Energy-efficient Wastewater Reuse – The Renaissance of Trickling Filter Technology

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Abstract

New generation trickling filter systems are evaluated as an energy-efficient way to treat wastewater for later reuse. Depending on the reuse application, a trickling filter plant can be designed to generate the appropriate effluent quality for different applications such as crop fertilization, irrigation, or feed water for subsequent treatment or industrial use. Here carbon removal, nitrification or denitrification can be selectively achieved, while conserving scarce energy and recycling valuable nutrients. A short review of the state of the art trickling filter design and operation with an evaluation of current possibilities and advantages using trickling filters for water reuse will be provided. The energy consumption of 3 investigated trickling filter plants was 0,057kWh/m³ or 0,175kWh/kg-COD for Batumi tskali WWTP in Georgia, 0,12kWh/m³ or 0,22kWh/kg-COD for Managua WWTP in Nicaragua and 0,11kWh/m³ or 0,16kWh/kg-COD in Walvis Bay WWTP in Namibia. Finally a sustainable trickling filter configuration is suggested to achieve various reuse goals in the background of varying seasonal influent and effluent characteristics.

INTRODUCTION

Poor wastewater treatment is one of the biggest enemies of a safe and sustainable water supply all over the world. Next to frugal handling of existing water resources, the treatment of wastewater towards future reuse is important. Unfortunately, the allusive effect of improving water supply through groundwater recharge or surface water improvement must be weighed off against the capital cost, the cost of energy demand, and other variable costs of wastewater treatment facilities. With the costs per unit energy constantly rising, it is of utmost importance that future wastewater treatment preparing wastewater for reuse is energy-efficient. Especially in developing countries important points to consider are reliability and simplicity of a wastewater treatment process. Low maintenance unit operations are important to ensure a continuous treatment of incoming wastewater (Sperling, 1996).

Up to the 80's trickling filters have been promoted in the western hemisphere to be an energy-efficient process for using microbial systems to treat wastewaters. There, the only need for energy is for lifting the effluent by pumping it for distribution on top of the filter. By using a hillside for gravitational flow pumping costs can be reduced even further. The water then trickles through a bed of suitable media where a biofilm cleans the water. The main difference to, for example, an activated sludge system is that the oxygen demand is often satisfied by natural ventilation only, without any need for energy intensive aeration and high-tech equipment. However, with increasing effluent demands and process issues such as media clogging in conventional, stone packed trickling filters, along with a poor understanding of nutrient removal characteristics coupled to poor modelling of actual processes inside trickling filters led to a decline in their use (Parker, 1999).

Along with newly developed plastic media and the increased importance of sustainability the trickling filter is going through a renaissance. Especially in combination with other unit operations, such as anaerobic pre-treatment and optimized process design, these new generation trickling filter systems are able to treat wastewater to very high standards, while offering low energy demand and a high degree of simplicity and robustness. It is for these reasons that all over the world new trickling filter projects are implemented, whereby many of them receive funding from institutions such as the KfW (Development loan Corporation, Germany) that focus on sustainable development.

When treating wastewater with the intent to reuse it for various purposes, the goal is often not to treat the wastewater to the lowest levels possible. The most economical way would be to treat the water exactly to the point of quality required for the reuse goal (Table 1).

Table 1: Discharge limits for water reuse in various countries with effluent criteria for COD, BOD, NH_4 and NO_3 for a selection of regions

	BOD mg/L	**COD** mg/L	**NH_4** mg/L	**NO_3** mg/L
Jordan[1]				
Discharge to streams	60	150	15	45
GW recharge	15	50	5	30
Cooked vegetables, playgrounds	30	100		30
Field crops	300	500		45
Trees, green areas	200	500		45
EPA[2]				
Urban reuse (unrestricted public access)	10			
Urban reuse (restricted public access)	30			
Food crops	10			
Non-Food crops	30			
WHO[3]				
Irrigation of crops likely to be eaten uncooked, sports fields, public parks	20			
Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees	240			
Kuwait				
Water reuse	20	100	15	
Oman				
Vegetables likely to be eaten raw	15	150	5	50
Vegetables to be cooked	20	200	10	50
Dubai[4]				
Unrestricted irrigation	5	150	5	50
Restricted irrigation	20	200	10	50

[1](JS: 893/2002) [2](EPA, 2012) [3](WHO, 2006) [4](Dubai Municipality, 2011)

New generation trickling filter technology (N-TF) combined with an intelligent plant design and operation will allow a high flexibility. This includes the ability to treat waters to effluent quality comparable to AS and AS-BNR processes. Additionally, trickling filters can offer the ability to produce a variety of effluents treated to meet specific local needs during seasonal variations at very low operational and maintenance costs. A more detailed comparison of AS and AS-BNR processes versus N-TF systems is provided by Lempert (2013).

Trickling Filter Process

A trickling filter is a fixed-growth biofilm treatment system where the wastewater "trickles" through a media on which a biofilm grows. The wastewater is distributed at the top of the filter with the use of rotating distributor arms that can be either hydraulically or electrically driven. Oxygen is provided to the system through ventilation openings at the bottom of the filter through which air can freely flow. The media is placed onto a substructure usually made out of parallel beams placed on concrete feet.

In trickling filters heterotrophic and autotrophic bacteria are limited mainly by space, assuming oxygen is supplied in excess though ventilation. In the upper section of a trickling filter heterotrophic bacteria will use BOD as substrate. Nitrifyers cannot compete due to their slow growth and lower metabolic rate. With increasing depth of the trickling filter, BOD concentrations decrease to a point where heterotrophic biomass growth is low enough to allow nitrifyers to grow (refer to Figure 1). This has been described in many publications available (Evans et al, 2004; Parker & Richards, 1986; Pearce & Jarvis, 2011). It is reported that nitrification will start when the soluble BOD concentration is below 20mg/L (Parker &

Richard, 1986). The inflow BOD load and the designed filter height will then determine the amount of nitrification to be anticipated.

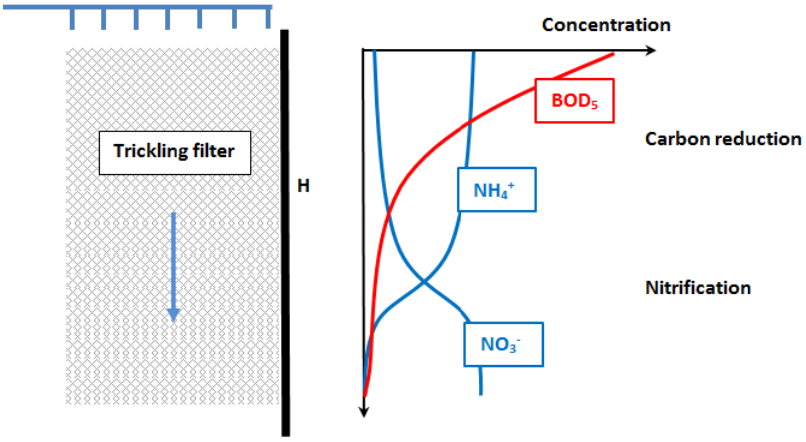
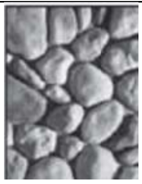


Figure 1: Trickling filter depth versus BOD and NH4 removal, Gujer, 1999

Media Types of Trickling Filters

One important component of the trickling filter is the biofilm carrier. The ideal carrier material has a large surface area, it is highly durable and it has a high void space to avoid clogging and to ensure oxygen supply (Daigger & Boltz, 2011). There are many types of material that can be used as a carrier in a trickling filter. The most common ones are rock, structured plastic cross flow or vertical fill and random media. A number of studies have shown the superiority of cross-flow media in comparison to vertical, random or stone media (Sarner, 1978; Parker & Merrill, 1984; Boller & Gujer, 1986; Richards and Reinhardt, 1986) but the vertical flow media still has advantages for industrial and roughing applications with organic loads above 2-2,5 kg/m³. Table 2 shows characteristics of a selection of trickling filter media types available.

Table 2: A selection of trickling filter media

Media type		**Specific surface area** m^2/m^3	**Void space** %
Rock, Slag or Lava[1]		~ 40-80	50-60
Polypropylene cross flow[2]		100 to 240	>97
Polypropylene vertical flow[2]		125	>97

[1](Daigger & Boltz, 2011), [2]Manufacturer: GEA 2H; BIOdek

Configurations of New Generation Trickling Filter Systems

Trickling filters can be used for carbon removal, nitrification or denitrification (ATV-DVWK-A 281). Nitrification can be performed either in the same trickling filter as carbon removal or as tertiary treatment in a separate filter. Depending on the process train configuration, media and dimension, different treatment goals can be achieved. The treatment goal, process design and approximate power consumption is shown in Table 3.

Table 3: Trickling filter processes and respective approximate energy requirement

	Treatment Goal	**Process Design**	**Approximate energy requirement for water treatment***
A	BOD roughing, BOD <40-100mg/L	High rate Trickling filter Design by loading rate (>1,5 Kg/m^3-day)	<0,15kWh/m^3
B	Full BOD removal, BOD <10-20 mg/L	Equation based Filter design (Velz)	<0,15kWh/m^3
C	Partial nitrification, NH4 <15	Equation based Filter design (Velz + Gujer/Boller)	<0,15kWh/m^3
D	Full Nitrification, NH4 <1-2	Equation based Filter design (Velz + Gujer/Boller)	<0,2kWh/m^3 (single stage) <0,3kWh/m^3 (double stage)
E	Partial denitrification, 50-80% TN rem.	Equation based Filter design (Velz + Gujer/Boller), mass balance for anoxic treatment	<0,3kWh/m^3
F	Full denitrification, >90% TN rem.	Equation based Filter design (Velz + Gujer/Boller), mass balance for anoxic treatment and other post-treatment (like RO, sand filter, etc.)	<0,4kWh/m^3

*A, B and C have identical energy consumption, since only the filter diameter is enlarged to reduce the required loading rate to achieve a higher treatment quality. An appropriate recirculation rate to dilute highly loaded influent waters is considered. D,E,F include additional pumping needed for the process and not needed for dilution.

(Referring to Table 3 with processes A-F)

(Process A/B) BOD removal can be achieved using single trickling filters (or many in parallel) with media suitable for BOD reduction (Figure 2). Heterotrophic growth produces a large amount of biomass. In new generation trickling filters large channel cross flow media is often used to avoid clogging. Usually these trickling filters are sized so the volume is not enough to allow for nitrification. With this setup, effluent BOD values can reach below 25mg/L BOD (process B). For partial BOD-removal the filter design must consider oxygen limitation and weight due to excess heterotrophic sludge production. Maximum loads of 2,5-3Kg-BOD/m^3-day, high strength vertical channel media and high flushing should be considered (Process A).

(Process C-D) In a trickling filter series, the primary trickling filter for BOD removal would be designed to meet a BOD of <25 mg/L (Figure 2). Then the secondary filter can be designed using a smaller channel media for increased surface area for higher nitrification capacity. An intermediate clarification step may be applied to reduce solids load to the nitrification trickling filter. Here, the clogging potential is minimal, since nitrification biomass generation is low. This process has been investigated in many publications (Boller & Gujer, 1985, Muller et al., 2006, Hu et al, 2003). Trickling filters in series allow for separate nitrification (tertiary nitrification). Tertiary trickling filters can also be added to existing AS systems to allow for low cost nitrification (Hu et al, 2003, Muller et al., 2006). New generation trickling filters allow the design with different types of media layered according to anticipated biomass production from large channel cross- or vertical flow media to small channel cross flow media. Large channel media can be placed in the top layers for heterotrophic growth, and small channel media in the bottom layers for autotrophic growth (Figure 2). This setup reduces pumping cost, since the water will not have to be pumped two times; instead the first trickling filter is enlarged in diameter to allow for nitrification.

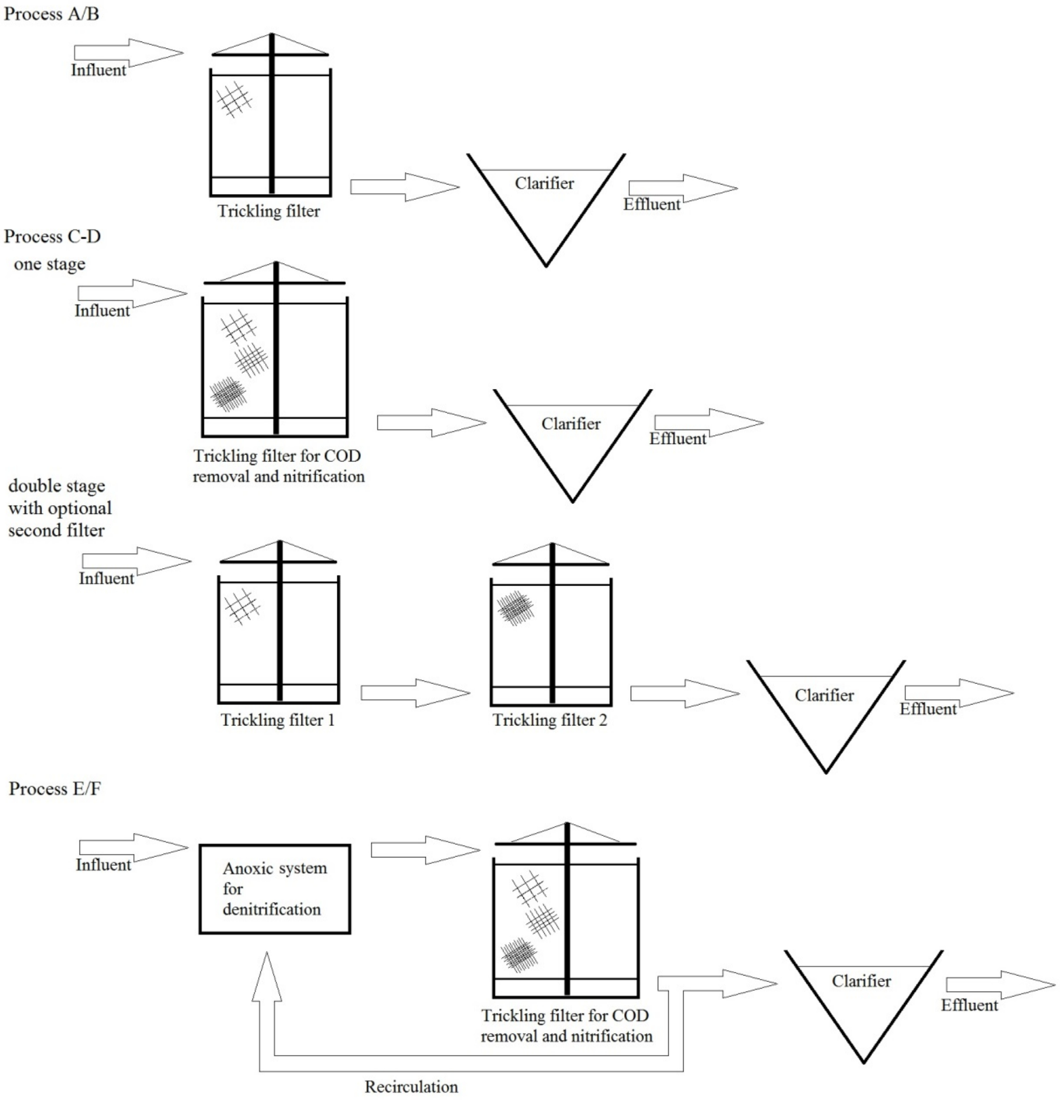


Figure 2: Trickling filter configurations from single filter configuration for BOD roughing applications to recirculation into anoxic chamber for denitrification. Processes A and B are for BOD removal, Processes C and D are for BOD removal and for nitrification, processes E and F are for integrated denitrification.

(Process E/F) Combination of trickling filters for BOD removal and nitrification with an anoxic system allows for integrated denitrification (Figure 2). This can be activated sludge (Vestner, 2003) or fixed film technologies, as well as sealed trickling filter systems (Dorias, 1996). While solutions A-D are rather well known and state of the art, the degree of TN removal in solution E and F will have a higher degree of complexity, capital and operational costs. The degree of denitrification is determined through the amount of recirculated nitrate. Special designs of this version can reach TN in the effluent to below 10 mg/L.

ENERGY CONSUMPTION FOR WATER REUSE

Water reuse is an option to decrease the energy demand needed for water supply. Water can be produced through various processes as seen in Figure 3. Sources for water can be the groundwater, from ocean desalters or others. The energy needed per m³ water reaches from 0,77kWh/m³ when pumped from groundwater up to 3,57kWh/m³ when produced by desalination. Water needed for agricultural or other purposes would have to be gathered the same way if not reused after treatment.

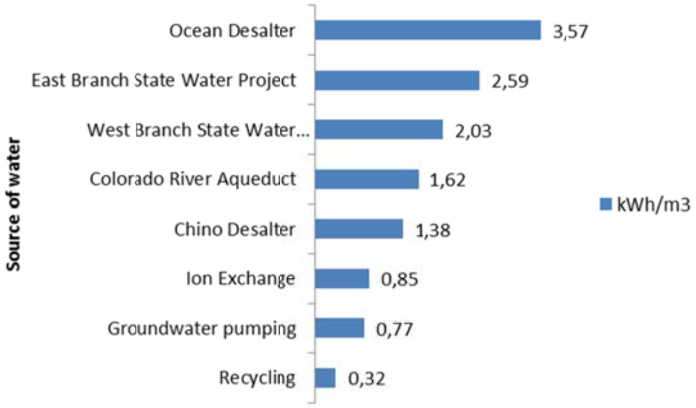


Figure 3: Energy consumption of potable water production through various processes. Source: California's Water – Energy Relationship 2005 California Energy Commission, California, USA

When looking at up to 3,57 KWh/m³ needed for water production the option to reuse treated water at lower costs becomes more important. Reusing water from after activated sludge systems could be done at a cost of 0,4kWh/m³ and above, but much lower compared to desalinization. When looking at trickling filter treatment plants, the cost can be reduced further to values below 0,2kWh/m³ for equivalent treatment. The main energy requirement for the operation of trickling filters is the pumping energy for distributing the water on top of the filter media plus recirculation. Energy for aeration is often not needed, since the majority of trickling filters are operated with natural ventilation. If the location has a favorable geography and temperature precondition, it is possible to run a trickling filter with carbon removal and nitrification nearly without any energy input.

The energy consumption of 3 full scale plants has been investigated in terms of energy use per m³ and per kg-COD treated. These plants are partners in an on-going research project of the German Ministry of Education and Research (BMBF). The project is called EXPOVAL and the goal is to validate design guidelines for wastewater treatment plants in warm and cold climates. The authors (along others) are part of the subgroup to validate the design of trickling filters within this project.

The first plant is in Walvis Bay, Namibia. Here 2 out of 3 existing stone media filled trickling filters where upgraded with cross flow structured fill media in 2012. For the energy balance one filter with 45m in diameter and 3m depth was investigated. The filter is loaded with 5500m³/day at an incoming COD of 950mg/L, which is treated to 240mg/L. Ammonia is reduced from 51mg/L to 4mg/L (>90% nitrification). The costs to pump the water up to the distributors is 624kWh/day leading to 0,16kWh/kg-COD or 0,11kWh/m³ treated water (including nitrification). This excludes the energy needed for pre and post treatment.

The second investigated plant is the WWTP Batumi tskali in Georgia. The plant is designed to treat the wastewater of approximately 200000PE. The plant is equipped with standard grit removal and anaerobic ponds. The ponds are followed by 4 trickling filters of 28 meters in diameter and 5 m height, filled with structured media. The energy requirement for pumping of the water to the trickling filter distributors is in average of 3750kWh/day to pump 65800m³/day. The water is treated from 197mg/L COD and 9,9mg/L NH4-N to <33mg/L COD and <0,5 mg/L NH4-N. This leads to 0,35kWh/kg-COD or 0,057kWh/m³ (at >95% nitrification). The calculation excludes power consumption of pre-treatment and includes an elevation advantage from anaerobic pre-treatment to trickling filter system. Additionally the sewer is a combined waste and storm water sewer (approximately 50% storm water).

The third treatment plant is located in Managua, Nicaragua. The plant is momentarily treating an average flow of 100000m³ per day. It includes pre-treatment with standard screens, grit removal and primary settling. Following the primary settlement tanks there are 6 trickling filters with a diameter of 35m and a height of 5.1m each filled with cross flow structured media. The trickling filters are sized only for BOD removal; however, partial nitrification is taking place. The filtered COD in the effluent of the trickling filter is below 50mg/L, the incoming COD is approximately 600mg/L. The plant reported an energy consumption of 0,12kWh/m³ of treated water. For this treatment 0,22kWh/kg-COD (at ˜40% nitrification) are used. The power consumed is for the complete treatment train. The results of all 3 plants are summarized in Table 4.

Table 4: Energy consumption of full scale trickling filter systems in Batumi, Managua and Walvis Bay

Plant/ Source	**COD-removal**		**COD-removal + nitri.**		**Notes**
	kWh/m³	kWh/ kg-COD	kWh/m³	kWh/ kg-COD	
Batumi tskali WWTP			0,057 w/o elevation: (0,114)	0,35 w/o rain: (0,175)	High storm water fraction ~50%, Elevated pre-treatment ~50% Values for full plant Full Nitrification
Managua WWTP	0,121	0,22			Values for full plant Partial Nitrification
Walvis Bay WWTP			0,11	0,16	Values for secondary treatment, Excl. pre- and post-treatment Full Nitrification Partially industrial inflow

PROPOSED TRICKLING FILTER CONFIGURATION

Configuration

Discussed processes A-F in Table 3 offer a wide possibility of designing a suitable trickling filter process for different reuse goals, as needed locally. For an increased flexibility in water treatment for reuse a new generation trickling filter configuration is suggested to allow for a high degree of flexibility (Figure 4). The configuration includes anoxic treatment, a series of Trickling filters and clarifiers. The goal is to produce several different effluent qualities at the same time to preserve nutrients when it is needed or to remove them when it is required. Additionally the configuration can be adapted to react to varying seasonal conditions as needed.

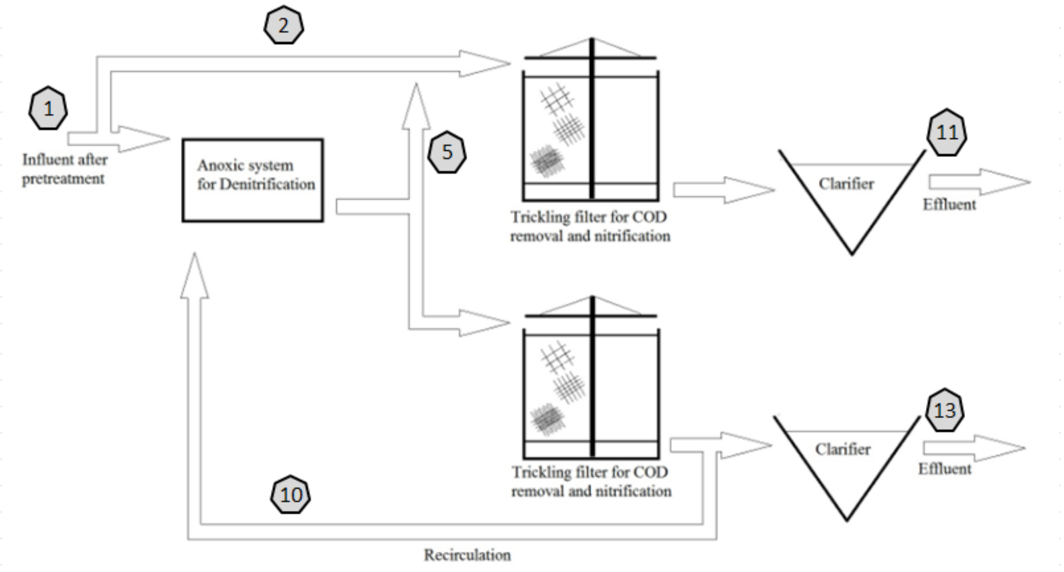


Figure 4: Proposed multi-effluent trickling filter configuration including pretreatment, anoxic tank, trickling filter 1 and 2 (BOD removal and nitrification), 2 clarifiers, (possible tertiary nitrification or P-removal) and post treatment

1: Inflow after pretreatment, 2: Bypass to Filter 1, 5: Mix-flow to filter 1, 10: Recirculation from filter 2, 11: Effluent from Filter 1 after clarification (To post treatment), 13: Effluent from Filter 2 (To post treatment)

Trickling filter systems can be designed to offer the most possible flexibility when combining them with anoxic treatment. The proposed process consists of an anoxic unit designed to allow for >90% denitrification, two parallel trickling filters, one designed to do 50% nitrification as standalone, and the other one to do 100% nitrification as standalone (exemplary case) plus two clarifier units (with optional intermediate clarification). The filters consist of optimized corrugated sheet media with reducing channel size from top to bottom for media surface area optimization and to avoid clogging. Referring to Figure 4, in the anoxic chamber raw influent can be combined with a nitrate rich recirculation flow to allow for denitrification. Some of the raw influent can bypass the anoxic chamber to be loaded on trickling filter 1 with more BOD to produce a non-nitrified wastewater if needed. The other loop would go through the second trickling filter that will do full nitrification. Because the water exiting from the anoxic unit will be lower in BOD due to denitrification, it allows nitrification in the subsequent filter (for simplicity assuming optimum anoxic conditions). This setup creates two effluents, one where only BOD was removed, and the other one which would be fully nitrified and denitrified depending on the recirculation ratio. The flows can be changed alongside with seasonal inflow and needed effluent characteristics (flushing procedures, small operational adaptions or optional aeration in the anoxic unit may be needed, but is not considered here).

When the single unit operations are designed to handle a range of hydraulic loadings, the biology inside the trickling filters will shift with decreasing BOD loading from non-nitrifying to partial or full nitrification. Pre-treatment (screening etc.) and post-treatment (disinfection etc.) would be designed as usual.

Methods

The modelling was done using general mass balance concepts to calculate flows. Velz equation and Gujer and Boller equations were used to calculate trickling filter performance. The calculation of denitrification was simplified to show the concept. The influence of the clarifiers was not considered (hence, soluble BOD was investigated).

For design of trickling filters the Velz equation is used for modelling BOD removal. With a temperature correction coefficient the equation is now known as the modified Velz equation (WEF, 2000).

$$\frac{S_e}{S_{in}} = \frac{1}{\exp\left(\frac{k_{20} \cdot A_s \cdot D \cdot \theta^{T-20}}{q_A{}^n}\right)}$$

S_e = soluble BOD concentration in trickling filter effluent [mg/l]
S_{in} = soluble BOD concentration in influent to trickling filter [mg/l]
k_{20} = reaction rate coefficient at 20 °C [(l/ m^2s)^n]
A_s = specific media area [m^2/m^3]
D = media depth [m]
θ = temperature correction factor (typically set to 1.035)
T = wastewater temperature (here 20°C) [°C]
q_A = hydraulic loading (including recirculation) [l/ m^2s)]
n = flow exponent (typically set to 0.5)

Nitrification is calculated using a model developed by Gujer and Boller (1986) based on mass balance principles.

$$\frac{D \cdot A_s \cdot j_{N,max}(T)}{q_A} = S_{N,i} - S_{N,e} + N \cdot ln\left(\frac{S_{N,i}}{S_{N,e}}\right)$$

As = specific media surface area [m2/ m3]
jN,max = maximum nitrification rate (here 1,46 at 20°C) [g N / (m2·d)]
k = empirical factor describing decrease in nitrification rate with D (here 0,11) [m-1]
qA = hydraulic load of trickling filter [m3/ (m2·d)]
N = saturation parameter for substrate limitation (here 1) [g N/ m3]
SN,i = influent concentration of ammonium, including recirculation [mg/l]
SN,e = effluent concentration of ammonium [mg/l]

Additionally the following assumptions were made for simplification: Solids have not been considered, no simultaneous denitrification, influent water has been screened or settled, only BOD, NH_4, NO_3 and TN are considered, organic N, nitrite and others are ignored, 2mg/L BOD removed for 1mg/L NO_3 reduced, shifting trickling filter loadings may need flushing procedures or SK alteration. Other model parameters were set as in Table 5 shown below.

Table 5: Influent characteristics and trickling filter design used for modelling

Parameter	**Unit**	**Value**
Inflow		
Flow (=100%)	l/s	300
s-BOD	mg/L	140
NH_4	mg/L	30
NO_3	mg/L	0
TN	mg/L	30
Temperature	°C	20
Trickling filter Design		
Trickling filter one		
Diameter	m	25
depth	m	4
Volume	m³	1960
Media type	Cross flow	Type BIOdek KFP627
Surface area	m²	125m²/m³
Trickling filter two		
Diameter	m	40
depth	m	4
Volume	m³	5027
Media type	Cross flow	Type BIOdek KFP619
Surface area	m²	150m²/m³

Results

(All flows refer to Figure 4) For the proposed configuration when varying "flow 5" from 0% to 40% effluent "flow 13" reduces from 210L/s to 90L/s, where "flow 11" rises from 90 to 210L/s accordingly (all flows based on 100% incoming flow). When altering the recirculation rate flow 10 from 0-200% and "flow 5" from 0-40% the effluent BOD in "flow 13" can be set from 7.3mg/L to 1.9mg/L and for "flow 11" from 20.1mg/L to 38.8mg/L respectively (Figure 5).

A similar variety can be created for nitrogen removal. For example, when looking at nitrogen species for recirculation rates from 0 to 200% in the two effluent streams, it can be seen that ammonia in "flow 13" can be set from 25mg/L to 6.1mg/L while also reducing TN from 30mg/L to 6.9mg/L with increasing recirculation. In "flow 11" only little N-removal is anticipated, hence the water of "flow 11" could be suitable for crop irrigation. The water from "flow 13" could be discharged to a lake (Figure 6).

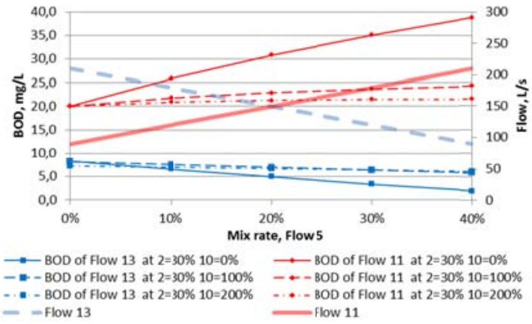


Figure 5: BOD concentration and volume of effluent "flow 11 and 13" with variation of "flow 5" and recirculation "flow 10".

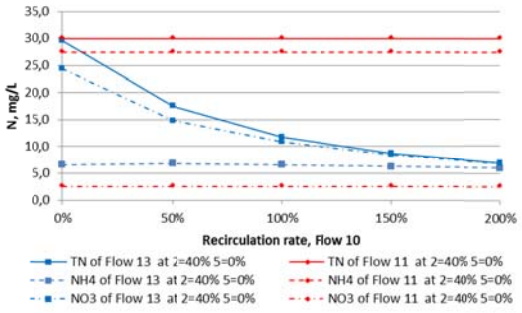


Figure 6: Nitrogen species for effluent "11" and "13" for different recirculation rates, "flow 2" of 40%, "flow 5" at 0%

Total nitrogen removal can be adjusted by +-5mg/L by setting “flow 2” from 30% to 50%. The proposed process allows for example to supply a larger quantity of water with nutrients as fertilizer supplement during the summer. During winter a majority of the water can be fully treated (full nitrogen removal) suitable for groundwater recharge or surface water discharge. In Table 6 these two cases are compared.

Table 6: Modeling of proposed trickling filter configuration for two reuse settings: setting one with BOD removal, nitrification and denitrification and setting two with only BOD removal.

Flow:		**Inflow**	**“Flow 11” Setting 1:**	**“Flow 13”**	**“Flow 11” Setting 2:**	**“Flow 13”**
“flow 2”	%		15%	15%	80%	80%
“flow 5”	%		0%	0%	0%	0%
“flow 10”	%		300%	300%	0%	0%
Flow	L/s	300	45.0	255.0	240.0	60.0
s-BOD	mg/L	140	9.0	8.7	42.6	0.7
NH_4	mg/L	30	3.8	5.2	27.9	0.0
NO_3	mg/L	0	26.2	5.5	2.1	28.6
TN	mg/L	30	30.0	10.6	30.0	28.6
s-BOD	kg/day	42000	404	2220	10222	44
NH_4	kg/day	9000	170	1314	6692	0
NO_3	kg/day	0	1180	1399	508	1714
TN	kg/day	9000	1350	2713	7200	1714
			Setting1:		Setting1:	
Energy Use	kWh/m^3			0.19		0.09
Energy Use	kWh/kg-COD			0.33		0.10

In Setting 1 “flow 2” will carry 15% of the influent volume and 300% of nitrified effluent is recirculated through the anoxic tank. 255L/s of fully nitrified effluent and a TN concentration of <10mg/L is produced. In this case BOD removal is greater than 94%, TN removal in sum is greater than 55% (excluding simultaneous denitrification and biomass N uptake). By reducing the recirculation (“flow 10”) lesser TN removal could be set. The low TN water may be used for surface water recharge or other suitable reuse. In setting 2 the recirculation is 0% while “flow 2” carries 80% of the influent. Here 240L/s of water with a BOD of 42mg/L is produced and can be used for crop irrigation during growth periods.

CONCLUSIONS

1) There is a need for flexible, simple, low maintenance and low energy consuming treatment of wastewater for reuse purposes. There is also a need for systems that are flexible enough to react to varying reuse needs during seasonal changes.
2) New generation trickling filter systems can be designed to meet multiple treatment goals at effluent qualities comparable to AS or AS-BNR systems. Additionally TF systems offer flexible configurations for later add on of nitrification and denitrification.
3) A flexible trickling filter configuration including anoxic pre-treatment, trickling filters and sedimentation was modelled. This system can produce an effluent with a BOD of <5mg/L, ammonia of <2mg/L and TN of <10mg/L along with an effluent without N-removal and BOD of for example 40mg/L. This configuration does not need to have multiple treatment trains to achieve multiple effluents, but the ability for flexible flow routing. This configuration can react to seasonal variations by adjusting flows inside the configuration if necessary.
4) The production of water can afford up to 3,5kWh/m^3 when produced by desalination. When groundwater is available 0,77kWh/m^3 may be needed for pumping. When reusing water from AS processes water can be made available for >0,4kWh/m^3 depending on sludge age. When reusing water treated by new generation trickling filter systems only 0,1-0,2kWh/m^3 are needed.
5) The energy consumption of 3 investigated single stage trickling filter plants was 0,057kWh/m^3 or 0,175kWh/kg-COD (excluding storm water) for Batumi tskali WWTP

in Georgia, 0,12kWh/m³ or 0,22kWh/kg-COD for Managua WWTP in Nicaragua and 0,11kWh/m³ or 0,16kWh/kg-COD in Walvis Bay WWTP in Namibia.

6) New generation trickling filter systems should be considered when water reuse is needed. When reusing water from trickling filter systems the process is be more cost effective than by producing water by other means.

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