherlands until 2006. In this note the norms for the water quality are set and discharge points which need to be improved are set out. The NW4 contains two different norms namely the Maximum Permissible Risk (MPR) (in Dutch Maximaal Toelaatbaar Risiconiveau) and the target values. The MPR values are related to the minimum water quality which needs to be reached within a short period of time. The target values are set as a norm to prevent any ecological effect for a longer time scale. Many Dutch water boards have made projections on what must be realized in order to comply with the MPR regulations. Some of the water boards already comply with the MPR quality, others need to build large-scale tertiary treatment facilities at their wastewater treatment plants (WWTPs). The additional operational costs associated with these extra measures can be 50% to 100% of the total operational costs.

The water quality of the surface waters in the Netherlands already improved in the past decades due to the redevelopment of large industrial discharges and extension and improvements of WWTPs. The decrease in concentration of pollutant in salt water stagnates. To improve the water quality in the coming years also diffuse discharges will be restricted and improved. The NW4 overleaps largely with the European Water Framework Directive.

1.3.2 European Law: European Water Framework Directive

The European Union presented in 2000 the European Water Framework Directive (WFD). The aim of the WFD is to have an ecological and biological balance for all surface waters, coastal waters, transitional waters and groundwater in Europe effectively working in 2015. The ecological quality status of water bodies is based on the status of biological, hydromorphological and physico-chemical quality elements (Borja, 2005). The presence of priority (hazardous) substances and endocrine disrupting substances is especially important (Bijnen and Moens, 2005).

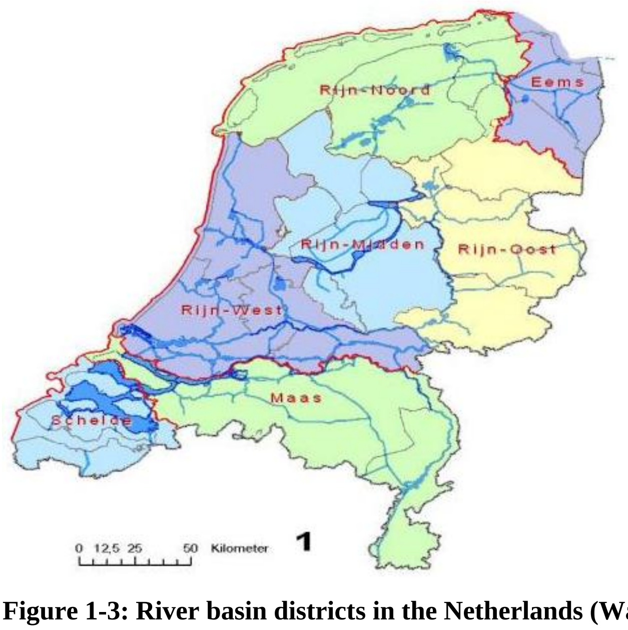

Figure 1-3: River basin districts in the Netherlands (Waternet)

The WFD is focused on catchment areas rather than on individual countries which means crossing country boarders. In the Netherlands there are seven River basin districts as shown in Figure 1-3. The Netherlands need to cooperate with Germany when dealing with the Rhine districts or the Eems district and with Belgium when dealing with the river Meuse district or the Scheldt district.

The European Water Framework Directive (WFD) is of major influence on water quality management in the European Union member states. In the near future water quality management must be based on ecological and biological elements, whereas until now this was based on physico-chemical elements.

The European commission, responsible for the WFD, presented a list of priority (hazardous) substances, which are present in surface water (cadmium, mercury, lead, nickel, organochlorine compounds, pesticides, polycyclic aromatic hydrogencarbonic compounds, phosphor, nitrogen and endocrine disrupting substances). According to Jiang et al. (2005) most of the synthetic endocrine disrupting substances (EDS) are introduced by anthropogenic inputs but they can also be naturally generated. Natural endocrine disrupting substances are more active at extremely low concentrations (<10 ngL^{-1}) compared to synthetic endocrine disrupting substances. Because of the serious impact, which endocrine disrupting substances have on natural waters and on human health, advanced treatment will be necessary to remove these substances from WWTP-effluents and CSO water. By the end of 2009 plans should be available with actions necessary in order to achieve the required water quality in 2015.

Without setting any priorities the following measures can be taken to comply with the WFD in the future:

- improvement of the sewer network. A large part of the water in a sewer system is infiltrated groundwater. Storage within the system will increase when less groundwater infiltrates;
- reducing the pollution in the water bodies caused by CSOs. This can be done by a reduction of CSO frequencies and/or by treatment of CSO water;
- improvement of the existing WWTPs to reduce the phosphor and nitrate load in the effluent. This can be done by advanced treatment at the WWTPs or, if necessary, new advanced techniques need to be developed;
- development of techniques to remove priority (hazardous) substances. In the first place the focus must be on the removal of organic micro pollutants and endocrine disrupting substances, in the second place on heavy metals and rest micro pollutants;
- improvement of the bacteriological and viral quality of WWTP-effluent.

The future norms for WWTP-effluent disposal and CSOs are not precisely known yet. The main aim is to remove all CSO constructions by the year of 2050. As long as CSOs are operational they have to comply the WFD. Treatment of CSO water will be one of the possibilities.

1.4 Quality and fluctuations of the flow

When designing a treatment facility for the treatment of CSO water fluctuations of the flow rates are important to take into account. Installations are designed for a specific flow rate and do not treat the water efficiently anymore when more or less water enters the installation.

Information about the fluctuations of the physical and chemical water quality is of major importance for the design of a treatment facility, because the efficiency predominantly depends on the quality of the combined flows (Geiger, 1998). During long periods of Dry Weather Flow (DWF) in the sewer, sediment deposition takes place. Pollutants attach to the deposited sediments and these sediments act as stores of pollutants that are released into the sewer flow as the sediments are eroded during a storm event (Skipworth et at., 2000). According to Gruber et al. (2005) the deposition of solids during dry weather circumstances is smaller in steeper systems than in flat systems. As a result of this the discharge loads during a CSO are smaller in steeper systems.

According to Krebs, et al. (1999) the first flush effect is of major importance for the fluctuations in CSO water quality. The first flush effect denotes the high load of pollution in the overflow water, at the beginning of a storm event. During an event a wave front is formed from the sewage which was already in the system. This wave contains the initial concentrations of the sewage water resulting in total load increase due to an increase of the flow rate. After the first flush, dilution of the sewage water takes place, because stormwater contains less pollutants than sewage water. The first flush effect needs to be taken in account when dealing with a medium catchment inclination in a relatively small area. Under storm weather conditions sediments will be discharged on the surface water by the first flush effect. This effect has a large impact in sensitive catchment areas. In the Netherlands first flush effects do not occur frequently, but sometimes a high load of pollution comes at the end.

In Table 1-2 the typical composition of domestic wastewater is given. The composition of CSO water lays within the range of untreated wastewater and stormwater, depending on the dilution factor caused by the stormwater. The listed parameters in Table 1-2 are Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD_5), Total Nitrogen (N_{tot}), Ammonia ($N\text{-}NH_4$) and Total phosphorus (P_{tot}). SS can lead to the development of sludge deposition and anaerobic conditions when untreated wastewater is discharged on surface water according to Metcalf & Eddy (2003). If biodegradable organics (BOD_5 and COD) are discharged to surface water the biological stabilisation can lead to depletion of oxygen and even to septic circumstances. Nutrients (P and N) are essential for growth but can lead to undesired growth of aquatic life (Metcalf & Eddy, 2003) which is called eutrophication.

Table 1-2: Typical composition of untreated domestic wastewater (Metcalf & Eddy, 2003)

Compounds	Concentration (mg/l)
TSS	210
COD	430
BOD_5	190
N_{tot}	40
$N\text{-}NH_4$	25
P_{tot}	7

In Slovakia research has been done by Sztruhár et al. (2002) to provide general data for pollution load calculation of CSOs. In this study three towns were selected with different sewer systems and geographic conditions. Water samples were taken manually from the inflow to the CSO chamber just upstream of the weir. At the end of the monitoring program results of eight CSO events were collected. With the collected data the Event Mean Concentrations (EMC) in [kg/m^3] were calculated for several pollutants.

$$EMC = \frac{\sum Q_i c_i \Delta t_i}{\sum Q_i \Delta t_i}$$ (Sztruhár et al., 2002)

In which Q_i is the discharge during time interval *i* [m^3/min], c_i is the concentration of the pollutant during time interval *I* [kg/m^3] and Δt_i is the length of the time interval *I* [min]. The results of these calculations are presented in Table 1-3.

Table 1-3: Event Mean Concentrations of urban storm runoff parameters (combined sewers) in Slovakia (Sztruhár et al.,2002)

Parameter	EMC (mg/l)	Parameter	EMC (mg/l)
TSS	430	Zn	0.57
COD	445	Cd	<0.02
BOD_5	175	Pb	<0.20
N_{tot}	16.8	Cu	<0.50
$N\text{–}NH_4$	6.21	Cr	<0.20
$N\text{–}NO_3$	1.28	Ni	<0.10
$N\text{–}NO_2$	0.10	As (μg/l)	3.0
P_{tot}	2.63	Non-polar extractable substances	3.97
$P\text{–}PO_4$	0.63	Faecal coliforms (CFU[a]/ml)	1.3×10^5

[a] CFU – colony forming units.

According to Gruber et al. (2005) and Suárez and Puertas (2005) it is difficult to relate results of CSOs measured at a specific site to other locations. This is due to complex processes like the formation and remobilisation of sewer solids. The research done by Suárez and Puertas (2005) gives more insight in this complexity. Measurement of SS, COD and BOD_5 were done at CSO facilities in six cities spread out trough Spain. The EMC values were calculated and compared between the cities. The values for COD were between 293mg/l and 834mg/l, for BOD_5 between 166mg/l and 389mg/l and for SS between 229mg/l and 733mg/l.

In case no information is available about the quality of the flow, data can be used of similar catchment areas according to Geiger (1998). When there is even no information available about similar catchment areas, primary techniques like sieves, screens and settling tanks can be applied. These techniques are described in chapter 2.

1.5 Problem description

Until now the CSO problem in the Netherlands is approached mainly quantitative due to the Wet Verontreiniging Oppervlaktewater. CSO flow rates and frequencies were in the past decades the main subject of research. These frequencies were translated into regulations. The quality of CSO water had no priority in most of the investigations. This was due to a lack in legislation where no importance was notified and also because of the variation in physical and chemical quality, which makes it difficult to get a good impression of the pollution load. The time fluctuations in quality depend on catchment area, land use and drainage specifics (Geiger, 1998).

The European Water Framework Directive (WFD) requires are an ecological and biological balance for all surface waters, therefore heavy metals, endocrine disrupters and priority (hazardous) substances need to be measured in surface water as well in CSO water. These substances are different from the classical substances like suspended solids, chemical oxygen demand and nitrogen. In order to reduce quality effects of a CSO the frequency of the spills can be reduced by building extra storage and returning the water to the WWTP or treat the stormwater separately, by increasing the flow to the WWTP or by disconnecting stormwater of the combined sewer or CSO water can be treated separately.

Most of the substances which need to be removed from the CSO water are suspended or colloidal. Removal of suspended solids from WWTP-effluent and CSO water will immediately lead to a quality improvement and, in addition, it will prevent filtration steps to clog. According to Daligault et al. (1999) and Nieuwenhuijzen et al. (2001), heavy metals, Chemical Oxygen Demand (COD), Biodegradable Oxygen Demand (BOD), hydrocarbons, viruses and bacteria (Metcalf & Eddy, 2003) are partly removed when suspended solids are removed. For heavy metals (Cadmium, Cupper, Lead) the removal efficiencies are about 28%, for COD and BOD removal efficiencies are 50-75% during intense storm events. The mean removal rate of hydrocarbons was 26%. These removal efficiencies were measured during research in Brunoy in France (Daligault et al., 1999).

All these earlier mentioned measures to reduce CSOs will not guarantee that CSOs will not occur at all. When a CSO occurs in an urban area the population will be confronted with odour problems, visual pollution ((toilet)paper, rubber, plastic foils, etc) and bacteria which can cause a health risk. To prevent this pollution treatment of CSO water will be necessary. The aim of this research will be to find a treatment technique or a combination of techniques to treat CSO water in a way that odour problems, visual pollution and bacteria growth are brought to a minimum. The focus must be on SS removal because this will lead immediately to a quality improvement of the surface water. The treatment techniques which are described in this research are primary and secondary techniques, adsorption techniques and disinfection techniques. Primary treatment removes a portion of suspended solids and organic matter. Secondary treatment is the removal of biodegradable organic matter (in solution or suspended) and suspended solids. Adsorption techniques can reduce the concentrations of for example endocrine disrupting substances and disinfection of the water can decrease public health risks.

In the Netherlands CSOs occur on average five to ten times a year per location. Therefore, a treatment facility for CSO water needs to be able to:

- Survive long periods without feedwater;
- Start up and work within one or two minutes;
- Handle wide and quick variations in flow rate;
- Cause no inconveniences to inhabitants.

All of the treatment facilities need to comply with specific requirements, e.g. facilities need to be reliable, robust, automatic, sustainable, cost effective, simple to operate, facilities should reduce pollution streams and must have a small footprint. A small footprint means a small amount of square meters. An important issue, with respect to CSO treatment, is that constructions need to be built to prevent odour caused by the CSO water and noise inconvenience caused by the treatment facilities to inhabitants. In urban areas there is often little space to place large treatment facilities.

However, some treatment techniques require a continuous feed flow, like biological systems. In biological systems, the micro organisms will starve when there is no flow through the system. When during a storm event a CSO occurs, micro organisms will not recover quickly enough to treat the water. There is not enough information on the ability of micro organisms to be maintained in a healthy way with a side stream of dry weather flow (Landon, 2002). Because of these difficulties with biological systems they are not described further on in this research. A physical chemical system may be not able to start up within a few minutes. Therefore flow sensors located upstream in the sewer system are strongly recommended (Landon, 2002).

In the coming chapters different techniques will be described (chapter 2, 3, 4 and 5) after which criteria are set (chapter 6) and designs are made of techniques for the treatment of CSO water (chapter 7 and 8).

2 Primary treatment techniques

In chapter 1 has been explained that during primary treatment a portion of suspended solids and organic matter are removed (Metcalf & Eddy, 2003). In this chapter several primary treatment techniques will be described. It speaks for itself that not all techniques can be described and that equivalent techniques will have the same results.

2.1 Wetlands

According to Uhl and Dittmer (2005) wetlands are generally vertical flow soil filters with a detention basin on top of the filter layer. A drainage system with pipes leads the filtrated CSO water to the outflow structure. A throttle in the outlet structure controls the filtration rate and the detention time. Sand with a diameter 0-2 mm is recommended (Uhl et al., 2005), which should contain 10-15% of carbonate to enable long-term nitrification and retention of heavy metals. In Figure 2-1 a configuration of a wetland is given and in Figure 2-2 a schematic cross-section of a structured wetland for CSO treatment is presented. The vegetation on the filter is mostly reed. This vegetation keeps the top-layer of the filter bed permeable. The filter bed can clog when the vegetation is not sufficient enough developed. Additionally, a pre-treatment is necessary to minimize the chance that the filter bed clogs. A disadvantage of wetlands is the large area that the filter requires. An advantage is that a wetland can fit perfectly into a rural area.

In order to remove ammonium and heavy metals carbon can be added to the filter (Uhl and Dittmer, 2005). By adding ferric to the filter, adsorption of phosphorous increases. The main processes in a wetland are reducing the peak flow, removal of suspended solids and removal of soluble and suspended pollutants. To ensure that there are no anaerobic conditions in the filter, it must be drained completely after every CSO event.

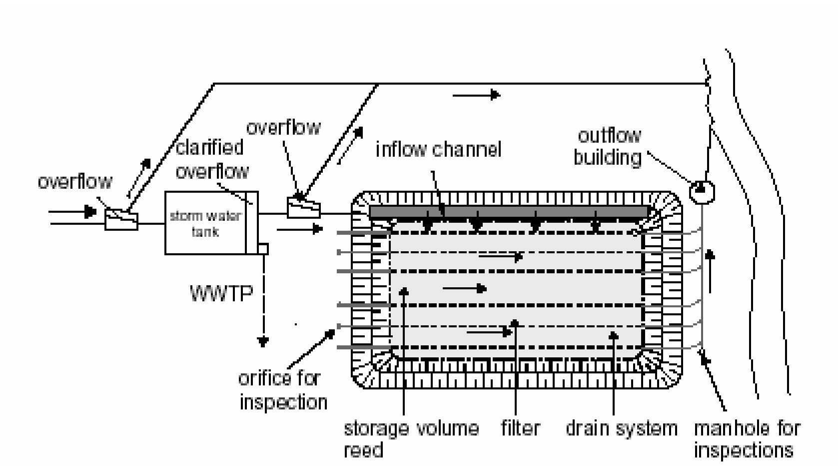

Figure 2-1: Configuration of a wetland as part of a CSO treatment (Uhl and Dittmer, 2005)

A general design procedure can not be followed because of the wide variation in quality of CSO water and the uncertainties of long-term behaviour of the filter. The dimensioning procedure of a filter (Uhl et al., 2005) should contain two steps, at first dimensioning the detention volume and secondly dimensioning the filter area. As a guideline flow rates should not exceed 0.15m^3/(ms) to avoid damage of the filter by erosion (Uhl and Dittmer, 2005; Uhl et al., 2005).

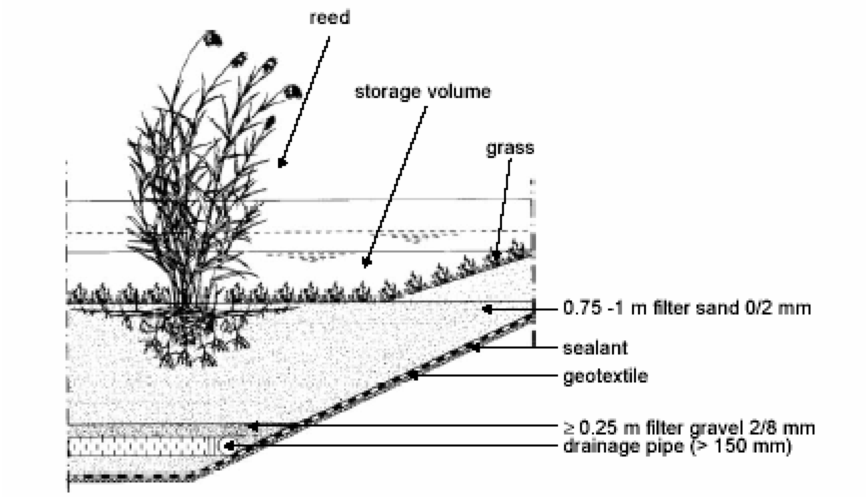

Figure 2-2: Schematic cross-section of a structured wetland for CSO treatment (Uhl and Dittmer, 2005)

Uhl and Dittmer (2005) describe operational experiences with wetlands. In the filter are aerobic conditions, therefore no denitrification takes place. During long dry periods mineralization and subsequent nitrification of organic nitrogen can take place in the filter. After a long dry period a high nitrate (NO_3-N) load is washed out, resulting in a high peak load in the first effluent. The influent quality has no effect on the removal rates. Wet periods of several days or weeks will lead to depletion of the filter and the removal efficiency will decrease. The effluent contains very low concentrations in Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD) and suspended solids (SS). The removal rates measured in a full-scale filter (Uhl et al., 2005) are for COD ca. 84%, for NH_4-N ca. 96%, for BOD >66%, for SS >90% and for NO_3-N -210%. The negative removal rates for nitrate are due to the wash out of nitrate caused by denitrification of organic nitrogen during long dry periods.

2.2 Settling and storage tanks

Storage tanks are built to provide extra storage in the sewer system. This is a quantity control and can be used on-line or off-line. If a storage tank is filled and finally flows over, untreated water flows into the catchment area. By Krebs et al. (1999) two different types of storage tanks are described. If a first flush effect is expected, the tank needs to act as a storage tank. This means that there will be no flow through the tank. At the end of a storm event the tank is emptied by pumping the water back into the sewer system. If there is no first flush effect expected, the tank needs to be used as a settling tank with a constant flow through the tank to the receiving water. In this way the suspended solids concentration in the overflow water will decrease by sedimentation. In this case a storage tank is built like a settling tank, so it will be possible to remove solids. The flow velocities are low to provide optimal conditions for solids to settle. The hydraulic surface load must not exceed 10 m^3/h/m^2 and expected SS removals of 50-70% are highly uncertain (David and Matos, 2005). The combination of settling and storage is applied in the Netherlands.

The University of Leuven in Belgium carried out a feasibility study on flocculation in storage sedimentation basins (De Cock et al., 1999). Different models were set up to estimate the effect of coagulation-flocculation on the efficiency of a storage sedimentation basin. The input in the models was based on a sedimentation basin in Amersfoort in the Netherlands. This basin was divided into an off-line storage part and a storage sedimentation part. First of all the results show that flocculation-sedimentation by the addition of coagulants can be a solution to reduce the negative effects of a CSO. Secondly the results showed that a good mixing zone is necessary for a good flocculation. This can be done by placing a stirrer or by adding the coagulants in the sewer system, upstream of the storage tank but that has a risk of sedimentation in the sewer system.

However, building storage is expensive due to the large tanks which storage requires which leads to high construction and material costs. To reduce these costs advanced settling techniques are being developed. Advanced settling techniques can reduce the storage volume to one third of the original volume.

2.3 Coarse screens

Coarse screens (uniformly spaced bares) can be applied as primary treatment or as pre-treatment for advanced treatment systems. The main aim of a coarse screen is to prevent solids from entering the overflow pipe (Butler and Davies, 2000). Two types of coarse screens can be distinguished: horizontal reciprocal screens and tangential flow screens. The horizontal reciprocal screen is made of narrow stainless bars, as pictured in Figure 2-3. The screen is placed parallel to the flow direction. A horizontal screen can run continuously and cleaning takes place automatically during filtration or by hand after filtration. A tangential flow screen contains a fine mesh cylindrical screen. Water comes in at a tangential direction and solids will swirl towards the centre where they are collected and water passes through the screen. In this way less particles will accumulate on the screen compared to the horizontal reciprocal screen (Metcalf & Eddy, 2003).

Coarse screens have a mesh width of 25-50mm (Metcalf & Eddy, 2003) and can get clogged when the receiving water contains a large amount of floating material. Disadvantages of coarse screens are the maintenance costs and the extra energy which is necessary for the automatic cleaning of the screen. In case electrical power is not available a disposable mesh sack can be used. This system works as a screen but does not require power, on the contrary it requires maintenance because the sack needs to be removed after every spill (Butler and Davies, 2000).

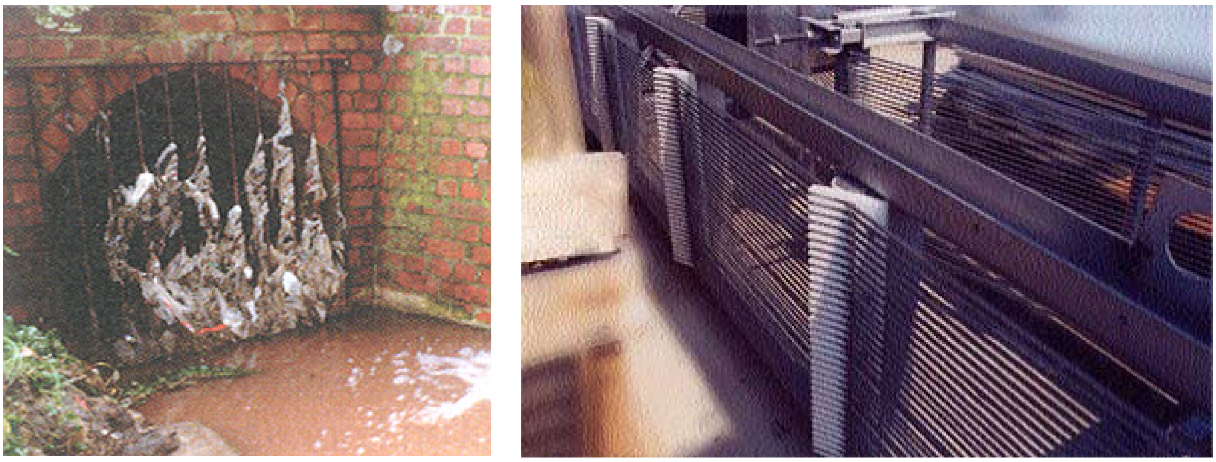

Figure 2-3: On the left an end of pipe bar screen (Water-Technology) and on the right a horizontal CSO screen (Headworks® Inc.)

2.4 Sieving treatment

Sieving treatment has the same aim as coarse screening, namely the prevention of solids to enter the overflow pipe. This technique can also be applied as a pre-treatment. The mesh width is smaller than 6mm. In Birkenfeld in Germany a rotary drum sieve filter is applied to treat CSO water. This type of sieve is combined with a storage tank and an emergency overflow construction, and has been described in more detail in Brombach and Pisano (1997). When the storage tank is filled the excess water will flow towards the sieve with a mesh width of 4mm. When the headloss increases the sieve starts to rotate. A brush on top of the sieve is used to clean the sieve additionally, the sieve can also be cleaned with a backwash. If the sieve is not cleaned properly clogging will occur. Figure 2-4 illustrates the rotary drum sieve as used in Birkenfeld. This rotary drum sieve showed removal efficiencies for settable solids of 18.2% and for COD 20,5%. After a storm event the sieve chamber is emptied by gravity. The residual water will carry most of the accumulated material. In Denmark research has been carried out by Andersen et al. (2005a) with a rotary drum sieve followed by a disc sieve. The mesh width of the rotary drum sieve was 100 μm and 20μm for the disc sieve. The removal efficiencies of SS were by the rotary drum sieve 50-80% and additionally 5-40% removal by the disc sieve.

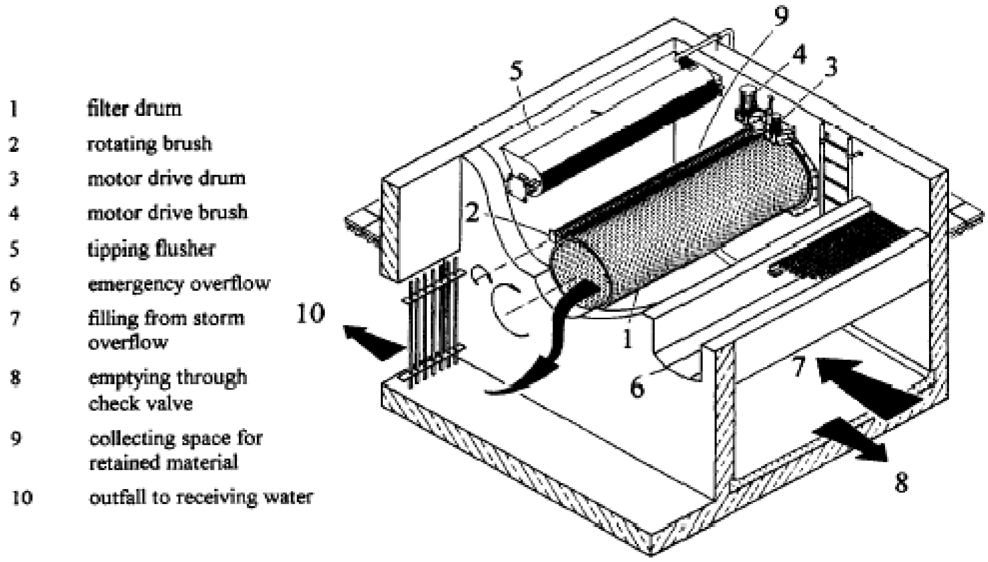

Figure 2-4: Rotary drum sieve at the Birkenfield storm overflow tank (Brombach and Pisano, 1997)

2.5 Inclined bar screen

Inclined bar screens are frequently applied at WWTPs, pumping stations and polder pumps in The Netherlands. It is a continuous self-cleaning screening belt that removes fine and coarse solids (Metcalf & Eddy, 2003), as pictured in Figure 2-5. The mesh width of this screen is in the range of 0.5 to 30mm.

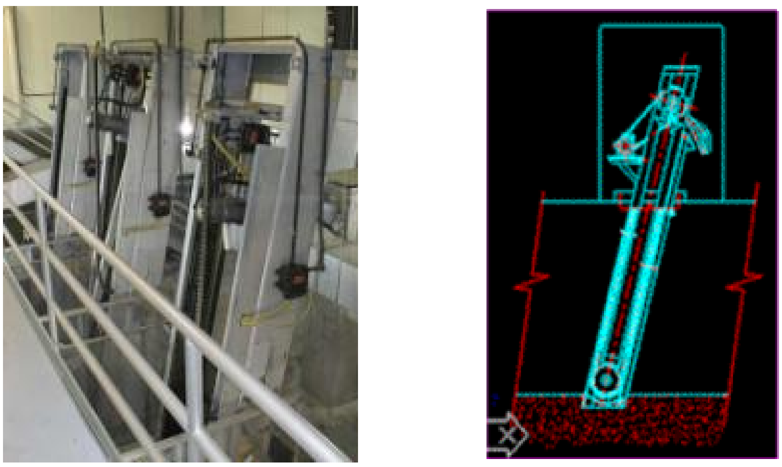

Figure 2-5: Inclined bar screen (Lenntech Water treatment & air purification Holding B.V.)

When the screen is in operation, the water flows trough the inclined screen. The screen is periodically raked by a mechanized comb system (Lenntech Water treatment & air purification Holding B.V.). This comb system is switched on by a level switch at the upstream side or by a time clock. A doctor blade at the top of the travel removes the screenings collected by the moving combs (Lenntech Water treatment & air purification Holding B.V.). The removed screenings are dropped in a skid plate and transported to a container.

2.6 Netting TrashTrap™ System

The Netting TrashTrap™ System (EPA, 1999d) of Fresh Creek Technologies Inc. is a modular floatable collection system located at the CSO outfall. Using nets is an inexpensive and simple way of removing trash and floatables without using electrical or mechanical power. The construction and the method of installation are determined for each location. Three models of netting systems exist, namely in-line, end-of-pipe and a floatable model (Fresh Creek Technologies Inc.), the in-line model and the end-of-pipe model are illustrated in Figure 2-6. The floatable model can be applied when water levels change.

The netting mesh size opening is available in many sizes: from 5mm up to 625mm. Typical net size openings used for CSOs in the USA are: on the Eastcoast and Midwest 125mm; on the Westcoast 5mm. The standard nets (Fresh Creek Technologies Inc.), are designed to hold up 0.7m^3 of floatables and a weight of 227kg (EPA, 1999d). Flow velocities above 2m/s require special, more expensive, high velocity nets (EPA, 1999d). In general the nets need to be replaced regularly to prevent odour annoyance to the surroundings and visual pollution. Replacement of the nets will take about 30 minutes. The removal efficiencies for floatables measured at several sites in the USA are between 93-97% (EPA, 1999d).

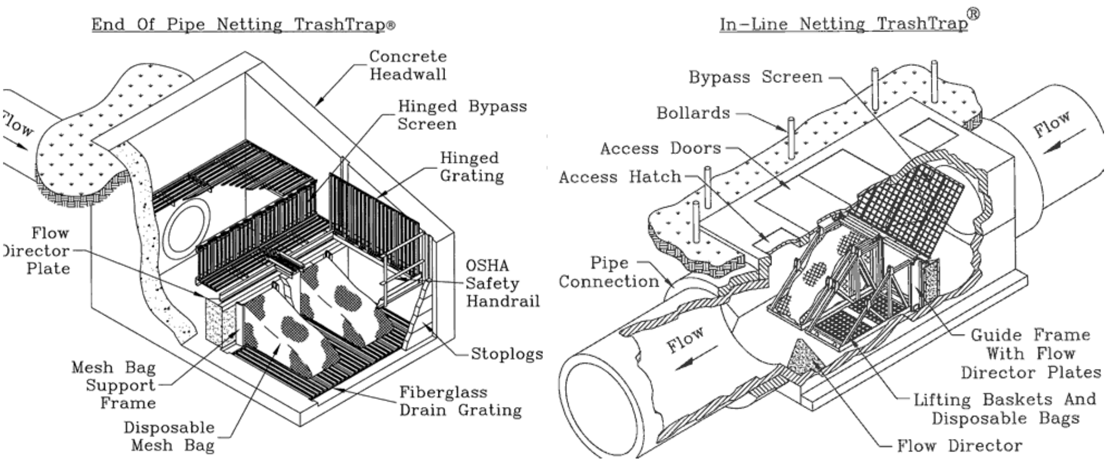

Figure 2-6: Netting TrashTrap™ (Fresh Creek Technologies Inc.)

The netting TrashTrap™ system has no moving parts and no complicated cleaning procedure (Fisher, 2002). The life expectancy of the netting TrashTrap™ system is about 20 years. The costs of the Netting TrashTrap™ system are 300% lower compared to mechanical screens (Fisher, 2002). Typical construction and installation costs for commercially available netting systems range from € 20.000-€ 120.000. Operating costs and maintenance costs are estimated at € 800 per year (EPA, 1999e).

3 Advanced treatment techniques

In this chapter the advanced treatment techniques will be described. As stated in chapter 1 advanced treatment is the enhanced removal of suspended solids and organic matter from wastewater (Metcalf & Eddy, 2003). The primary techniques mentioned in the pervious chapter will not remove suspended solids and organic matter effectively enough to comply with the WFD regulations, for which advanced treatment techniques are needed. Advanced treatment techniques that remove nutrients, metals, suspended and colloidal substances and dissolved macromolecules will become important in the near future. Treatment techniques have to be extended with adsorption, for example activated carbon or resins, and oxidation to remove organic micro-pollutants. Techniques which are able to remove organic micro-pollutants will remove pesticides, hormone disrupting substances and medicinal substances as well (Kramer and Jong, 2005).

Research on these advanced treatment techniques for WWTP-effluent has shown good results (e.g. Te Poele et al., 2004). Techniques like activated carbon, membrane filtration and rapid sand filtration have proven to work for WWTP-effluent. For the treatment of CSO water these techniques are not yet feasible. Thus innovations and new solutions are needed. It speaks for itself that not all techniques can be described and that equivalent techniques will have the same results.

3.1 Hydrodynamic Vortex separation

In the USA hydrodynamic vortex separation (HDVS) devices are applied for the removal of suspended solids and other easy settable particles. In Europe this separation technique is being used in a lesser extend. HDVSs are high rate rotary flow devices designed for the removal of solids, which have a specific density that differs significantly from the density of the medium (Andoh and Saul, 2003). Water containing suspended solids enters in tangential direction the vortex. The water velocity moves the solids in a swirling action towards the vortex. The system is self-inducing so there are no moving parts. Because of the gravity the solids will be pulled down. The floor of the vortex is under a slope to sweep the solids towards a central drain. Vortex separators can be applied when dealing with extremely high flows (Metcalf & Eddy, 2003).

According to Boner et al. (1995) comparing removal efficiencies of vortex separators is complicated because of the number of variables associated with the operation of the process. Variables which can differ per location but also from storm to storm are for example the composition of the influent, the effluent, the underflow hydraulics, the particle size of the solids and the settling velocities. The effectiveness of a HDVS does not only depend on the water quality, it also depends on the nature and placement of the internal components (Andoh and Saul, 2003).

According to Andoh and Saul (2003) HDVSs show high removal rates where the influent solids concentrations are high. And when the influent solids concentrations are low the removal rates will be low, marginal or even negative. This can be explained because high solid concentrations in the influent are associated with an increased fraction of settleable solids according to Andoh and Saul (2003).

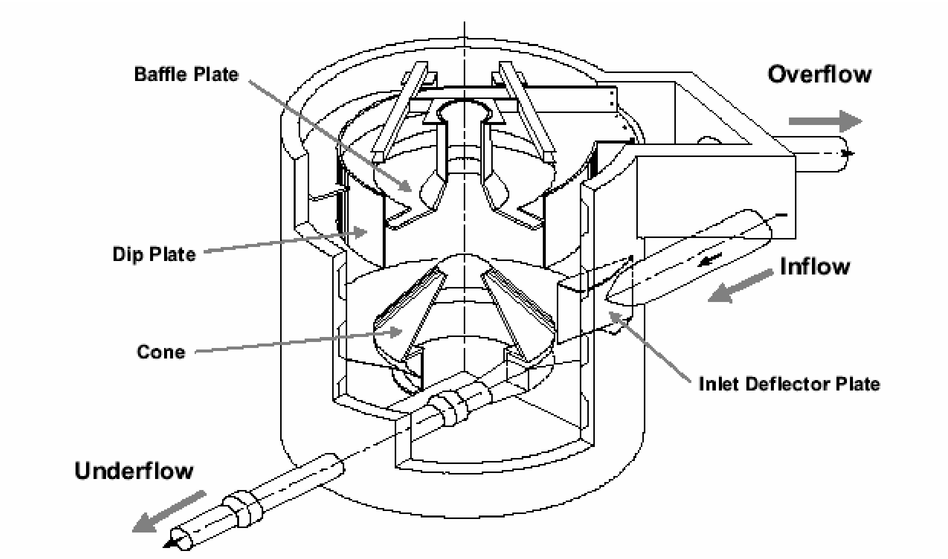

Figure 3-1: Cut-away view of the Storm King® (Andoh and Saul, 2003)

In the past years more advanced vortex separators were developed. The Swirl Concentrator, the Fluidsep® and the Storm King® (illustrated in Figure 3-1) are examples of these advanced vortex systems, which are used for treatment of CSO water. In these systems inorganic chemicals (coagulants) can be dosed for coagulation and flocculation. In this way removal efficiencies increase dramatically (Averill et al., 1997) and colloidal matter, which will not settle by gravity, will also be removed (Helliwell and Harper, 1993). For the removal of materials, which will not settle or float (some buoyant aesthetic solids), an ADVS will not work effectively. When dealing with these kinds of materials a screen can be placed in front, or after the HDVS device (Andoh and Saul, 2003). Vortex separators will have a volume of 50-70% of that of a conventional CSO tank (Weiß, 1997) assuming an equal spilled COD load. Vortex separators with chemical dosage claim to have a smaller footprint than lamella plate clarification (Landon, 2002).

3.2 Lamella plate clarification

Lamella plate clarification is a form of advanced settling combined with storage. This type of clarification is widely applied in the wastewater industry. The process is mostly combined with dosage of coagulant or polymer to bind particles but it will also work without any chemicals. In a lamella clarifier solids settle at the lamella and will fall down into a sludge basin from where it can be pumped away. An inclined plate settler is presented in Figure 3-2.

There are many types of lamella, for example plates and tubes. A lamella settler will reduce the retention time with one third to a quarter compared to the retention time of a conventional settling tank. Which also means that the area necessary for lamella settling can be one-third to a quarter of the area of a conventional settling tank (Takayanagi, et al. 1997). In Brunoy and Vigneux in France, research has been done with lamella separators (Daligault, et al., 1999). The mean removal efficiency for suspended solids was for Brunoy 54%. The removal range for Brunoy was 0-90% and for Vigneux between 0% and 60%. During the test period high removal rates were reached when the amount of suspended solids in the influent exceeded 300mg/l. High settling velocities caused this.

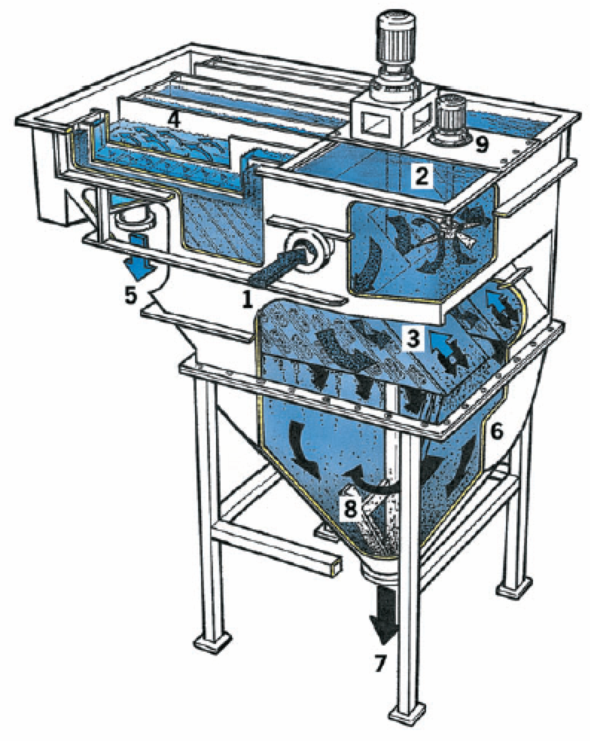

Figure 3-2: Inclined plate settler. 1 feed inlet, 2 flocculation chamber, 3 lamella plate packet, 4 overflow launder, 5 overflow outlet, 6 sludge hopper, 7 underflow outlet, 8 rake with dive unit, 9 flocculation agitator (Metso Minerals Industries Inc.)

3.3 Chemically enhanced high rate sedimentation

Chemically enhanced high-rate sedimentation is applied in two commercial technologies, namely the Actiflo® (Veolia Water) and the DensaDeg® (Ondeo Degremont). The main advantages (Marsalek, 2005) of these techniques are the very high rate of treatment, which allows a relatively small footprint. The high coagulant and coagulant aid dosages make high pollutant removal rates possible.

3.3.1 Actiflo®

The Actiflo® method was described by Plum et al. (1998) and Marsalek (2005). It is a very compact and prefabricated physico-chemical treatment, the system footprint is between 5 and 20 times smaller than the footprint of conventional clarification systems of similar capacity (Krüger, 2005). Algaes, SS, BOD, COD and phosphorus will be removed. The process scheme of an Actiflo® is presented in Figure 3-3. First of all the wastewater is finely screened and degritted. Secondly metal salt is dosed into the water. After rapid mixing microflocs are formed. These flocs will bind ortho-phosphate (PO_4). In the injection mixing tank polymer is dosed, which will form larger flocs in the flocculation tank where also the microsand is added to the water. The microsand will incorporate into the flocs, which makes the flocs heavier than in conventional precipitation systems. Because of this weight, the flocs can easily be removed by sedimentation (Krüger, 2005). After this stage the water enters the settling zone with lamella. The sludge is treated with a hydrocyclone, the residual water together with the microsand is returned to the injection mixing tank.

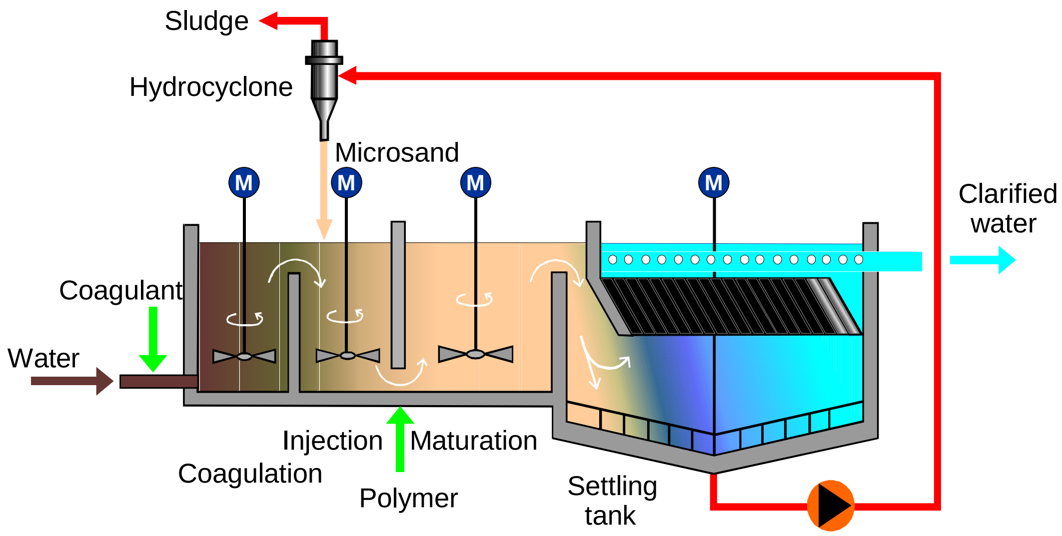

Figure 3-3: Actiflo® process (Krüger, 2005)

When a sewer system has a large concentration time, the capacity of the Actiflo® plant is relatively smaller than for a sewer system with a small concentration time (Plum et al, 1998). Treatment efficiencies obtained with the Actiflo® system are high. The Actiflo is not sensitive for influent concentration fluctuations and shows limited sensitivity to hydraulic peak loads (Plum et al., 1998). A disadvantage of the Actiflo® system is that the start up time is between 10 and 30 minutes (David and Matos, 2005). The retention time in the installation is about 10 minutes (David and Matos, 2005).

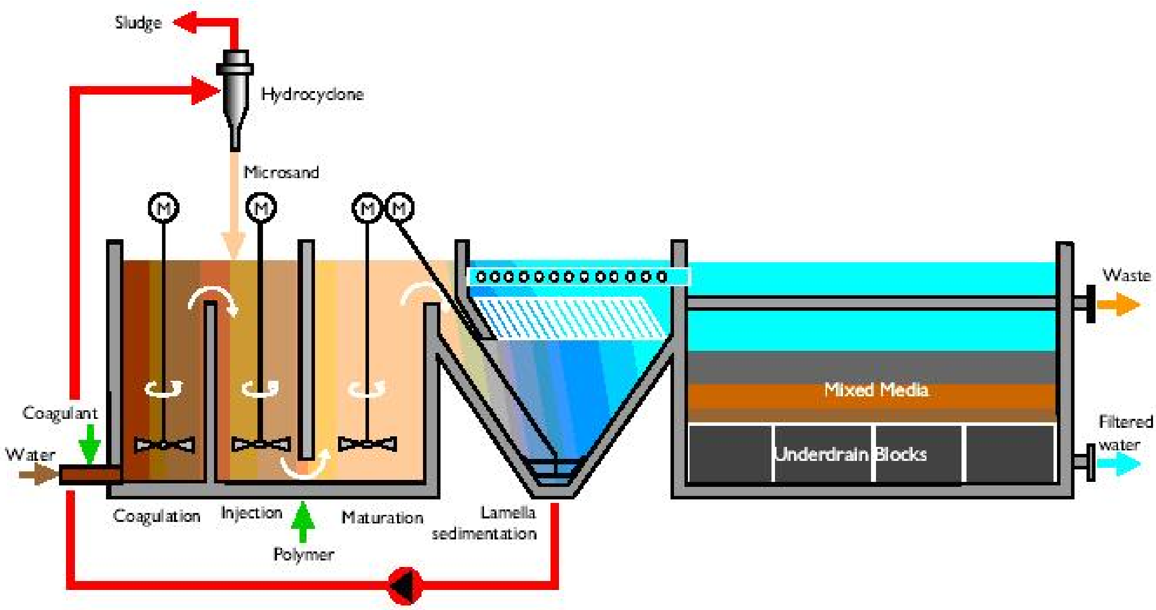

Figure 3-4: The Actifloc™ processcheme (Krüger, 2006)

Tests were done with river water from Harrestrup Å in Denmark (Plum, et al., 1998). The used service load was 50m/h. Treatment efficiencies for SS were 66-91%, the effluent concentration was between 6-7.2mg/l. For Total-P the effluent concentration was between 0.062-0.088 mg/l with removal efficiency of 63.5-93.6%. COD removal efficiencies were between 15.4-75%, the effluent concentration between 13-33mg/l. For COD the removal efficiency is the highest with the highest influent concentration. In Fujisawa in Japan tests were done with CSO water (Horie et al., 2005). In this research 75% of BOD was removed, 80% of the SS and 80% of Total-P. The Actiflo® needs 1/20 of the area of a conventional storm water tank.

The Actiflo® system can be expanded with a mixed media filtration. This process is called Actifloc™, which is illustrated in Figure 3-4. This mixed media filter uses a minimum of three granular materials of different sizes and specific gravity. The coarse material is at the top of the filter and becomes finer towards the bottom (Krüger, 2005). After backwash stratification takes place. The water flows in downflow direction trough the filter bed. Because of the fine particles and pore sizes is the filter bed able to remove Cryptosporidium and Giardia lamblia (Krüger, 2005).

Under the mixed filter bed is a direct media retaining underdrain placed. This drain is made of several prefabricated blocks of plastic with a stainless steel top. These blocks are necessary for the support of the gravel, for the distribution of the backwash water and to distribute the air evenly over the filter bed (Krüger, 2005).

3.3.2 DensaDeg®

Two types of the DensaDeg® were designed, the DensaDeg® and the DensaDeg® 4D. The DensaDeg® 4D was especially designed for high rate clarification at CSOs and for sanitary sewer overflows (SSO). This system combines four functions (Marsalek, 2005) in one process: grit removal, grease and oil removal, clarification and sludge thickening. A schematised picture of the DensaDeg® 4D is presented in Figure 3-5.

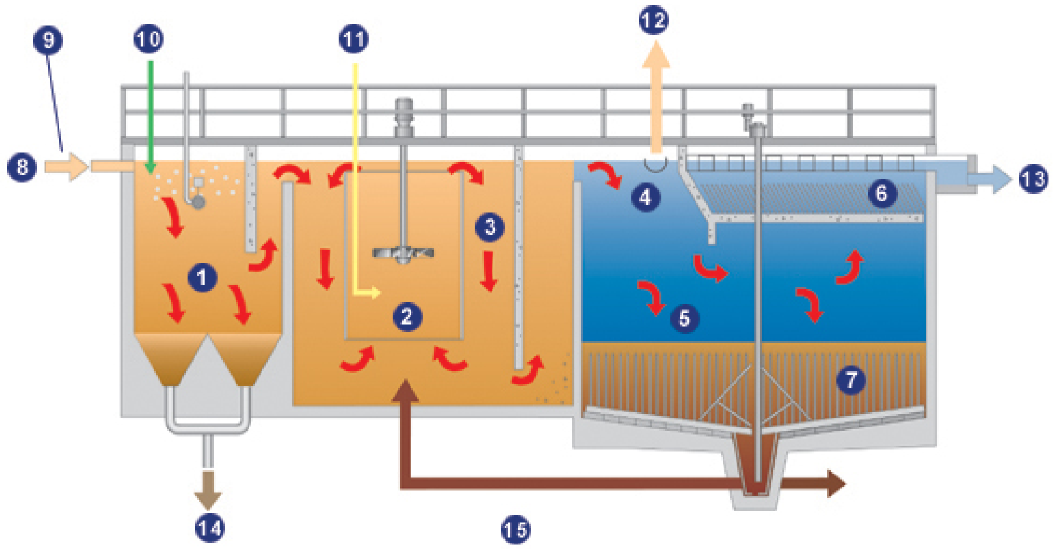

Figure 3-5: Schematic DensaDeg® 4D (Ondeo Degremont). 1 Grit removal/ coagulation, 2 Flocculation, first stage, 3 Flocculation second stage, 4 Grease and scum removal, 5-6 Pre-settling and lamellar settling, 7 Sludge densification and thickening, 8 Raw water, 9 Coagulating Agent , 10 Air, 11 Flocculation agent, 12 Grease and scum draw-off, 13 Treated Water, 14 Grit drawoff, 15 Sludge recirculation

The raw wastewater enters the first chamber [1] where grit removal takes place. The water is aerated [10] and a coagulating agent [9] is added. The water will flow to the second chamber [2] where a flocculation agent [11] and thickened sludge from the clarifier [15] are added. An axial mixer mixes the suspension. In this stage of the process flocculation takes place. In the third chamber [3] a plug flow reactor is created where flocculation continues and grease and scum are separated from the solution. The flocculated solids will settle in the clarifier [5]. The finer solids removal takes place in the lamellar [6]. The clarified water is accomplished in effluent launders above the lamellar tubes. The sludge is thickened [7] and a part is recirculated (Marsalek, 2005).

Advantages of the DensaDeg® 4D are (Ondeo Degremont):

- a compact layout compared to normal settling;
- high optimised efficiencies;
- automatic control of start up;
- low effluent values for SS, COD and BOD_5;
- solids removal efficiencies typically greater than 85%.

A disadvantage of the DensaDeg® system is that the start up time is between 10 and 30 minutes (David and Matos, 2005). The retention time in the installation is about 10 minutes (David and Matos, 2005). There is little experience with the DensaDeg® 4D for the use of CSO treatment. In Hamilton, Ontario in Canada a research has been carried out in 2003 (Marsalek, 2005).

3.4 Dissolved air floatation (DAF) system

In DAF systems, air at a pressure of several atmospheres dissolves in the CSO water and is later released under atmospheric pressure. During the pressure phase, released air bubbles attach to suspended solids and take the solids to the water surface where they are removed. The advantage of the DAF system over a settling tank is that small particles, which slowly settle, can be removed more completely and in a shorter time (Metcalf & Eddy, 2003). The DAF system can also be applied in combination with chemical addition.

The design criteria for a DAF system depend largely on the type of surface of the particulate matter. To ensure high yields, laboratory tests and pilot tests are necessary. The performance of the DAF system depends on the ratio of the volume of air to the mass of solids required to the degree of clarification (Metcalf & Eddy, 2003). The hydraulic loading rate is between 3-10m/h and the theoretical retention time is 20-40 minutes (Lenntech Water treatment & air purification Holding B.V.)

According to bench scale testing by Boner (1993) a DAF system alone obtained removal efficiencies for suspended solids of 90% and combined with chemical addition a removal efficiency of 99%. In France research was carried out by Lainé (1998). The processes applied during the research were coagulation/flocculation with an anionic polymer, a DAF system followed by sand filtration and UV disinfection. Results showed constant concentrations of SS in the effluent of the DAF system. This means that the influent concentrations of TSS (Total Suspended solids) do not affect the effluent. Removal efficiencies for TSS obtained by the DAF system can exceed 90%. The efficiencies of the DAF system reached its maximum level in the first minutes of operation, which is very important because the installation has to be able to work intermittently. Together with the removal of TSS also pollutants attached to the TSS are removed. This resulted in removal efficiencies of 80% - 90% for BOD_5, phosphorus and metals. The combination of these processes led to very high overall removal efficiencies, to physico-chemical pollution removal and microbiological disinfection, regardless the ingoing concentrations.

3.5 Direct sand filtration of wwtp influent

Little research has been carried out into direct influent filtration. Nieuwenhuijzen et al. (2001) explored the characteristics of direct influent filtration as a pre-treatment step for advanced particle removal. At WWTP Leiden-Noord in The Netherlands a pilot installation was placed. The filter column was operated upflow and downflow. Different filter media like gravel, quartz sand and anthracite were applied. Raw wastewater after screening with 6 mm mesh width was used. The quality of the wastewater was of course influenced by daily and weekly variations, but also rain events played a role.

During upflow filtration problems with clogging of the filter bed occurred. As a result of this the filter bed broke up and was lifted through the column. This happened with the sandfilter after a runtime of 220 minutes at a filtration rate of $10m^3/m^2h$. The average runtime was influenced largely by the incoming suspended solids loads. During downflow filtration filter runtimes of 70 minutes were used. These are lower than during upflow filtration because of a faster clogging of the top layer of the filter. The downflow filters performed better compared to the upflow filter on the removal of SS, COD and phosphorous removal. The addition of iron chlorine led to a higher removal of COD and phosphorous. The addition of polymer resulted in a higher removal rate of SS and COD.

3.6 High rate synthetic media filtration

Synthetic medium filtration like a Fuzzy Filter® which was described by Jimenez et al. (2000) and Marlasek (2005) can be used as a polishing step after physical separation technologies like a vortex separator or sedimentation. The influent of the filter has to be clear of heavy solids and coarse floatable materials. The effluent of a Fuzzy Filter® can be applied as feedwater for disinfection.

A Fuzzy Filter® can best be compared with a rapid sandfilter. A sandfilter removes particles with diameter 8-80 micron. A Fuzzy Filter® removes particles with diameter 5-80 micron. Fuzzy Filters® have some advantages compared to a sandfilter, namely (Schreiber LLC):

- high filtration rates with flow rates up to 90m/h (Jimenez et al. 2000), for rapid sand filtration flow rates are between 5-20m/h;
- low backwash waterflow;
- no loss of filter medium, the filter medium is obtained between two perforated plates;
- completely enclosed filter unit;
- low operation costs;
- Large storage capacity in the filter bed.

The water passes the filter medium for partical removal. This filter medium consists of polyvinyllidene balls which are highly porous (85%), as pictured in Figure 3-6. The porosity of the medium can be modified by compressing the filter. This means that during a first flush the medium can be compressed a little to prevent clogging and when diluted water enters the filter the medium can be compressed more to remove smaller particles. A Fuzzy Filter® is most of the time applied as an upflow filter (Marlasek, 2005 and Schreiber LLC) but can also be used as a downflow filter. A schematised picture of the filter is presented in Figure 3-7.

Figure 3-6: Filtermedium Fuzzy Filter ® (Bosman Watermanagement B.V., 2006))

When the filter is compressed, the top layer of the filter medium is more compressed than the lower part. As a result of this the larger particles will be removed immediately at the bottom of the filter and the top layer will remove the smaller particles.

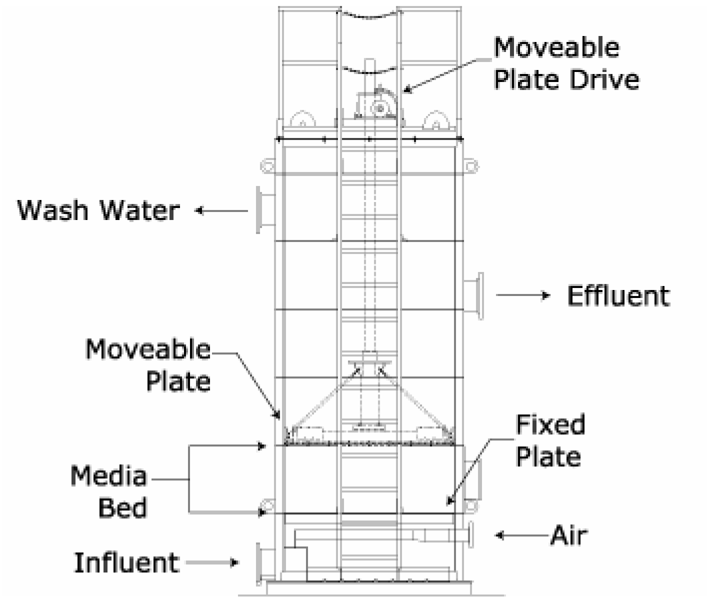

Figure 3-7: Schematic Diagram of the Fuzzy Filter ® (Schreiber LLC)

The schematisation of the cleaning procedure is presented in Figure 3-8. It depends on the feedwater quality how frequently a cleaning needs to take place. A cleaning procedure takes about 10 minutes.

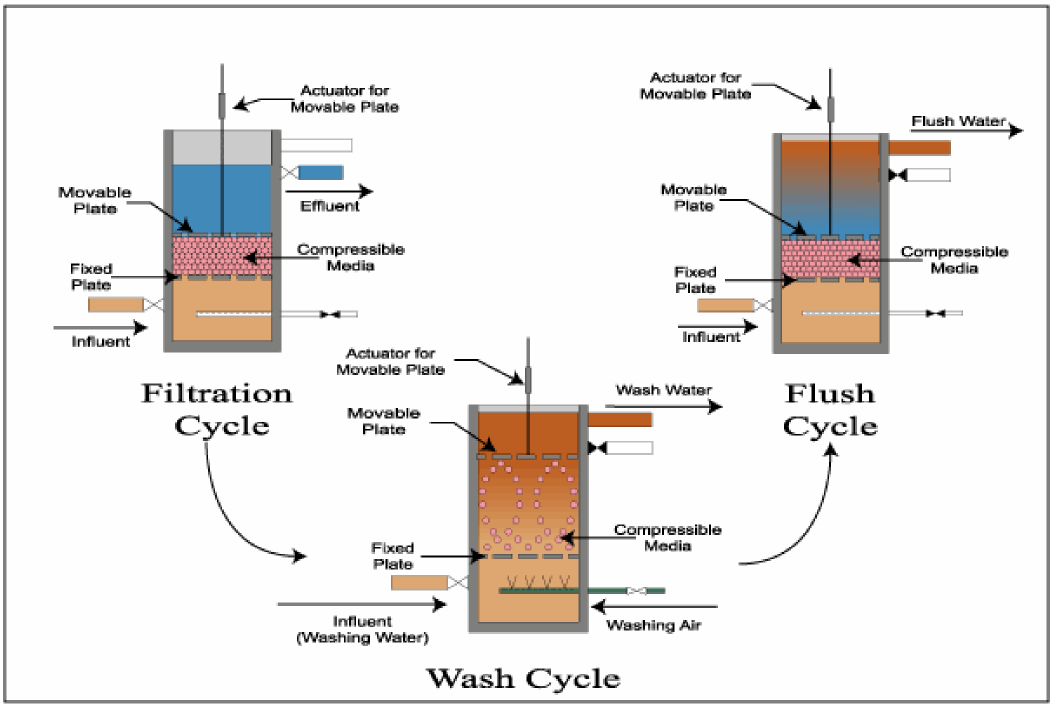

Figure 3-8: Cleaning procedure of a Fuzzy Filter® (Schreiber LLC)

The Columbus Water Works of Columbus, Georgia in the USA (Marlasek, 2005) tested the Fuzzy Filter® for the control of CSOs at the demonstration facility on the Chattahoochee River for a period of five years. During these five years 40 spills occurred. The Fuzzy Filter® treated effluent from vortex separators. The filter medium was slightly compressed and the configuration was downflow. The loading rates varied between 40-

68m/h. Fine particulate matter with diameter of 10-20 micron was removed. The pollutant removal rates for total suspended solids were 70%, for oil and grease 80%, for phosphorous 60% and for heavy metals 50-70%. A correlation between total suspended solids removal per unit volume of the filter medium was found. As well as a relation between the headloss across the filter medium with the volume of the filter medium.

The United States Environmental Protection Agency (USEPA), supported by the Rockland County Sewer District No.1 (RCSD) and the New York State Energy Research and Development Authority (NYSERDA), conducted a demonstration project at the pollution control plant in Orangeburg, New York in the USA (Pakenas et al., 2002). In this project Continuous Deflection Separation (CDS), fuzzy filtration, and UV light disinfection were tested. The pilot plant was set up at the screening building of the WWTP, receiving water from one of the three influent channels. The Fuzzy Filter® was fed with the water from the CDF with mesh width of 600 or 1200 microns and backwashed once or twice a day for approximately 45 seconds. Different compression ratios and loading rates were tested. The Fuzzy Filter® was effective in removing particles larger than 50 micron. The system was most effective with a 20% compression and hydraulic loading rates between 24 to 48$m^3/h/m^2$. The SS removal had an average of 40%. For the compression modes of 10% and 30% with the same hydraulic loading rates were consistently less.

3.7 Membrane filtration

During membrane filtration a semi permeable membrane divides two phases, this is shown in Figure 3-9 (Scherrenberg, 2004). The permeability of the membrane depends on the pore size and on the particle size. The inflow of the membrane is called feedwater, the water which passes the membrane is called permeate water and the part which is resisted is called the concentrate. The driving force for membrane filtration is the pressure difference between the feedwater and the permeate. This driving force is called the Trans Membrane Pressure (TMP).

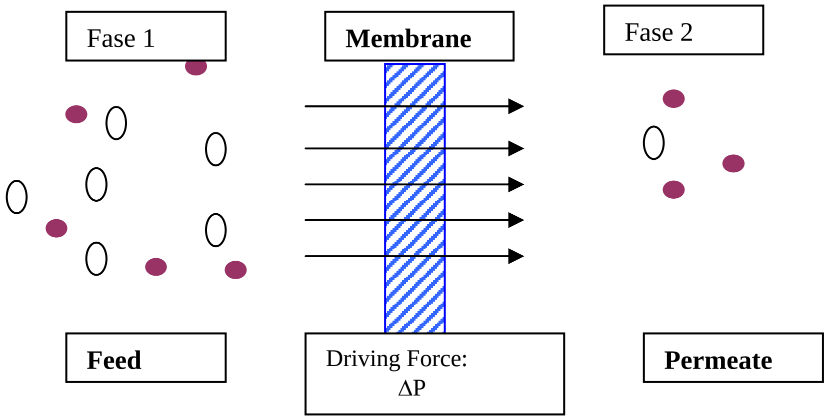

Figure 3-9: Membrane filtration schematised (Scherrenberg, 2004)

When pressure is used as a driving force the performance of the membrane will decrease in time. Especially the flux will decrease. The flux is the volume, which is treated per unit of time and per square meter. Fouling is deeply influenced by the operational mode: constant TMP or constant flux (Ravazzini et al. 2005a). A decrease in the flux is caused by fouling of the membrane and by concentration polarisation. When the flux decreases the TMP is increased to maintain the permeate flow. The membranes need to be cleaned when the TMP is too high. This cleaning can be done by a back-flush or a forward-flush. After a certain period of time, which depends on the fouling capacity of the feedwater, the membranes need to be cleaned with chemicals.

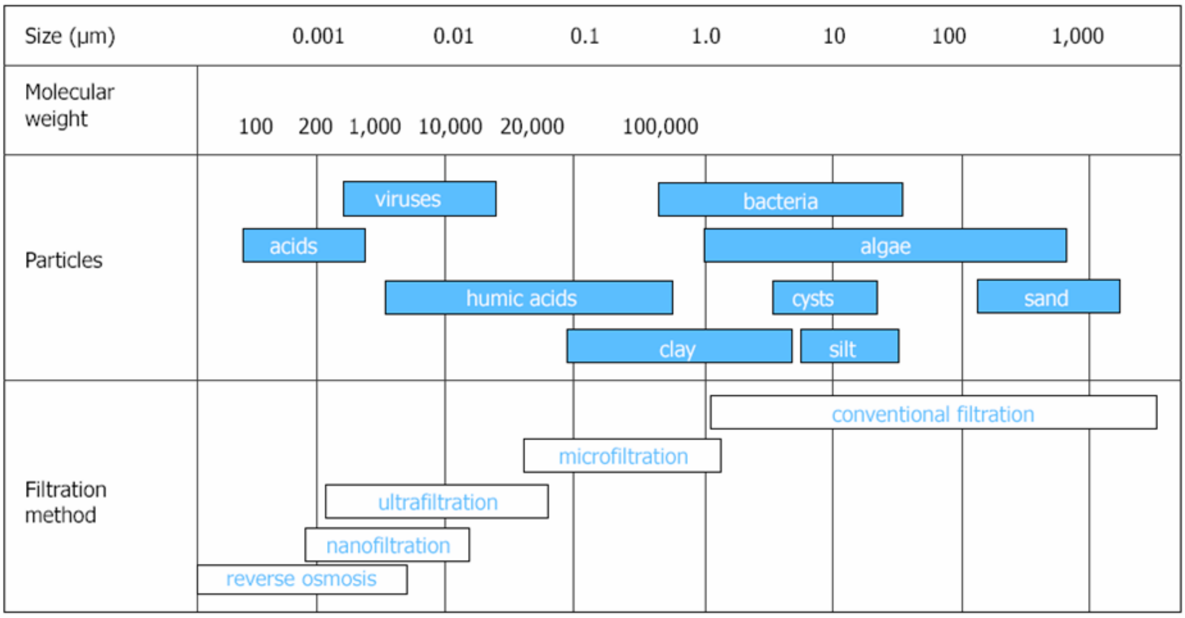

Figure 3-10: Filtration spectrum (De Moel et al., 2006)

Most of the membranes are made of polymers or macro molecules and are available in many different types, for example tubular, flat plate, hollow fibre and spiral wound.

A filtration spectrum, as illustrated in Figure 3-10, shows which filtration technique is best suited for specific particles. It also shows how high the driving force (pressure) needs to be. The most important parameters on which the membrane type depends, are the particle size and the origin of the particles.

Using membrane filtration for the treatment of raw sewage water, typical limitations of biological processes (Ravazzini et al., 2005b) like influence of temperature, feed stability, toxicity and start up period, are avoided. In the next coming paragraphs microfiltration and ultrafiltration will be described.

3.7.1 Microfiltration

The specific pore size for microfiltration (MF) is 0.08 to 10µm (Scherrenberg, 2004). Because of this pore size it is only possible to remove a large part of the suspended solids. Very common membranes with pore size 0.1-0.4µm are used. The advantage of these large pore sizes is that the TMP can be relatively low, namely 0.3 to 3 bar. MF membranes are available as plate, capillary and tube.

Lab scale experiments with microfiltration have been done by Bendick et al. (2004) to determine the membrane pore size capable of reducing bacteria to negligible levels. Primary sewage effluent from Allegheny County Sanitary Authority, Pittsburgh in the USA was used to simulate CSO water. Primary sewage effluent contains less suspended solids but it contains bacteria levels, which can also be expected in CSO water. For the experiments Membralox Tl-70 Alpha membranes with pore sizes of 0.2µm, 0.8µm, 2.0µm and 5.0µm were used. These membranes are ceramic, tubular microfiltration membranes. Membranes with a pore size of 0.2µm produced a slightly greater permeate flux than the 0.8µm membranes. This behaviour is believed to occur due to sever internal fouling. The 0.2µm membrane appears to be a barrier to Faecal Coliforms, Escherichia Coli and Enterococci, while the 0.8µm membrane shows breakthrough of bacteria.

Modise (2003) used for pilot scale experiments seven kinds of polymeric microfiltration membranes with pore sizes 0.2µm to 0.8µm. As feedwater primary effluent was applied which was pretreated by a swirl separator of Allegheny County Sanitation Authority

WWTP. The results show that membranes with pore sizes 0.45μm and smaller, were able to reduce the levels of Faecal Coliforms Bacteria (FCB), Escherichia Coli and Enterococci to below detection limits except for one membrane with pore size 0.3μm.

Table 3-1: Mean values for feed and permeate water quality (Till et al., 1998)

		Primary Effluent	
Parameter	Pore size	Feed	Permeate
Log reduction CFB	0.45 μm	4.8	
	1.2μm	3.3	
COD (mg/l)	0.45 μm	194.0	54.6
	1.2μm	242.2	83.8
SS (mg/l)	0.45 μm	110	1.8
	1.2μm	98.8	2.1
Turbidity (NTU)	0.45 μm	80.8	2.3
	1.2μm	97.9	2.4

Till et al. (1998) did pilot tests at the Cranfield University Sewage Treatment Works with two types of microfiltration. The applied tubular membranes had both a length of 2.4m and an internal diameter of 15mm. The applied pore sizes were 0.45μm and 1.2μm. The feedwater was primary effluent which was taken after the first sedimentation tank. The crossflow velocity was 2.4m/s and the TMP was 0.6-0.8bar. The parameters which were measured, are the log reduction of Faecal Coliform Bacteria (FCB) and the removal of COD, SS and turbidity. The results of the experiments are in Table 3-1.

Immediately (Till et al., 1998) after the start up, breakthrough of FCB occurred for both of the used pore sizes. The removal of FCB increased in the first 3 minutes, after 3 minutes the situation was more or less stable.

3.7.2 Ultrafiltration

The pore size of ultrafiltration (UF) membranes is in the range of 1,5 to 100 nm (Scherrenberg, 2004). The TMP is between 0.3 and 7 bar. Dissolved salts and smaller molecules can pass the membrane. Suspended solids, bacteria and viruses are retained, which is illustrated in Figure 3-11. UF membranes can be applied for the pre-treatment of surface water when producing drinking water, for the treatment of (industrial) waste streams and as pre-treatment for nanofiltration or reversed osmosis.

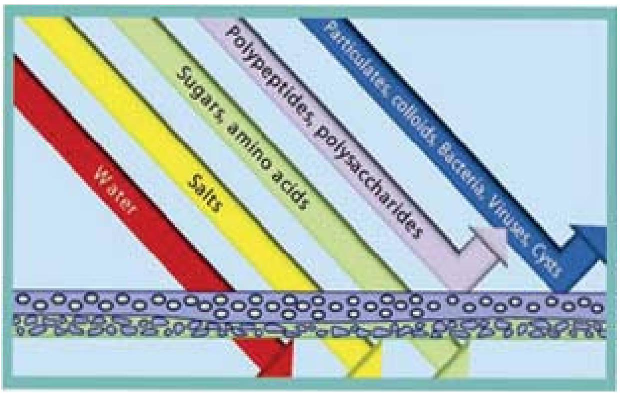

Figure 3-11: Ultrafiltration (Air2Water LLC)

When dealing with raw wastewater the feed first passes a simple mechanical pre-treatment and is then filtrated directly on a membrane (Ravazzini et al., 2005b). The UF membranes separate the undesired compounds of the water. According to Ravazzini et al. (2005b) is the permeate free of particles, micro organisms and bacteria. BOD, P and N are not removed, thus the permeate contains a large amount of nutrients which makes reuse for irrigation an option. The low turbidity (<1 NTU) and the absence of particles make it possible to produce high quality water of the permeate. Odours and organic compounds which are not removed with UF need to be removed when high quality water is produced. The concentrate contains a large amount of bacteria and micro organisms.

A disadvantage of this system is the fouling of membranes. Ravazzini et al. (2005a) investigated fouling of crossflow ultrafiltration membranes during filtration with raw wastewater which was taken from the WWTP De Groote Lucht, Vlaardingen in the Netherlands. The raw wastewater was pre-filtered on a 0.56mm sieve. The crossflow membranes were tubular membranes with pore size of 30nm. The batch tests were conducted at two different modes, namely constant TMP and constant flux. The results of the experiments with a constant TMP showed that an increasing TMP increases fouling formation at any crossflow velocity. Increasing crossflow velocity decreases the fouling formation and backflushing is necessary to control fouling. The best reached productivity is 80l/m^{2}h at TMP 0.3bar and crossflow velocity of 2m/s. The filtration run in this experiment was 1 minute, the experiment took 6-7h. During experiments at constant flux and crossflow velocity of 2m/s, the best reached productivity was 60-70l/m^{2}h.

The advantages of membrane filtration are that the process can work discontinuous and that a high automation and remote control can be implemented (Ravazzini et al., 2005b). These advantages and the quality of the permeate make direct UF useful for CSO treatment.

4 Adsorption techniques

Adsorption techniques are used to remove dissolved pollutions, for example heavy metals. In this chapter activated carbon and zeolites will be described. No information has been found yet about these treatment techniques being used for the treatment of CSO water.

4.1 Activated Carbon Filtration

Activated carbon is the most applied adsorption technique for the treatment of wastewater. Activated carbon is used for the removal of organic compounds and some inorganic compounds like nitrogen, sulphides, heavy metals (Metcalf & Eddy, 2003) and endocrine disrupting substances. Most of the organic molecules are retained at the surface of the activated carbon (STOWA, 2005). Activated carbon can be applied in a view ways, for example in a Granular Activated Carbon (GAC) filter, by inline addition of Powdered Activated Carbon (PAC) and in a continuous moving bed adsorption (MBA) (STOWA, 2005). When using activated carbon for the polishing of WWTP-effluent mostly GAC is used (Metcalf & Eddy, 2003). The GAC has a diameter of 0.25-3mm and is placed in a fixed bed, which is illustrated in Figure 4-1. A fixed bed column can be operated singly, in series or in parallel (Metcalf & Eddy, 2003).

Figure 4-1: On the left activated carbon filter (Odis Filtering LTD.) and on the right GAC (China)

After a certain period of time, which depends on the polarity of the removed compound, the filter will break through. At this moment the GAC needs to be regenerated and reactivated (STOWA, 2005). This regeneration and reactivation is done at high temperatures in combination with oxidizing gases (Metcalf & Eddy, 2003).

The filter bed can get clogged when suspended solids enter the system; so good pre-treatment, which removes suspended solids, is necessary. Larger organic compounds, like humic acids, can block pores of the activated carbon. As a result of this blockage the smaller organic micro pollutants cannot adsorb on the activated carbon anymore.

4.2 Zeolite

Zeolite is a natural occurring ion exchange material, which is used for the removal of ammonium and for water softening. When using zeolites for water softening a complex aluminosilicate with sodium is used. Softening is for the treatment of CSO water not of major importance, therefore only the removal of ammonium will be described in this paragraph.

For the removal of ammonium a naturally occurring cationic inorganic zeolite clinoptilolite can be applied (Metcalf & Eddy, 2003; Sarioglu, 2004) or a synthetic zeolite. Both natural and synthetic zeolites have the same features, which are a high level of ion exchange capacity, adsorption, porous structure, molecular sieve and a low density (Sariogle, 2004). Because of a longer lifetime, the synthetic zeolite is mostly applied (Metcalf & Eddy, 2003). The efficiency of cationic ion exchange depends on the temperature, the pH, the contact time, the concentration of the cation in solution and the structural characteristics of zeolite (Sarioglu, 2004).

Clinoptilolite is the most abundant natural zeolite that occurs in relatively large minerable sedimentary deposits in sufficient high purity in the world (Sarioglu, 2004). Clinoptilolite naturally contains the cations calcium (Ca), potassium (K) and sodium (Na) and removes besides ammonium, heavy metals and organic substances (STOWA, 2005; Sarioglu, 2004). The treatment performance for zeolite is presented in Table 4-1.

The ions, which are removed by zeolites, are ammonium (NH_4^+) and nitrate (NO_3^-). The regeneration of the zeolite is done with lime ($Ca(OH)_2$). The ammonium ions, which are removed (Metcalf & Eddy, 2003) from the zeolite, are converted, because of the high pH, to ammonia, which is stripped in a later stage. In this system extra care should be taken to prevent calcium carbonate precipitation in the pipelines, the stripping tower or in the zeolite ion exchange bed. The filter needs to be backwashed regularly.

Table 4-1: Treatment performance for the treatment of WWTP-effluent (STOWA, 2005)

parameter component substances	average influent to process (ppm)	average effluent of process (ppm)	process parameters (research/full scale)
NH_4	50	1	Zeolite exchange process, research
colour	> 20 ppm PtCo	< 10 ppm PtCo	full scale
organics	not known / limited	not known / limited	research
(heavy) metals	low (10 – 0,01) and high (>100) concentrations	< 0.1 – 0,001	full scale; research

Synthetic zeolites have two problems (Metcalf & Eddy, 2003). The first problem is that the resin has a higher affinity for sulphate compared to nitrate. As a result of this sulphate will limit the capacity for the removal of nitrate when it is present in the water. The second problem is that nitrate dumping can occur. This is also caused by the higher affinity for sulphate compared to nitrate. Sulphate can displace nitrate, when the nitrate adsorption has passed breakthrough, causing a release of nitrate. When high sulphate concentrations (greater than 25% of the sum of sulphate and nitrate) are present in the water, nitrate selective resins are advantageous (Metcalf & Eddy, 2003).

The treatment process (STOWA, 2005) can be operated in batch or in continuous mode. When using a batch process a mixed tank is applied. In the tank the zeolite is mixed with the water. The adsorption capacity can be increased by using a smaller particle size (Sarioglu, 2004), which gives a higher surface area. When the reaction is complete, the zeolite is separated from the water, regenerated and reused. Packed bed columns are used in continuous mode. This is usually a downflow system. The regeneration is done by backwashing with a regeneration solution.

Just like the activated carbon process SS have a negative effect on the process. The maximum SS concentration is 2-3mg/l (STOWA, 2005). Often multimedia (sand and anthracite) filtration is applied as a pre-treatment step. When the concentration in organic substances is high, an extra pre-treatment is needed, this can either be a macroporous resin or activated carbon (STOWA, 2005). The zeolite process produces a waste stream, which contains high concentrations of salt.

For the design of a column one of the most important parameters is the flow rate. From lab experiments which were carried out by Sarioglu (2004) was concluded that the time required to reach saturation increases with decreasing flow rates.

5 Disinfection techniques

Sewage water contains a large amount of bacteria and pathogenic micro organisms, which can be dangerous for the public health. Escherichia coli, Streptococci, Cryptosporidium Parvum and Giardia for example can cause diarrhoea. Salmonella can cause typhus and Hellmint eggs can cause worms. To reduce the chances of diseases, the wastewater should be disinfected especially when the water is discharged near recreation places. This does not mean that disinfection should be used only in summertime when people swim in the water; some bacteria and viruses can stay active for a long time, which makes it necessary to disinfect the discharged water during the whole year (Van der Graaf, 1996).

Disinfection is the process of destructing or inactivating pathogens by oxidation or radiation (EPA, 1999a). Disinfection can also occur through the removal of solids. Physical reduction of pathogens is accomplished through (membrane)filtration, sedimentation and flotation. For the oxidation of pathogens chlorine is commonly applied in the past, but this technology may not be feasible at all CSOs. Reasons for this are (EPA, 1999b):

- intermediate and highly variable flow rate;
- high SS concentration;
- variation in temperature;
- variation in bacteriological composition;
- chlorine can be prohibited in the receiving water;
- CSOs are often located in remote areas, this requires automated systems.

Because chlorine disinfection may not work in all situations new techniques were developed. For example ultraviolet (UV) radiation, ozonation, chlorine dioxide, peracetic acid and electron beam irradiation (E-beam) are other options. E-beam disinfection uses a stream of high rate energy electrons which are directed into a thin film of water or sludge. The electrons break up the water molecules and form among other substances oxidizing hydroxyl radicals (EPA, 1999b). In this chapter only chlorination, UV and ozonation will be described.

5.1.1 Chlorination

It is very common to use chlorine in gaseous form (Cl_2) or as ionised solid, for example calcium hypochlorite ($Ca(OCl)_2$) or sodium hypochlorite ($NaOCl$). The behaviour of these substances are almost identical (Van der Graaf, 1996).

$Cl_2 + H_2O \rightarrow HCl + HOCl$
$Ca(OCl)_2 \rightarrow Ca^{2+} + 2\ OCl^-$
$NaOCl \rightarrow Na^+ + OCl^-$

$OCl^- + H_2O \rightarrow HOCl + OH^-$

The main components (Conlan and Wade, 2002) of a chlorination disinfection system are a chlorine generating tank and a contact tank. When hypochlorite solution is applied, also a chemical storage tank is needed. In the USA the dosage (Conlan and Wade, 2002) in the contact tanks is usually 5-20mg/l.

Together with ammonia in the water chloramines can be formed. This substance will be active as a disinfectant but it is less powerful than chlorine. It depends on the pH which type of chloramine is produced (Van der Graaf, 1996).

NH_3 + HOCl	$\leftrightarrow NH_2Cl + H_2O$	(pH > 8,5)
NH_2Cl + HOCl	$\leftrightarrow NHCl_2 + H_2O$	(pH 4,5 - 8,5)
$NHCl_2$ + HOCl	$\leftrightarrow NCl_3 + H_2O$	(pH < 4,5)

Trichloramine (NCl_3) is hardly found. Dichoramine ($NHCl_2$) and monochloramine (NH_2Cl) are more common and can react with each other.

$NH_2Cl + NHCl_2 \leftrightarrow N_2\ (g) + 2\ HCl$

This means that there is a certain ration between the amount of ammonia and the amount of chlorine at which all ammonia is oxidized to nitrogen gas (N_2) (Van der Graaf, 1996). For complete oxidation 7.6mg Cl_2 per mg N is needed.

$2NH_3 + 3\ Cl_2 \leftrightarrow N_2\ (g) + 3\ HCl$

Chloramines are 25 to 100 times (Van der Graaf, 1996) less active than free chlorine, and therefore there is a need to dose more chlorine than there will be used for the formation of chloramines. In this way free chlorine stays in the water. This overdosing of chlorination is called breakpoint chlorination. When breakpoint chlorination is practiced properly, the bactericidal effect is considerably good and the viricidal effect is considered modernate (EPA, 1999a). When working with breakpoint chlorination it can be necessary to dechlorinate the effluent to protect the receiving waters. This dechlorination can be done with sulfur dioxide or with sodium bisulfate (EPA, 1999a).

In CSO water with low suspended solids concentrations a quick dosage of chlorine is enough to kill the pathogens, according to EPA (1999a; Conlan and Wade, 2002). When the CSO water contains a high concentration in suspended solids the disinfection process is controlled by two mechanisms (Conlan and Wade, 2002). In the first mechanism the individual and small clumps of bacteria are killed by the chlorine. The bacteria inside the suspended solids are not affected. The second mechanism to remove or kill these bacteria is the advanced removal of suspended solids. Other options are a longer contact time or a higher dosage of chlorine.

According to EPA (1999a) chlorine oxidizes the germ cells, it changes the cell permeability, it changes the cell protoplasm, it inhibits the enzyme activity, it damages the cell DNA and RNA and it reacts strongly with lipids in the cell membrane. For this reason cells with high lipid concentrations in their cell membrane (bacteria) are easier to destruct with chlorine than cells with a small concentration of lipid in their cell membrane (viruses, cysts).

Advantages of chlorination are (Van der Graaf, 1996):

- some decrease of BOD;
- prevention of algal bloom by slowing down the algal growth;
- more cost effective in comparison to other disinfection methods;
- availability of reliable dosing, measuring and control equipment;
- decrease of ammonia in the water.

Some disadvantages of chlorination are (Van der Graaf, 1996):

- chlorine gas is very poisoning, so stringent safety regulations are necessary;
- marginal chlorination does not give enough deactivation of viruses and some faecal pathogens;
- no colour removal;
- bacteria can be embedded in suspended solids, so suspended solids need to be removed before the chlorination (EPA, 1999);
- possible formation of carcinogenic disinfection by-products, like trihalomethanes (THM) and hydrocarbons.

The formation of carcinogenic THMs is a serious problem.

The quality and the composition of the CSO water can change rapidly. This means that the dosage of chlorine needs to be adjusted as quickly as the composition and the flow of the water changes. To maintain a certain chlorine concentration in the water at least online flow measurement needs to be done, but also the suspended solids concentration needs to be measured.

5.1.2 Ultraviolet radiation

UV radiation is one of the most common applied alternatives to chlorination in North America (Gehr et al., 2003). In the Netherlands it is used in drinking water treatment plants.

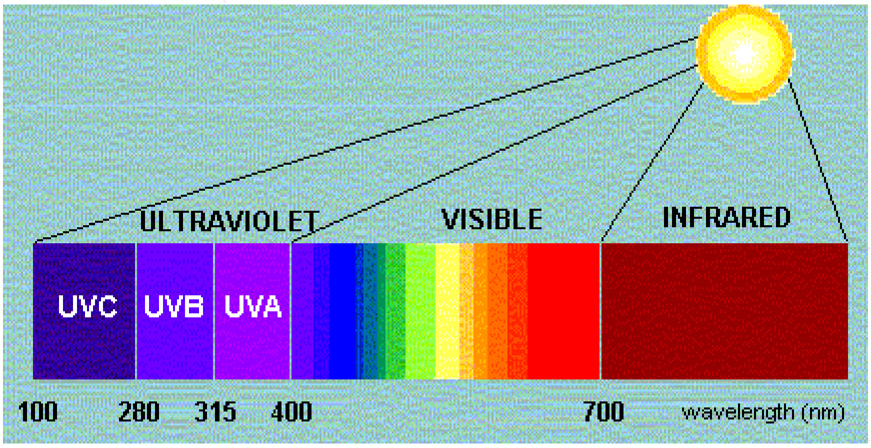

Figure 5-1: Radiation spectrum (Australian Government)

Ultraviolet radiation (UV) is light with wavelengths between the visible and roentgen rays as illustrated in Figure 5-1. UV light has energy and is electromagnetic.

UV light is subdivided into three classes (Scherrenberg, 2003), which are named below:

- UV-A: 315 – 400 nm (Gives the brown taint on the skin),
- UV-B: 280 – 315 nm,
- UV-C: 200 – 280 nm,
- UV-vacuum: 100 – 200 nm.

For disinfection UV-C rays are most efficient, especially UV-C with a wavelength of 254nm as illustrated in Figure 5-2. The high energy level of this UV-C light affects the bindings in DNA, as a result of this, the genetic material becomes unreadable and the cell will be unable to function. Many types of bacteria are capable of repairing the damage done by UV. This makes it very important that the dosage is high enough to kill the bacteria instantly (Scherrenberg, 2003; Conlan and Wade, 2002).

The intensity which is needed to kill the cell, depends on the type of organism, the turbidity of the water and the flow pattern in the reactor (Scherrenberg, 2003). The radiation field close to the lamps is more intense than further away. Because radiation cannot be mixed through the water the hydraulic pattern of the reactor needs to be designed well. The best way is to make use of a plug flow reactor (PFR). The absorbance coefficient of the water gives an indication of the UV demand. This coefficient is different for each water. The UV dose can be calculated by multiplying the intensity per unit surface (mW/cm^2) with the exposure time (s) (STOWA, 2005).

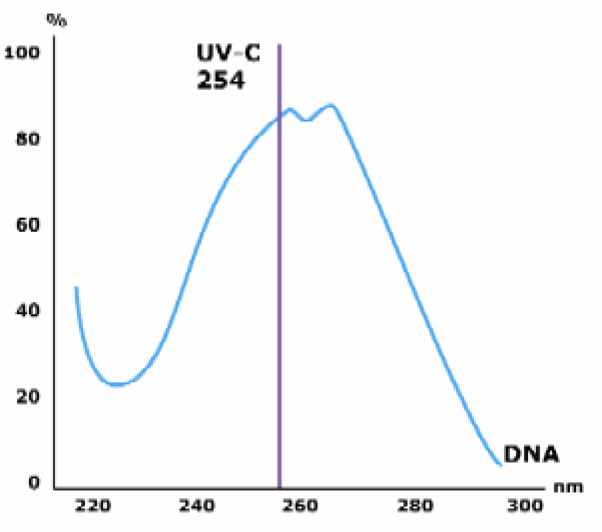

Figure 5-2: Reduction of DNA (Scherrenberg, 2003)

Suspended solids (SS) have an unfavourable effect on the disinfection process. First of all organisms, which are present in SS, are hard to reach with radiation and secondly can SS have a shadow working, what causes the real dose to be lower than calculated (Van der Graaf, 1996). This agrees with the results of a pilot research in the City of Columbus, Georgia in the USA, by Boner et al. (1995) who concluded that higher disinfection efficiencies were associated with a higher removal of SS. A reduction of SS to 40-80 mg/l is enough to stand up for UV disinfection. (David, 2005). The critical particle size is in the range of 9-10 μm, below this size particles cannot shield or embed bacteria (Gehr et al., 2003). Iron, sulphates, nitrates and phenols can absorb UV light (STOWA, 2005). In Table 5-1 an overview is given of substances which can cause a negative effect of UV disinfection.

Table 5-1: Disturbing substances for UV disinfection (STOWA, 2005)

Constituent	Effect
BOD, COD, TOC	No, or minor effect
Humic material	Strong adsorbers of UV radiation
Oil and grease	Can accumulate on quartz sleeves of UV lamps, can absorb UV radiation
TSS	Absorption of UV radiation, can shield embedded bacteria
pH, Alkalinity, Hardness	Can impact scaling potential

The advantages of UV disinfection are that no (hazardous) chemicals are added to the water or need to be stored (Averill et al., 1997), the disinfection has a shorter contact time (20-30s) compared to other disinfectants (Conlan and Wade, 2002) and that UV light is more effective on viruses than chlorine. A disadvantage is that UV light can react with aromatic compounds and nitrate, this reaction can produce compounds that exhibit mutagenic activity (Till et al., 1998). Other disadvantages are that UV light has no remaining disinfecting activity, that there is a chance of ozone production (Van der Graaf, 2003) and that electric shocks can occur which can cause skin and eye burning.

According to Conlan and Wade (2002) UV systems generally are unsuitable for the treatment of stormwater, because of the relatively high flows, high SS concentrations and the low transmittance of the wastewater. The lamps will foul and need to be cleaned regularly with wipers and periodically with chemicals (EPA, 1999c). UV systems are also poor at responding to sudden rapid changes in flow and runoff debris may foul or damage the lamp sleeves or wiper mechanisms (Conlan and Wade, 2002). Turning on and off the UV lamps will reduce the efficacy with every on/off cycle (EPA, 1999c). An UV installation can start within a minute. UV disinfection after coagulation/flocculation, DAF and sandfiltration (Lainé, 1998) gave good results. Removal efficiencies of >4.1 log for E.coli and >3.1 log for Entrococci were obtained. Entroviruses were completely removed, Salmonellae >85%, Giardia cysts 94% and 75% of the Helminth eggs were removed.

5.1.3 Ozonation

Ozone is an unstable structure of oxygen. Ozone can be in the atmosphere or dissolved in water. Ozone contains three oxygen atoms which results in a very reactive and unstable molecule. The half-life time is 20-30 minutes (Van der Graaf, 1996) and a concentration in air higher than 10% can be explosive. A structure of ozone is pictured in Figure 5-3. Ozone is one of the most powerful oxidisers there is. It can inactivate all types of bacteria and viruses, it can oxidise organic material (Scherrenberg, 2003) and pharmaceuticals like antibiotics and betablockers (Larsen et al., 2004).

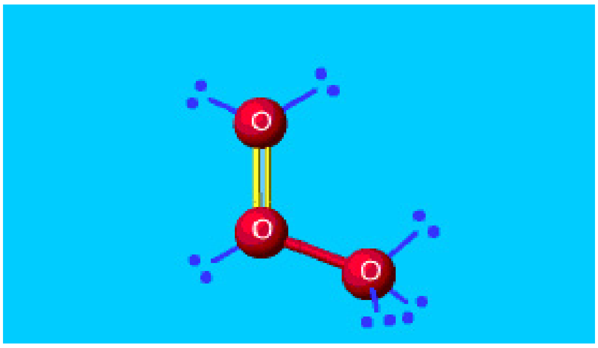

Figure 5-3: Structure of ozone (Elmhurst)

The main components (Conlan and Wade, 2002) of an ozonation disinfection system are the generating plant, the contact tank and the off-gas destruction unit. The disinfection efficiency of ozone is related to the amount of ozone transferred into the water (EPA, 1999b), the characteristics of the wastewater and the contact time (Conlan and Wade, 2002). Ozonation is sensitive to SS, and BOD concentrations greater than 30mg/l. The typical mixture of ozone with air is 0.5-1% together with a contact time of 5-15 minutes.

The kinetics of ozone reactions are very complex mainly because the reaction rates differ with different chemicals dissolved in the water. Another reason for complexity is caused by the ozone decomposition products, which interact with micro organisms (Gehr et al. 2003). Ozone decomposes in clear water solution as follows (Van der Graaf, 1996):

$O_3 + H_2O \leftrightarrow HO_3^+ + OH^-$
$HO_3^+ + OH^- \leftrightarrow 2\ HO_2\bullet$
$O_3 + HO_2 \leftrightarrow HO\bullet + 2\ O_2$
$HO\bullet + HO_2 \leftrightarrow H_2O + O_2$

The oxidation of organic material reduces the BOD and COD concentrations. Ozone also demolishes colour, scent and SS. The activity of ozone depends on the pH. The ozone will decompose partially and the rate increases above pH 7.5 with increasing pH (Van der Graaf, 1996)

The advantages of ozonation are:
- it deactivates almost all the pathogenic micro organisms;
- it reduces the turbidity, BOD and COD;
- the effluent becomes oxygen rich;
- it increases coagulation (EPA, 1999b);
- it requires short contact time (EPA, 1999b).

The disadvantages (Van der Graaf, 1996) of ozonation are:
- the formation of bromate as disinfection by-product;
- the production of ozone needs to be in situ;
- high initial costs;
- high ozone demands for wastewater due to reactions of ozone with organic compounds, inorganic compounds and SS (Gehr et al., 2003);
- because ozone is very poisonous, strict safety measurements are necessary;
- it forms nitric oxides and nitric acids which can cause lead corrosion (EPA, 1999b);
- it is a more complex technique than chlorination or UV disinfection, because of this complicity it requirs complex equipment and efficient contact tanks (Conlan and Wade, 2002).

The disadvantages cause that ozone is not applied frequently for the disinfection of wastewater.

Carcinogen disinfection by-products, like bromate, are produced when bromide-ions react with ozone (Scherrenberg, 2003). Bromide-ions can be dissolved in water. Bromate and other bromide-productions can react with Natural Organic Matter (NOM) and form bromide hydrazines. The formation of bromate can be diminished by reducing the pH or by dosing ammonium. As a result of ammonium dosage bromide amines will be formed.

The calculation for the ozone dosage is based on the gas flow and the concentration applied to the contactor versus the gas flow out of the contactor and the ozone residual in the water phase (EPA, 1999b). The composition of CSO water will differ continuously; to retain a good disinfection the ozone dosage needs to change simultaneously with the water quality. To reach this, sensors need to be placed and online measurements need to be taken, which makes the process more expensive and difficult.

6 Selection of the treatment processes

6.1 Selection criteria

When choosing the treatment configuration for CSO water one should take several criteria into account. The most important criteria are the quality of the water which arrives at the CSO and the amount of overflow water. In the Netherlands the water quality of CSO water is not measured, see also paragraph 1.5. The amount of overflow water is measured at some locations and can therefore be used. It has to be taken into account that due to climate changes more extreme rainfall is expected and therefore larger flows can occur. Besides the amount of overflow water, several other criteria are important. These criteria are described in the next coming paragraphs without giving priority.

6.1.1 The treatment facility must be able to survive long periods without feedwater

CSOs occur in the Netherlands between five to ten times a year per location. This frequency does not say anything about the deviation of the CSOs during the year and it also does not say anything about the duration of a CSO. It does make clear that a CSO treatment facility will have no feedwater for most of the year.

A biological system needs feedwater as a food supply for the bacteria. When there is no food supply the bacteria will die. A possibility to keep the biology alive is to feed the biological system constantly with diluted wastewater, a so-called bleed stream. This water is then treated by the biology. The effluent should then be returned to the sewer to prevent a continuous flow of water into the receiving water.

Chemicals can get old and lose their reactivity when they are stored for a long period. Some coagulants can be maximally stored for half a year. This means that the chemicals need to be checked regularly, which will cost money.

6.1.2 The treatment facility must be able to handle wide variations in flow rate and loading rate

Information about fluctuations in flow rate and loading rate can be found in paragraph 1.4. Dealing with wide variations in flow rate and loading rate is difficult. An installation, for example sand filtration, is designed for a specific flow rate. When more or less water needs to be treated the process will not work efficiently anymore. A possible solution is building a storage tank in front of the treatment facility. By doing this, variations in flow rates can be stabilized and a constant flow can enter the treatment installations.

The first flush effect tells us that a wave front from sewage only can be formed. This means that the water, which arrives first at the treatment facility, can be pure sewage. After the wave of sewage, diluted water arrives; this can be diluted so extremely that the water quality is comparable with rainwater. If a treatment step is designed for sewage water, the diluted water will not be treated effectively. When the installation is designed to treat rainwater, and sewage water enters the installation instead, it has a high risk of clogging. If clogging occurs, no water or just a small amount of water can be treated. As a result of this CSO water will flow untreated via an emergency by-pass into the receiving water. A possible solution is an installation, or a combination of techniques, which is able to adjust to different pollution loads. For example a Fuzzy Filter®, which is described in paragraph 3.6, can be used, because adjustment of the filter bed porosity is easy.

6.1.3 The treatment facility must be able to start up within a couple of minutes

CSOs can occur within minutes after it has started to rain. To prevent untreated water to come into the receiving water, the treatment needs to start up within minutes and must be able to operate when the water arrives. To be sure that the treatment facility starts up in time, sensors need to be placed which measure for example the height of the water level in the sewage system.

6.1.4 Advanced removal of SS is necessary

Advanced removal of SS does not only decrease the visual pollution but it also gives good removal results for many pollutants like heavy metals, PAX, bacteria and viruses, which are bound to SS. This is also described in paragraph 1.5. Advanced treatment of CSO water will also be necessary in the future to comply with the WFD regulations.

6.1.5 Chemical dosage needs to be as less as possible

Like mentioned before, chemicals can lose their reactivity when they are stored for a long period. Chemicals can be stored for about half a year. However this is not the only problem with chemicals. When dealing with chemicals, special safety measures need to be taken to prevent fire, explosions or health risks for the mechanics.

The dosing rate of the chemicals needs to be adjusted to the amount of CSO water and the pollution of the CSO water to maintain a constant (optimal) concentration of the chemicals. For the measurements of the amount of water a flowmeter is necessary. Measuring the pollution will be difficult, because it cannot only depend on the turbidity. When the dosing rate is to low the chemicals will not work properly and the pollution will not be removed affectively. When the dosing rate is to high the chemicals will react with the pollutions, which will be removed, but the residual concentration of the overflow water will be to high. As a result of this chemicals will come in the receiving water.

6.1.6 The treatment facility must have a small footprint and cause no annoyance to the surroundings

Because CSO constructions are often in urban areas, there is little space to place a treatment facility. This means that treatment facilities need to be compact or placed under the ground.

To prevent annoyance to the surrounding area caused by noise or bad odors, measures need to be taken. This can be done by using sound-demping materials and odor treatment facilities.

6.1.7 The maintenance costs need to be as low as possible

Of course the costs need to be as low as possible, but a good and efficient treatment of the CSO water must be the first aim.

To reduce costs, a treatment facility needs to operate fully automatic. An alarm signal should be given to the operators when the stock of chemicals is almost empty or when there are problems which need to be solved.

6.2 Selection of treatment processes

To select a technique for SS removal a multi criteria table is made, see Table 6-1. In this table the different techniques which are applied for the treatment of CSO water (chapter 2 and 3) are compared for the different selection criteria which are mentioned in paragraph 6.1. The techniques are graded between 1 and 10. A 10 is given when the technique satisfies the criteria completely. Each selection criterion weights differently and is graded between 2 and 5. The calculation of the final result is done by adding up the multiplications of the grade with the factor for a certain technique and dividing the result by the summation of the factors.

Table 6-1: Multi selection criteria table

	Survive long periods without feedwater	Handle wide variation in flow rate and loading rate	Start up time within minutes	Advanced removal of SS etc	Minimum chemical dosage	Small footprint an no annoyance to the surroundings	Maintenance costs as low as possible	Result
Factor	5	5	4	5	3	3	2	
Wetland	4	5	7	3	10	1	8	5.0
Settling/Storage tank	10	10	10	2	10	3	9	7.7
Sieving/screening	10	10	10	1	10	10	9	**8.3**
Netting TrashTrap™	10	10	10	1	10	10	9	**8.3**
Vortex	10	6	10	2	10	7	9	7.4
Lamella	10	7	10	4	5	5	7	7.0
Actiflo®	7	4	5	8	4	6	5	5.7
Densadeg®	7	4	5	8	4	6	5	5.7
DAF	9	6	10	7	7	5	5	7.3
Direct Sand Filtration	8	5	10	8	9	7	6	7.6
Fuzzy Filter®	10	8	10	8	9	8	6	**8.6**
MF	6	5	10	9	6	9	2	7.0
UF	6	5	10	10	6	9	2	7.2
Activated Carbon	10	6	10		10	7	6	**8.3**
Zeolites	10	6	10		6	7	7	7.9
UV	10	6	10		10	8	5	**8.0**
Ozone	6	3	5		1	4	3	3.9
Chlorine	7	4	7		1	5	4	5.0

6.2.1 Wetlands

It becomes clear from Table 6-1 that wetlands are not an option for the treatment of CSO water in the urban areas in the Netherlands. Wetlands have a large footprint for which there is no space in an urban area. Another disadvantage is that flow rates should not exceed 0,15 m^3/ms, see also paragraph 2.1. Nevertheless, when the use of area is not an issue and when the amount of overflow water is relatively small this technique is a good alternative. One of the major advantages is that a wetland fits perfectly into nature.

6.2.2 Primary techniques

Primary techniques can be applied as an individual treatment step or as a pre-treatment step for other installations. Primary techniques remove floatables but do not remove SS and dissolved substances. Settling and storage tanks do not treat the water to standards that will fulfil the WFD requirements, only the spill volume and frequency will decrease.

Storage tanks have a large footprint and are expensive to built. Despite these disadvantages settling and storage tanks are built frequently. When a storage tank is already built and the overflow frequency and volume are still causing problems to the receiving water, the tank should be applied as a pre-treatment step or for example lamella can be placed in it.

Screening and sieving systems are small and robust systems which remove large pollutants, see also paragraph 2.4 to 2.5. Regularly checks are needed to prevent clogging of the screen or sieve when it is not cleaned automatically. The chance of pump failure or clogging of pipelines is reduced when using sieving or screening as a pre-treatment.

The Netting TrashTrap™ system is an inexpensive way of reducing the floatables in the CSO water. A major advantage of the Netting TrashTrap™ system is that it can be placed inside a sewage pipeline. In this way it does not cause any annoyance to the surroundings. The Netting TrashTrap™ system does not require any chemical dosage. After one or more CSOs, depending on the situation, the nets need to be replaced. The applied net which is filled with floatables can be transported to the rubbish-dump. A new net can be placed.

An advantage of a vortex separator is that it has a small footprint. A major disadvantage of Vortex separators is that they are designed for a certain flow. The treatment process does not function efficiently when more or less water enters the vortex separator. A vortex separator does not need any pre-treatment but it only removes the larger particles. Because of the earlier stated disadvantage a vortex separator is not reliable enough to be used as a pre-treatment step for advanced suspended solids removal. The vortex separator will not be described in this research any further.

6.2.3 Chemically enhanced high rate filtration

The Actiflo® and the Densadeg® systems use chemicals like polymer and ferric chlorine to form flocs which will settle easily. The use of chemicals is a disadvantage because it will ask for maintenance and it brings a certain health risk. Another disadvantage caused by the use of polymer, is the time which is needed to prepare the polymer. Polymer cannot be prepared in advance and it takes about 15 minutes to prepare the solution. This means that these installations cannot start up within 2 minutes. An advantage is that these systems are small, have relatively high removal efficiencies and can be implemented in already existing systems.

The United States Environmental Protection Agency (EPA) writes about the advantages and disadvantages of chemically enhanced high rate filtration or ballasted flocculation in a fact sheet (EPA, 2003). One of the advantages is that this system requires less area compared to a storage tank, which reduces the construction costs. Disadvantages are that the start up time is typically 15-20 minutes and that it may take several hours to achieve the optimal chemical dosage (EPA, 2003). During storm events the suspended solids concentrations vary which requires monitoring and adjustment of the microsand concentration and the overflow rate (EPA, 2003). This makes it not applicable for CSO treatment and therefore the Actiflo® and Densadeg® will not be described any further in this research.

Lamella separation is a part of the Actiflo® and the DensaDeg® system, but it can also be used on its own. As was stated in paragraph 3.2 lamella separation reduces the retention time with one third to a quarter, compared to the retention time of a conventional settling tank. This means that the footprint of lamella settling can be one third to a quarter of the area of a conventional settling tank. This reduces the construction costs. Lamella separation can be combined with chemical dosage to increase the removal efficiencies. An advantage of lamella is that it can be placed in an already existing storage tank. Because of this advantage the lamella separation will be used in further research.

6.2.4 Dissolved air floatation system

Dissolved Air Floatation (DAF) systems need more maintenance compared to other installations, for example lamella plate clarification. The removal efficiencies which can be reached by a DAF system are high but it depends largely on the type of surface of the particulate matter. For CSO water this is a changing factor which might result in low removal yields. The possibility of low removal rates combined with the hydraulic loading rate of 3-10m/h and a theoretical retention time of 20-40 minutes make the DAF system not applicable for CSO treatment because the system will be unreliable and has a large footprint.

6.2.5 Filtration techniques

Filtration techniques will require a pre-treatment to prevent clogging of the filter media. Direct sand filtration needs at least screening with a mesh width of 6mm as pre-treatment. This requirement leaves two options as pre-treatment, namely a sieve or the Netting TrashTrap™ system. Because filtration rates will not exceed $10m^3m^2h$, see also paragraph 3.5, this technique is not feasible for the treatment of CSO water and it will not be described any further in this research.

With a Fuzzy Filter® it is possible to filtrate water with high flow rates, up to 90 m/h. The porosity of the filter medium can be adjusted to the size and the amount of the SS particles in the water. Pre-treatment is necessary, otherwise the pumps and the filter medium will get clogged rapidly. The installation can be switched on and be operational within a couple of minutes. Chemicals can be dosed for advanced phosphorous removal. It is a relatively small installation which can survive long periods without feedwater. Because of these advantages the Fuzzy Filter® will be described further in this research.

When using membrane filtration, at least fine sieving is necessary to prevent clogging. Ravazzini et al (2005a) used a fine sieve of 0.56mm, which makes it possible to use a sieve or the Netting TrashTrap™ system as pre-treatment. Membranes need to be cleaned regularly with chemicals. With membrane filtration advanced removal of SS is possible. Experiments with direct ultrafiltration of WWTP-influent were already carried, as was mentioned in paragraph 3.7.2 and showed good results. For this reason and because of the more advanced removal of SS has ultrafiltration the preference above MF.

6.2.6 Adsorption techniques

Activated carbon can remove organic micro pollutants, heavy metals, sulphides and nitrogen. Advanced SS removal is needed before the water enters an activated carbon filter. SS cause clogging of the filter media. An activated carbon filter has a small footprint and can start up within a couple of minutes. The costs can be high because of the regeneration of the activated carbon.

Pre-treatment is also necessary for zeolites ion exchange. Zeolite can remove ammonia and heavy metals. The installation needs a small footprint comparable with activated carbon. The advantage of zeolites is that the regeneration is simple, low priced and can be done on site which is not possible for activated carbon. Synthetic zeolites have two problems (Metcalf & Eddy, 2003). Two disadvantages are that the resin has a higher affinity for sulphate compared to nitrate and that nitrate dumping can occur. The fact that zeolites have a higher affinity for sulphur makes it not useful for the treatment of CSO, because sulphur will be in the CSO water especially in the first flush. Because sulphur concentrations can be high in the first flush, the zeolites can be saturated with sulphur and will not remove nitrate anymore.

6.2.7 Disinfection techniques

To have a good disinfection with UV treatment, pre-treatment with a reduction of SS to 40-80 mg/l is needed. Disadvantages are that UV installations are poor at responding to sudden and rapid changes in flow as was described in paragraph 5.1.2. and that the lamps foul very rapidly. The advantage is that the installation is small, *the start up time is within a minute* and no hazardous chemicals are added to the water, therefore is UV treatment described further in this research.

Ozone is very poisoning and can already be explosive in a mixture with air from 10% and higher. This is a major disadvantage because it brings an enormous risk for the surroundings when built in an urban area. Therefore, ozone will not further be described in this research.

Chlorine is in the world very frequently applied for the disinfection of water. A disadvantage is that chlorine is not effective at low dosing rates and carcinogenic by-products can be formed, see also paragraph 5.1.1. Chlorine has the advantages that it also decreases BOD and ammonia concentrations and that it is more cost effective compared to other disinfection methods. Because of these advantages chlorine disinfection will further be described in this research.

6.2.8 Conclusion

Based on earlier mentioned arguments a selection is made of techniques which will be further described in the following chapters. The primary techniques are wetlands, coarse screens, sieves and the Netting TrashTrap® system. Lamella separation with or without chemical dosage will be described. The filtration techniques are the Fuzzy Filter® and ultrafiltration. The adsorption techniques, activated carbon and for disinfection UV disinfection as well as chlorine disinfection will be used.

7 Designs and technical data

In this chapter designs are made of the selected filtration, adsorption and disinfection techniques from paragraph 6.2. The calculations are all made for a flow of ±1000 m^3/h CSO water. The aim of these calculations is to see how large the installations will become when this amount of water needs to be treated.

7.1 Lamella separation

The flow in a lamella plate settler can be counter current or co-current. For counter current (Van Dijk et al. 2004) flow the angle of the plates must be about 55° to 60° to ensure sludge removal. For co-current flow de angle can be less, namely 30° to 40°. The height is between 1 and 3 meters, the width between 3,4 and 8 meters. The thickness of the plates is about 5mm.

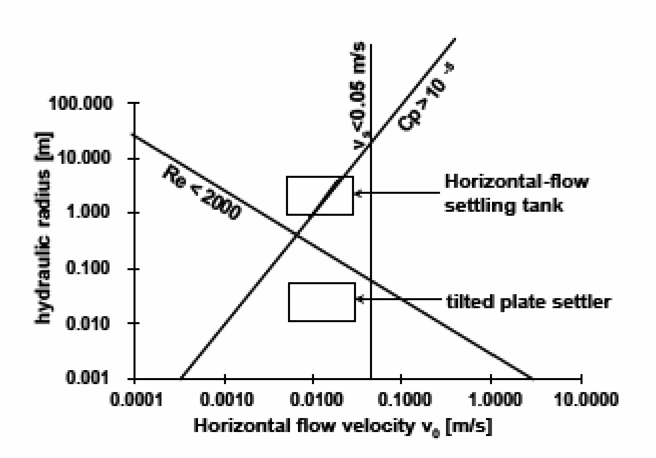

Figure 7-1: Hydraulic conditions for optimal settling (Van Dijk et al., 2004)

In Figure 7-1 the hydraulic conditions for optimal settling are presented. The Camp number and the Reynolds number both depend on the hydraulic radius and the horizontal flow velocity. The Camp number and the Reynolds number for flow in a tank can be calculated with the following formulas.

$$Cp = \frac{v_0^2}{g \cdot R} \qquad \mathrm{Re} = \frac{v_0 \cdot R}{\upsilon}$$

v_0 is the horizontal flow velocity in m/s, R is the hydraulic radius of a settling tank in meters, g is the gravity force m/s^2 and υ is the kinematic viscosity of the water. For good settling circumstances the flow is laminair, Reynolds number below 2000 and stable which means a Camp number larger than 10^{-5}. In Figure 7-1 the working areas for horizontal flow settling tanks and for lamella plate settling are also given. In the figure it can be derived that flow in horizontal flow settling tanks is turbulent and sometimes instable (Van Dijk et al., 2004). For lamella settling the flow is laminair and stable which will result in higher removal yield compared to horizontal flow settling tanks.

Facet International, Almere in the Netherlands, provided some information about the Facet M-Pack® which is a lamella separator that can be applied for the treatment of CSO water. It is a compact system which can also be placed in a manhole. No chemicals are added. Facet provided information about a storage basin in Buurse in the Netherlands. In Table 7-1 the dimensions are given for the different flows.

Table 7-1: Footprint area of the Facet M-Pack®

Flow	$180m^3/h$	$1000\ m^3/h$
Footprint	$21\ m^2$	$117\ m^2$
Height	$4.2\ m^2$	$23\ m^2$

7.2 Fuzzy Filter®

Bosman Watermanagement B.V., Piershil in the Netherlands provided information about the dimensions and maximum flows of the Fuzzy Filter®, which are listed in Table 7-2. According to this table the height of a filter will be between 4,5 and 6 meters. Because of this height the footprint is small.

Table 7-2: Sizes of the Fuzzy Filter®

Type	Size filter bed [m] × [m]	Max. flow rate $[m^3/h]$	Size installation (l×w×h) [m]
1	0,5 × 0,5	15	0,8 × 0,8 × 4,5
2	0,6 × 0,6	25	1,0 × 1,0 ×4,5
3	0,9 × 0,9	60	1,3 × 1,3 × 4,8
4	1,2 × 1,2	100	1,6 × 1,6 ×5,0
5	1,5 × 1,5	160	1,9 × 1,9 × 5,2
6	1,8 × 1,8	230	2,2 × 2,2 ×5,6
7	2,1 × 2,1	320	2,5 × 2,5 × 5,7
8	2,4 × 2,4	420	On request

There are several options when $1000m^3/h$ needs to be treated. For example three filters of type 7 can be chosen. This filter can treat $960m^3/h$ and has a footprint of $18.75m^2$. The advantage of this configuration is that an extra filter can be placed, this makes the treatment capacity $1280m^3/h$, in this way it is possible to backwash one filter and continuously treat the water, without overloading the three running filters. Four filters have a footprint of $25m^2$. The surface-loading rate of these filters is about $72m^3/m^2/h$.

7.3 UF filtration

The pore size of UF membranes is in the range of 1,5mm to 100nm (Scherrenberg, 2004). The TMP is between 0.3 and 7 bar. Dissolved salts and smaller molecules can pass the membrane. Suspended solids, bacteria and viruses are retained.

In paragraph 3.7.2 the research of Ravazzini et al. (2005a) has been described. The best reached productivity was at a flux of $80l/m^2h$ at TMP 0.3 bar and crossflow velocity of 2m/s. The filtration run in this experiment was 1 minute, the experiment took 6-7h. Using these experimental data for the treatment of $1000m^3/h$ CSO water leads to a total membrane area of 12.500m^2. These tubular membranes are available in 8'' membrane modules made of PVC. The membrane area of one module is 29m^2. This means that 432 modules are needed.

One module has an outside diameter of 0.25m and a length of 3m. When placing 10 modules above each other and 3 modules after each other, the height will be more than 2.5 meters and the length will be more than 9 meters. A number of 30 membranes will fit in here, so 15 of these rows are needed. When between the rows 2 meters of space is needed the total area of the treatment facility will be more than 300m^2. An option which reduces the required area and also the number of needed modules is using UF to treat a side stream of the CSO water. By doing this the quality of the CSO water still will increase but less modules are needed.

7.4 Activated Carbon

With the help of the design criteria presented in Table 7-3, the size of the activated carbon filters and the number of filters was determined.

Table 7-3: Design criteria for Granular Activated Carbon (STOWA, 2005)

Parameter	Unit	Value
Volumetric flow rate	m^3/h	50 – 400
Bed volume	m^3	10 – 50
Cross-section area	m^2	5 – 30
Length	m	1.8 – 4
Void fraction	m^3/m^3	0.38 – 0.42
GAC density	kg/m^3	350 – 550
Approach velocity	m/h	5 – 15
Effective contact time	min	2 – 10
Empty bed contact time	min	5 – 30
Operation time	d	100 – 600
Throughput volume	m^3	10 – 100
Specific throughput	m^3/kg	50 – 200
Bed Volumes	m^3/m^3	2,000 – 20,000

The maximum flow through one filter is 400m^3/h, thus for the treatment of 1000m^3/h at least 3 filters are needed. The flow per filter is 333m^3/h. The empty bed contact time is chosen at 5 minutes. This gives a bed volume of 28m^3, the height will be 4m and the diameter will be 3m. The total area of the three filters together will be 21m^2. The surface-loading rate is 48m^3/m^2/h.

7.5 Chlorine disinfection

The rate of disinfection depends on the contact time and the dosage of chlorine. This is described with a CT value. C stands for the residual concentration of the disinfection product in g/l and t stands for the contact time in minutes. The CT value is the multiplication of the c and T values. The CT values for free chlorine, chloramines and chlorine dioxide are presented in Table 7-4.

Table 7-4: CT values [mg-min/l] which give 99% inactivation of the organisms at a water temperature of 5°C (Lenntech Water treatment & air purification Holding B.V.)

Organism	Free chlorine pH 6-7	Chloramines pH 8-9	Chlorine dioxide pH 6-7
E. coli bacterie	0,034 - 0,05	95 - 180	0,4 - 0,75
Polio virus	1,1 - 2,5	770 - 3740	0,2 - 6,7
Giardia lambia cyste	47 - 150	-	-

Table 7-4 shows that free chlorine deactivates all three types of organisms. When a CT value of 150mg-min/l and a contact time of 30 minute are chosen for free chlorine the dosing rate will be 5mg/l. This is just the effective dosing rate. CSO water will contain a lot of organic compound, which will react first with chlorine.

For the reaction a plug flow reactor is needed with a retention time of 30 minutes. For 1000m^3/h the volume of the reactor will be 500m^3. When using a length width ratio of 4:1 and a height of 3 meters, the footprint becomes 167m^2.

7.6 UV disinfection

The main components of a UV disinfection system are mercury lamps, a reactor and ballasts. The light source of UV radiation can either be low-pressure or medium-pressure mercury lamps with high or low intensities (EPA, 1999c). Medium-pressure lamps are generally applied for large facilities. The start up time for low-pressure lamps is 1 minute and for medium-pressure lamps about 15 seconds.

The UV intensity of medium pressure lamps is approximately 15 to 20 times the UV intensity of low-pressure lamps, because of this the penetration capability is higher. Medium-pressure lamps operate at higher temperatures and have higher energy consumption compared to low-pressure lamps (EPA, 1999c). The higher temperature of medium-pressure lamps has the disadvantage compared to low-pressure lamps that variations in flow rate can cause more damage as a result of overheating. Low-pressure lamps can work without feedwater for about one minute, but medium-pressure lamps need a minimum flow to prevent overheating. To ensure a minimum flow a buffertank should be installed in front of the UV installation.

Andradakis et al. (1999) applied low-pressure mercury lamps for the UV disinfection of secondary effluent from Metamorphosis WWTP. The secondary effluent contained a mean SS concentration of 20mg/l, it was upgraded to tertiary effluent by a lab scale sand filtration. The inactivation rates for bacteria are for secondary effluent 0.107-0.303cm^2/mWs and for tertiary effluent 0.325cm^2/mWs.

Figure 7-2: Sita UV disinfection module SMP140, with 4 medium-pressure lamps providing >80mJ/cm^2 and a maximum flow rate of 1200m^3/h (A&C Engineering B.V.)

A&C Engineering B.V., Spijkenisse in the Netherlands, provided information about the Sita SMP140, see Figure 7-2. This UV installation can be placed inline. The installation has 4 medium-pressure lamps which provide a UV dosage of >80 mJ/cm^2. The diameter of the flow area is 400mm, the diameter of the flange is 1200mm, the length is 1200mm, the maximum height is 700mm and the maximum flow rate is 1200m^3/h. A good UV intensity can be attained by regulating the flow with a sensor which measures the UV transmission. Less flow means a higher intensity. The disinfection rate will increase by introducing small vorticities. The buffer tank which is needed to provide the installation of a minimum flow will have the largest footprint. When a buffer tank of 50m^3 is used the height will be 5m and the footprint 10m^2. The total footprint of the installation including the switch cupboard is 11m^2.

The lifetime of the lamps is on average 8760-14000 working hours (EPA, 1999c), but the lamps are usually removed after 12000 hours because the affectivity of the lamps decreases after 5000 working hours. The annual operational costs are the power consumption, cleaning chemicals and supplies, equipment repairs and the replacements of lamps, ballasts and sleeves (EPA, 1999c). Medium-pressure lamps cost 4 to 5 times the price of low-pressure lamps, but because of the higher intensity of medium-pressure lamps fewer lamps are needed. The reduced number of lamps can make up for the medium-pressure lamps (EPA, 1999c).

7.7 Conclusion

Table 7-5 gives an overview of the results of the calculations in this chapter. Lamella separation is easy to implement in an existing storage basin but removes merely 54% of the suspended solids. The Fuzzy Filter® has the smallest footprint, which is the result of the high surface loading. UF needs 432 modules which is an enormous amount, but it removes besides suspended solids also viruses and bacteria. Activated carbon has a footprint which is comparable with the Fuzzy Filter® which is also due to a high surface loading. UV disinfection is easy to implement and the installation is small. UV disinfection is more effective for the disinfection of viruses than chlorine dosage and no hazardous chemicals need to be added to the water. The conclusion is that UV disinfection has far more advantages than chlorine disinfection. Therefore chlorine disinfection will not be described any further in this research.

Table 7-5: Overview of the footprints

Technique	Flow (m^3/h)	Footprint (m^2)
Lamella	1000	117
Fuzzy Filter®	960	19
UF	1000	300
Activated Carbon	1000	21
Chlorine dosage	1000	167
UV	1200	11

8 Process Schemes

Figure 8-1 gives an overview of treatment techniques which have been described in the previous chapters. This scheme gives the possibilities for the treatment of CSO water and the removal rates of the different techniques. Some process schemes will be described in the next paragraphs of this chapter.

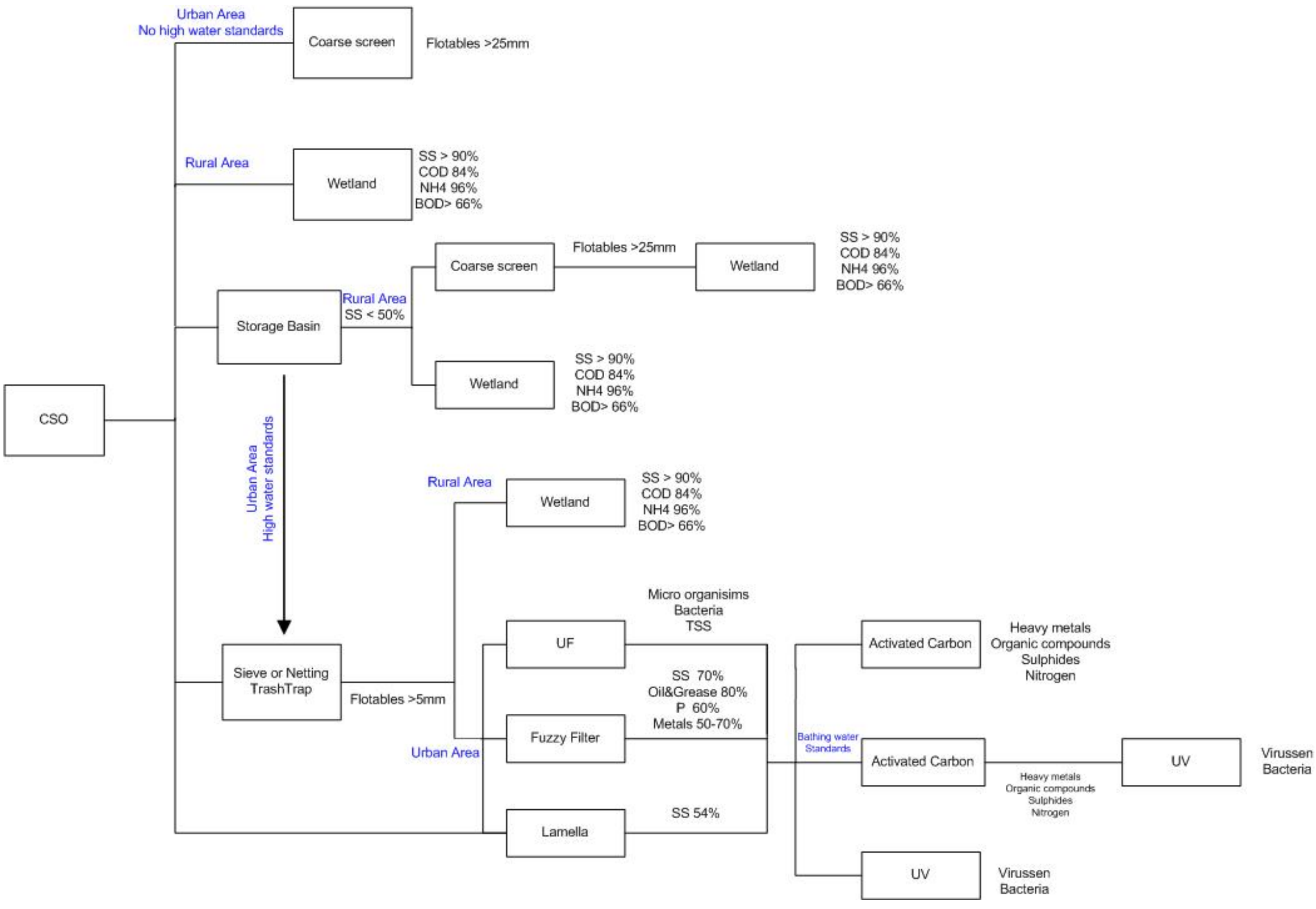

Figure 8-1: Schematization of possible process schemes

8.1 Process schemes for rural areas

In rural areas there is a possibility to use installations with a large footprint. A wetland needs many square meters but fits into the surrounding nature. When using an underground storage tank or a settling tank before a wetland floatables and SS are removed for a large part before the water enters the wetland, which prevents the filter of clogging. Another advantage of using a storage tank is that the overflow volume and frequency decreases. After a CSO the storage tank is drained. The drainage water will be pumped to the WWTP for treatment. A process scheme of this system is presented in Figure 8-2.

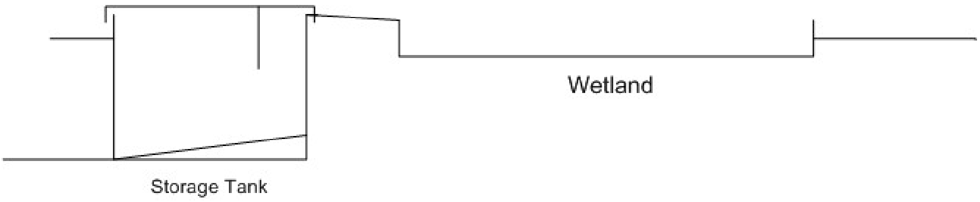

Figure 8-2: Combination of a storage tank and a wetland

8.2 Process schemes for urban areas with little space

The restrictions for surface water in urban areas is more strict compared to surface water in rural areas. The treatment of CSO water is therefore of more importance in urban areas. The problem which is closely connected with urban areas is space or open areas where a treatment facility can be built. Therefore techniques which combine advanced treatment with a small footprint are selected for urban areas.

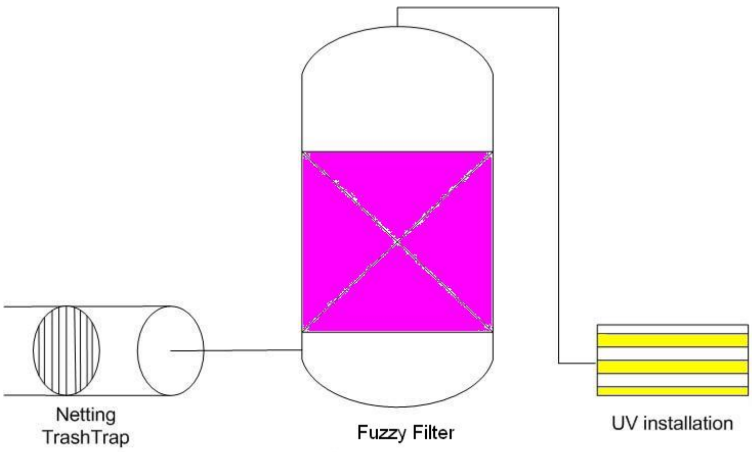

Figure 8-3: Combination of a Netting TrashTrap™, a Fuzzy Filter® and UV treatment

In Figure 8-3 the process scheme is presented of a combination of the Netting TrashTrap™ system, a Fuzzy Filter® and UV treatment. By combining the treatment techniques in this way a minimum footprint of 30m^2 is needed, which makes this combination the one with the smallest footprint. The Netting TrashTrap™ system and the UV treatment can be placed inline. The Netting TrashTrap™ system removes the floatables larger than 6mm, after this pre-treatment the water is treated by the Fuzzy Filter® where 70% of the SS, 80% of the oil and grease, 60% of the phosphor and 50-70% of the heavy metals is removed. After this step the water can be disinfected by UV light. An extension of Figure 8-3 with an activated carbon filter is presented in Figure 8-4. In this way a higher percentage of heavy metals will be removed and also organic compounds and sulphides and nitrogen. The footprint of this combination is 51m^2.

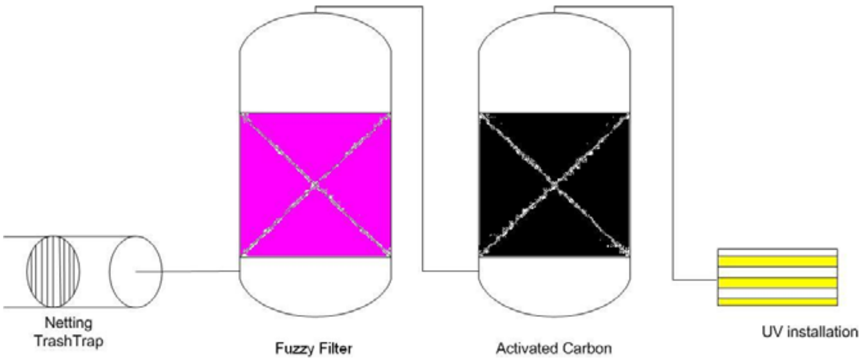

Figure 8-4: Combination of the Netting TrashTrap™ system, a Fuzzy Filter®, an activated carbon filter and UV treatment

Besides the Fuzzy Filter which requires the smallest footprint also lamella separation can be used. An advantage of lamella separation is that it can be placed inside an existing storage tank. When this is done, the quality of the water will increase without using extra area. In Figure 8-5 lamella sedimentation is combined with the Netting TrashTrap™ system and UV disinfection.

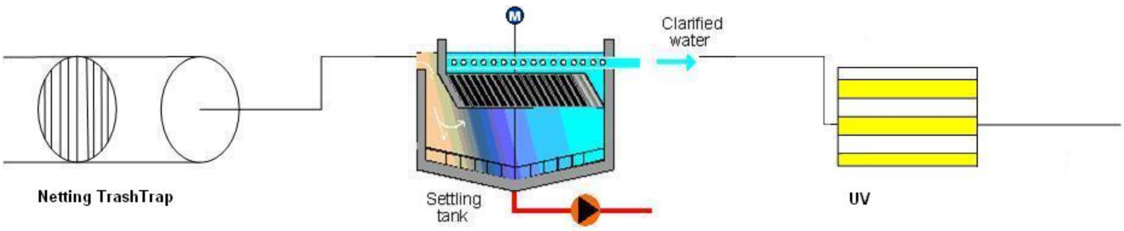

Figure 8-5: Combination of the Netting TrashTrap™ system and lamella sedimentation without chemical dosage and UV treatment

To improve the removal efficiencies of lamella separation chemical dosage can be applied to increase the weight of the flocs. This process can be seen as a part of the Actiflo® process. For example a polymer can be dosed or Iron(III)chlorine. The problem with polymer dosage is that the polymer solution needs to be made on site because it is not stable. Iron(III)chlorine can be stored for some months and has the advantage that it also binds phosphate. In Figure 8-6 a flow scheme is presented of the combination of the Netting TrashTrap™ system, lamella sedimentation with chemical dosage and UV treatment.

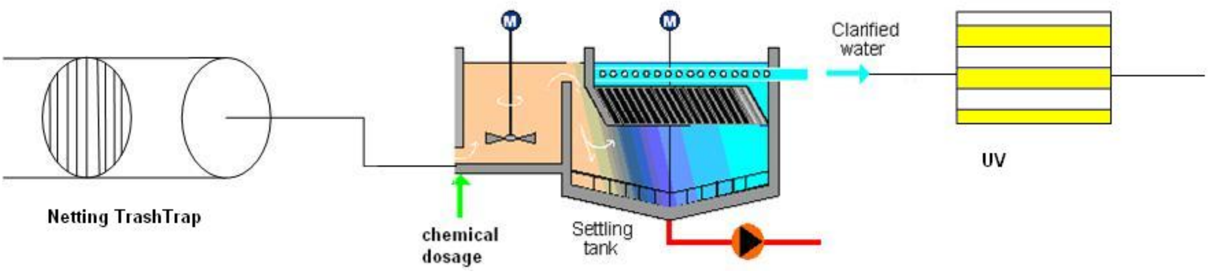

Figure 8-6 Combination of the Netting TrashTrap™ system and lamella sedimentation with chemical dosage and UV treatment

8.3 Process schemes for urban areas with plenty of space

When the area is not a restriction anymore but the water quality still is, ultrafiltration can be applied. Ultrafiltration treats the water to a high standard but needs many membrane modules, see also paragraph 7.3. In Figure 8-7 UF membrane modules are shown which need a large footprint, namely 300m^2 but they do remove suspended solids, bacteria and viruses. The Netting TrashTrap™ system cannot be used because the minimum mesh width of the Netting TrashTrap^{TM} system is 5 mm and for UF a smaller mesh width is needed.

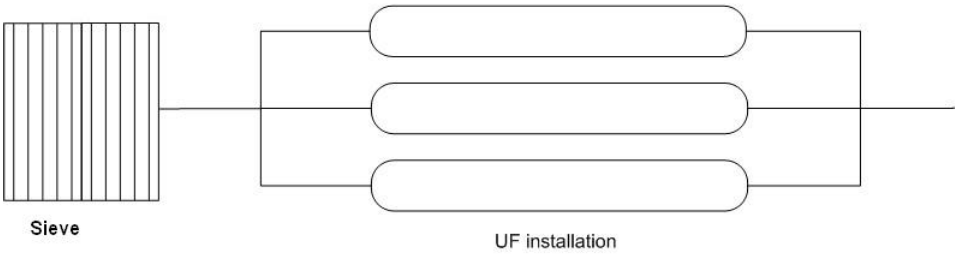

Figure 8-7: Combination of a fine sieve and UF membrane modules

To decrease the number of membrane modules it is possible to let a part of the influent of the membranes bypass the membranes (Figure 8-8) and mix the two streams before they reach the receiving water. The result of this process is that the total pollution of the overflow water will decrease and the total required footprint will also decrease.

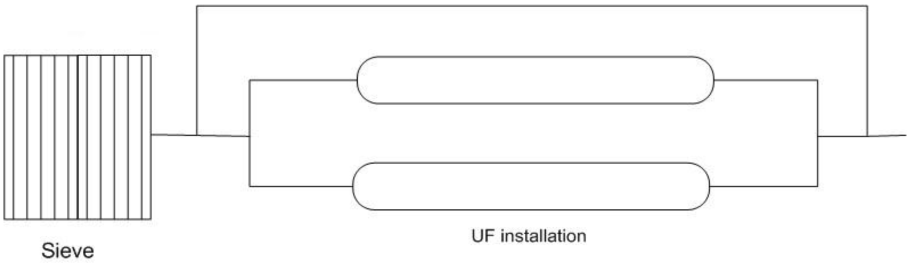

Figure 8-8: Combination of sieving and partial UF

As a pre-treatment step a fine sieve needs to be applied to prevent clogging and rapid fouling of the membrane. UV disinfection is not really needed. Activated carbon can be applied after the membrane modules to remove dissolved substances which are not removed with UF, as pictured in Figure 8-9. The required footprint will become then 321m^2.

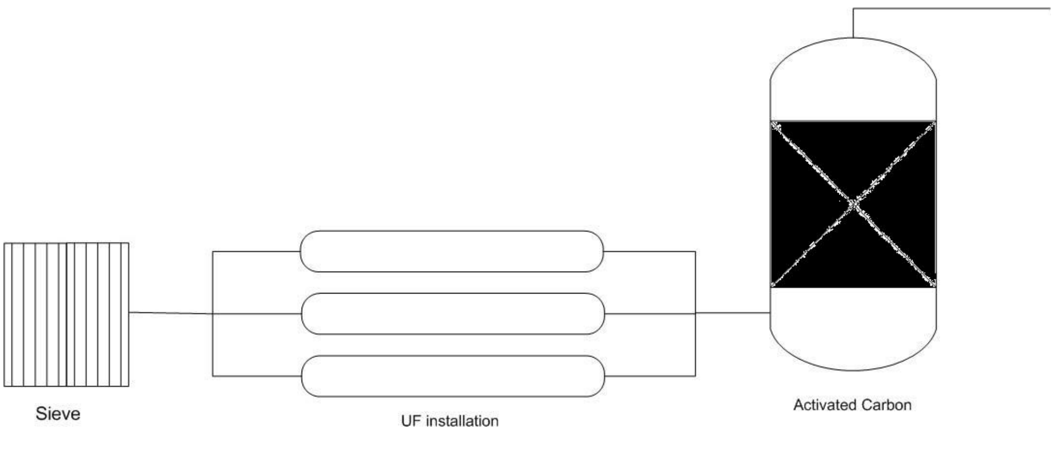

Figure 8-9: Combination of a fine sieve UF membrane modules and an activated carbon filter

9 Discussion and conclusions

Today's techniques for treatment of CSO water in urban areas are focused on the removal of visual pollution ((toilet)paper, rubber, plastic foils, etc), settable particles and colloidal particles, and not on the removal of dissolved particles and micro-pollutants. However this will most likely not be enough to prevent odour problems and will be certainly not enough to remove bacteria, to prevent health risks for the surrounding area and to fulfil the WFD regulations in the future. Therefore new techniques need to be introduced and developed. The development of new techniques for the treatment of CSO water asks for a wide and integral approach. Knowledge is needed on:

- Quality parameters of wastewater and runoff water;
- Dynamics of the dilution process in combined sewers during storm events;
- Physical and chemical treatment techniques.

During this research it has become clear that the quality of CSO water and the fluctuations in flow are two boundary conditions which have to be taken into account when designing a treatment facility. For example a first flush effect does not frequently occur in sewage systems in the Netherlands. It is possible that a first flush occurs, but a flush of pollutants can also occur at the end of a storm event or does not occur at all. This means that research on site needs to be carried out to determine the characteristics of a polluted flush before designing a treatment facility. Given the available knowledge of the fluctuations in flow and overflow water quality, diluted or not, it is possible to give an impression of which techniques are applicable for the treatment of overflow water.

For the removal of endocrine disrupting substances, heavy metals etc., techniques like settling and flotation will not reach the goals of the WFD. Advanced treatment, like adsorption by resin or activated carbon, membrane filtration or UV disinfection, seems to be necessary. Techniques which are used nowadays for the treatment of CSO water, will serve as a pre-treatment in the future. Most of these techniques are mentioned in chapter 2, Primary Treatment Techniques. They can be used for example to prevent clogging of activated carbon or to gain good results with UV disinfection. Treatment techniques like rapid filtration with sand or a synthetic medium can also be used to remove phosphor in combination with chemical dosage.

In rural areas more open land is available which can be applied for the treatment of CSO water, but in these areas health problems and pollution caused by CSOs are less problematic compared to CSOs in urban areas where the population is denser. The inconvenience caused by CSOs is also less problematic in rural areas. In the near future the development of new techniques should not only be focused on decreasing costs, but on the development of techniques which will work sufficient and can be used in urban areas. After that phase it will be possible to reduce costs and to optimise the processes.

Removal of suspended solids from CSO water will immediately lead to a quality improvement and, in addition, it will prevent filtration steps to clog. For the removal of suspended solids several techniques can be applied, namely UF filtration, rapid media filtration, sand filtration, lamella, DAF, Actiflo® etc. UF systems have the highest removal efficiencies but they are expensive and require a lot of maintenance. The costs for lamella plate clarification, vortex separation and DAF are similar, but lamella plate clarification and vortex separation are more robust systems than DAF and simple to operate. Lamella plates have the advantage that they can be placed inside an existing storage tank.

Synthetic medium filtration like a Fuzzy Filter® which is described by Jimenez et al. (2000) can treat large amounts of water with high flow rates. These flow rates vary between 20-90 m/h. High rate sand filtration has flow rates of 5 – 20 m/h. An advantage of the Fuzzy Filter® is that the filter bed medium can be compressed more or less. This means that during a first flush the medium can be compressed a little to prevent clogging and when diluted water enters the filter the medium can be compressed more to remove smaller particles.

A CSO disinfection system should be designed with site-specific loading characteristics in mind, and should be capable of handling a large first flush pollutant load (EPA, 1999a) in case this occurs. From paragraph 5 it becomes clear that all disinfection methods have the potential to produce toxic by-products. Blatchley III et al. (1997) did research to determine the effects of chlorination, UV and ozonation on the toxicity of WWTP-effluent in Indianapolis, Georgetown, Belmont and Southport in the USA. From this research it became clear that the site-specific nature of effluent toxicity will require a case-by-case study to provide specific information. This means that experiments need to be carried out before placing a disinfection system. Ozone reacts with organic substances, which are present in the CSO water. When high concentrations of organic substances are present in the water, which is the case for CSO water, it will require a high ozone dosage to disinfect the water. This makes ozone not useful for the treatment of CSO water (Gehr et al, 2003).

For some of the before mentioned treatment techniques in this report, dosage of chemicals is optional. The use of chemicals can improve the treatment process, but can cause damage to the environment as well, e.g. when a treatment facility does not work properly. To prevent underdosage or overdosage of chemicals flow measurements, which are linked to a dosing pump, are needed. The use of chemicals also increases the costs. This increase is not only caused by the price of the chemical itself but also because chemical stocks need to be refilled after a CSO or replaced when chemicals get old.

A treatment facility to treat the CSO water will require a lot of knowledge about the fluctuation of the flow and about the overflow water quality. Furthermore free area is needed to build the installations. When all of this is not available it might be a solution to reduce the inflow of the sewer system by for example roof drain redirection or building green roofs. A reduction of inflow will result in a reduction of the overflow water or even a reduction in overflow events.

The techniques that can be applied for the treatment of CSO water are lamella separation which is easy to implement in an existing storage basin but removes merely 54% of the SS. A Fuzzy Filter® which has the smallest footprint because of a high surface loading. UF needs 432 modules which is an enormous amount, but it removes besides SS also viruses and bacteria. Activated carbon has a footprint which is comparable to the Fuzzy Filter® which is also due to high surface loadings. UV disinfection is easy to implement and the installation is small besides this is UV disinfection more effective for the disinfection of viruses than chlorine dosage and no hazardous chemicals need to be added to the water.

It will likely be clear that there is no general solution which will work in all situations. Like for normal WWTPs research need to be carried out for every location in order to find the best treatment facility or combination of facilities which will fulfil the specific demand. The schematisation of possible process schemes (Figure 8-1) can help to determine which techniques are optional for research. When treatment of CSO water is not an option, reduction of inflow might be an option.

10 Recommendations

In the future practical research needs to be carried out to find the best solution for the treatment of CSO water. This practical research can be done on lab scale but preferably are experiments on pilot scale on site. During this research first the quality and the flow of the CSO water needs to be measured. Secondly different treatment techniques need to be tested. To ensure representative measurement, which can be used to design treatment facilities at other locations than the locations where the pilot tests were carried out, experiments at different locations need to be done. Maybe these experiments can lead to treatment facilities, which can be used in specific circumstances for example for CSOs in urban areas or in rural areas in the Netherlands. The results of experiments may also lead to standard series of small and short tests, which can be carried on site to find the best treatment facility for that specific location.

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