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Technical efficiency of some existing risk reduction options in treatment systems (D4.3.5)

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Summary

Risk reduction options regarding drinking water treatment can be placed in three categories - control, education/information and barrier. Describing the meaning of these categories and the relationship between them represents the introduction and entry in this report.

Furthermore examples and explanations for risk reduction options in the drinking water treatment are given. For the categories of *control* and *education/information* the general pattern of possible options are shown. For *barrier risk reduction* the process of estimating strategies, methods, efficiency and additional costs are shown and clarified with the help of a detailed section of examples. In this context the prioritizing of hazards and the identification of control measures are explained in detail. Therefore the concept risk reduction option is shown in the context of water safety plans.

The examples of barrier risk reduction options include some of the common drinking water treatment processes: filtration, coagulation/flocculation and usage of chemicals.

Contents

1 Introduction

This report is part of work package 3 about identification and description of possible risk reduction options in drinking water supply systems. The relation of this work package within the Work Area 4 is illustrated in figure 1. The risk reduction options are identified in a way that they address risks included in the Techneau Hazard Database. Hence these databases are connected with a consistent reference system.

The aim of this report is to give additional information to the Risk Reduction Option Database. Examples for estimating the risk reduction potential are developed for a number of risk reduction options identified earlier in work package 3 and included in the database. In these examples the risk reduction options are specified by explaining possible methods and strategies as well as by estimating the technical efficiency and economical costs.

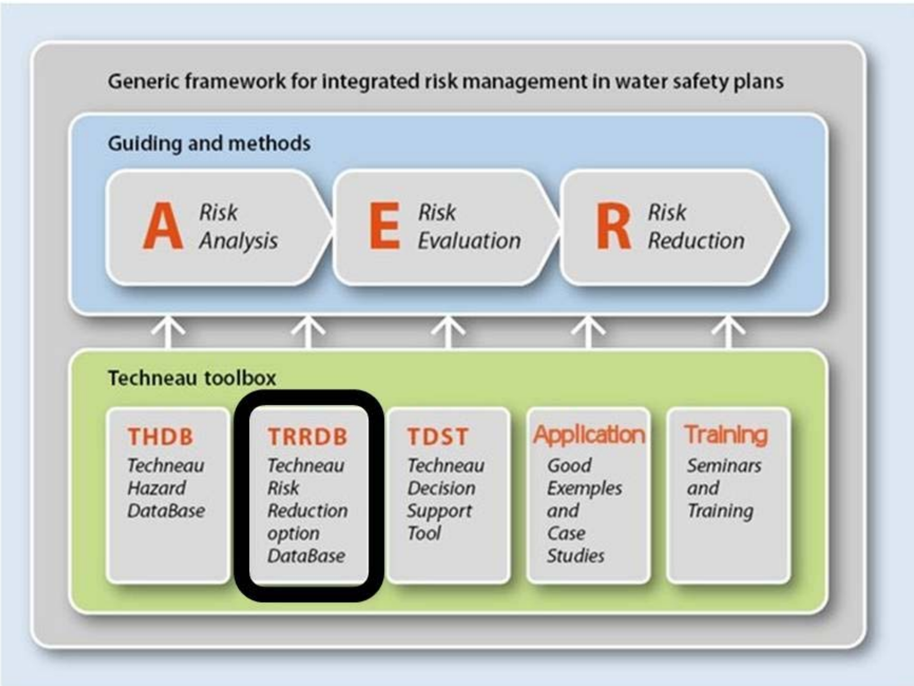

Figure 1: Illustration of the relation of this work to TECHNEAU Work Area 4

1.1 Overview of suggested risk reduction options for drinking water treatment

The risk reduction options listed in the TECHNEAU risk reduction option database, TRRDB (TECHNEAU 2009), are specified for each hazardous event in three different categories. It should be noted that the characteristics of the risk reduction options (RRO) differ significantly between these three categories. The categories are as follows (illustrated in figure 2):

- Control
- Education and Information
- Barriers

Risk reduction options of the category control play the role of regulations and give a legal framework for the water treatment and therefore influence the risk reduction options of other categories. Activities in the category education and information enable persons to understand the mechanisms of water treatment technologies as well as their aims. Therefore education and information is another basis for the installation and operation of drinking water treatment.

Drinking water treatment means basically processes which change the properties of incoming water with the result of potable water, suitable for drinking. Since most of the processes remove hazardous substances and change water characteristics in a way that they have no hazardous effect, the treatment processes itself represent a risk reduction option of the category "barrier". To design and construct additional treatment step – therefore finally the existence of a treatment process – is called "new barrier". At the same time the risk of failure and therefore malfunctioning of treatment can be reduced by options which can be e.g. optimisation or proper maintenance and operation of a treatment plant. These options are also included in the category barrier and are defined here as "existing barrier". The risk reduction options belonging to these two groups of barrier are affecting directly the water by improving their properties. Nevertheless they influence each other. The design and construction methods of a treatment process influence the possibility or necessity of implementing additional barriers to prevent its failure or to react to a failure. Further the barrier options are influenced by risk reduction options in the categories education/information and control. An example should illustrate the relationships between the categories:

- CONTROL
  the EU Drinking Water Directive (DWD) gives guideline values for a number of hazardous substances
- INFORMATION
  as a consequence of the DWD requirements, this information has to be given to the responsible persons in the design and operation of water treatment plants
- NEW BARRIER
  to produce drinking water complying with the DWD, the information which the relevant person has about the guideline values should

implicate the construction of a appropriate treatment process (X) to improve problematic parameters of the raw water

- EXISTING BARRIER (LEVEL 1)
  after construction and identification of possible failures of the treatment process X, risk reduction options to reduce the probability of occurrence or/and to reduce the consequences of failures are conducted
- EXISTING BARRIER (LEVEL 2)
  optimisation of the failure-risk reducing actions is conducted

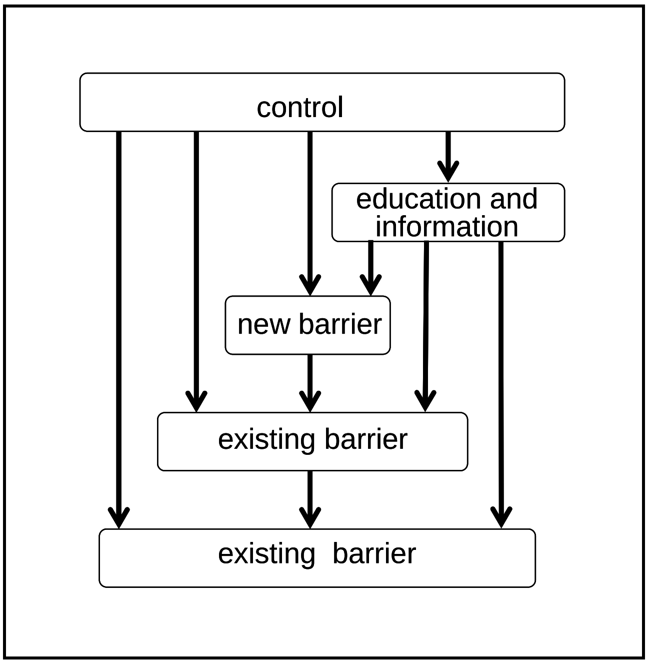

Figure 2: Classification of risk reduction options and their relation to each other.

1.2 How to use this report

This report helps the reader to understand the proposed structure and categories of risk reduction option in the area of drinking water treatment. It gives a high number of concrete examples for risk reduction options. Nevertheless it does not contain a complete list of hazardous events or risk reduction option for treatment processes since they depend strongly on individual systems and situations. Hence the example section can be used as an initial set of risk reduction options which can be taken into account and give the starting point to identify additional.

Further the report shows examples about method and strategy of risk reduction options as well as efficiency and additional costs. These examples can serve as model and help to conduct own estimation for other risk reduction options. They also provide more elaborate information about the listed examples of risk reduction options.

2 Control options: regulations

As mentioned in chapter 1.1 the control options are in the first line of the three risk reduction option categories. They influence both education and information risk reduction options and barrier options. Examples for control options are legislative elements like directives, laws and regulations. They are the driving forces to implement education and information as well as barrier options and give a framework, how and to what extent the barriers have to be implemented. The effect of one option of this category can be of outstanding importance since it induces and influences a high number of options of the categories education/information and barriers.

For the treatment of the water supply the legal guideline values for a set of parameters given in directives and ordinances are one principal control option. They represent a very clear demand and the treatment processes have to be designed and optimised according to the target water quality values provided. The concentration and other quality parameters have to be monitored and compliance with limit values has to be proved. The efficiency of this type of regulation control option depends on the availability of technical tools (treatment technologies), financial means and the enforcement system. Another important factor is, if all relevant hazardous substances are included with guideline values in the regulation or if ad hoc monitoring of suspected hazardous substances is conducted. On EU level the Drinking Water Directive (98/83/EC) and indirectly the Water Framework Directive include regulation for drinking water quality after the treatment processes.

Further, there are national ordinances and directives containing demands on the treatment process. EU countries have to transpose the two EU directives into national law and therefore comply with the values given in the directives.

Usually the installation and operation of drinking water treatment plants require an administrative decision. To support this licensing and as a help to meet the guideline values there are technical standards which give rules on how to design, construct and operate the relevant drinking water treatment processes. E.g. in Germany the German Technical and Scientific Association for Gas and Water (DVGW) gives technical rules for water treatment.

3 Education and Information options

3.1 Documentation and communication procedures

Documents containing information for communication should be prepared for different target audiences: technical personnel, management personnel and the public.

If information updates are prepared right after new information becomes available, it reduces the amount of updating required at the end of the year and will allow Water Service Authorities to receive more up-to-date progress reports for their own planning services.

Documentation includes:

- Description and assessment of drinking water system including programmes to upgrade existing water delivery.
- A plan for operational monitoring and verification of drinking water system.
- Water and safety management procedures for normal operation and incident/ emergency situations (including communication plans).
- Description of supporting programmes.

Communication strategies should include:

- Procedures for promptly advising of any significant incidents within the drinking water supply including notification of the public health authority.
- Summary information to be available to consumers, e.g. through the media, annual reports and on the internet
- Establishment of mechanisms to receive and actively address community complaints in a timely fashion.

4 Barrier options: technical efficiency and costs

Regarding the treatment aspect of the drinking water supply, the risk reduction actions from the category of barrier options have the greatest direct physical influence on the quality of the water and all other possible hazards. The higher level categories of control and education/information mainly represent options which have a positive influence to install or optimise barrier options and therefore have an indirect influence on water quality.

This chapter is structured according to the most common treatment processes for the drinking water production. These processes play the role of barrier risk reduction options. They reduce the consequences of hazardous events by minimizing or eliminating the effect of the hazardous event on the consumer. This is done for example by removing hazardous substances from the water.

A hazard is any agent that will cause an adverse health effect if it is consumed via drinking water. A hazardous event is an incident or situation that can lead to the presence of a hazard. According to the WHO, hazards may be microbiological, physical or chemical in origin. Identification of hazards is important to ensure that adequate protection measures can be applied and to identify treatment requirements.

At each step the intention is to determine what could happen that could lead to contamination, and the associated control measures for each hazard. Once hazard/s have been identified, consideration of the events that lead to their entry into the drinking water supply system is required.
Sources of potential hazards or hazardous events can be found in each step of the water supply system. These are listed in Table 2.

The impact of the hazard can be characterised by assessing the severity of the likely health outcome (in terms of the impact and population affected) and the probability of occurrence.

Prioritizing Hazards

A risk is the likelihood of the identified hazard/s causing harm to exposed populations in a specified timeframe including the magnitude of that harm and/or the consequences. In any system there may be a number of hazards (Table 1) and a large number of control measures. It is therefore important to rank hazards in order to establish priorities. The hazard assessment matrix in Table 2 (WHO[2]) is a guide to score the existing risks that could make water unsafe.

Table 1: Examples of sources of potential hazards or hazardous events in the water supply system

ELEMENTS OR PROCESSES OF A DRINKING WATER SYSTEM	POTENTIAL HAZARDS OR HAZARDOUS EVENTS
Source Water: Surface	• On-site septic tank systems • Domestic waste dumping • Land spreading of manure • Feedlot runoff • Municipal sewage effluent • Heavy metal, pharmaceutical residuals • Municipal landfills • Industrial activities • Leaking pipelines • Pesticide use • Petroleum refineries • Highway, railway accidents and spills • Recreational activities • Natural events – flooding, droughts, etc.
Source Water: Ground	• On-site septic systems • Domestic waste dumping • Municipal landfills • Graveyards • Land spreading of manure • Intensive livestock activities • Gas service stations – hydrocarbon contamination • Industrial plants • Leaking pipelines – hydrocarbon contamination • Sludge disposal areas and petrol refineries • Highway/railway accidents and spills
Treatment systems	• Water optimization – failure • Coagulant dosing – failure • Filtration – failure • Coagulation, flocculation and sedimentation – biofilm growth • Inlet flow control – failure • pH correction – inappropriate levels • Disinfection – under/over dose • Reservoir storage – contamination
Distribution	• Reservoirs – security control failure • Pump stations – security control failure • Distribution transmission mains – geological faults • Distribution water mains – geological faults • Re-chlorination points – under or over dosage • Main breaks – contamination of mains • Cross section with sewage pipes (microbial hazard)

ELEMENTS OR PROCESSES OF A DRINKING WATER SYSTEM	POTENTIAL HAZARDS OR HAZARDOUS EVENTS
Other water delivery systems	• Tank truck storage – loss of sterile conditions • Tank truck previous use – contamination • Cisterns – contamination

Source: CWWA, 2005

Table 2: Risk Assessment Matrix

LIKELIHOOD	RATING	CONSEQUENCE	RATING
Almost certain (once a day or permanent feature)	1	Catastrophic (Death expected from exposure)	100
Likely (once per week)	0.8	Major (Population exposed to significant illness)	70
Moderately likely (once per month)	0.5	Moderate (Large aesthetic impact)	20
Unlikely (once per year)	0.2	Minor (Small aesthetic impact)	2
Rare (1 in 5 years)	0.1	Insignificant (No impact)	1

Likelihood is determined by "how often" or "how likely" a hazard or a hazardous event occurs. It must take into account hazards that have occurred in the past and their likelihood of re-occurrence and must also predict the likelihood of hazards and events that have not occurred to date.

Consequence determines the severity of the results of the hazard/hazardous event and the seriousness or intensity of the impact of the hazard to human health.
RISK RATING = LIKELIHOOD × CONSEQUENCE

Multiplying the derived likelihood ratings with derived consequence ratings from the risk assessment matrix produces a risk rating.

E.g. a likelihood rating of 0.8 multiplied by a consequence rating of 70 would give a risk rating of 0.8 × 70 = 56, which would be ranked higher than an event with a likelihood of 0.2 and a consequence of 2 and a risk rating of 0.2 × 2 = 0.4.

A higher score implies that a bigger risk of a hazardous event occurring exists and should therefore be prioritised. A risk profile based on the calculated score is given in Table 3.

Table 3: Risk profile based on score calculated from risk assessment matrix

SCORE	RISK PROFILE
0-10	***Low*** These are systems that operate with minor deficiencies. Usually the systems meet the water quality parameters specified by the appropriate guidelines (e.g. in South Africa, SANS 241).
11-56	***Medium*** These are systems with deficiencies which individually or combined pose a high risk to the quality of water and human health. These systems would not generally require immediate action but the deficiencies could be more easily corrected to avoid future problems.
57-100	***High*** These are systems with major deficiencies which individually combined pose a high risk to the quality of water and may lead to potential health and safety or environmental concerns. Once systems are classified under this category, immediate corrective action is required to minimize or eliminate deficiencies.

In addition to regarding treatment process steps as barrier risk reduction options, actions like optimisation, improvement of maintenance and operation, failure prevention and failure repairing of existing water treatment plants can be risk reduction options of the category barrier.

In this section a set of common treatment processes in the drinking water production are presented as barrier options as well as examples of additional risk reduction options for optimisation and failure repairing are presented. They are further characterised by explaining the strategy and method in detail and conducting an estimation of their technical efficiency and costs.

4.1 Identifying Control Measures

Control measures are actions that reduce levels of hazards within water supply systems either by preventing entry, reducing levels or by restricting their production. Many control measures are effective against more than one specific hazard while some hazards may require more than one control measure for effective control. The assessment and planning of control measures should ensure that health-based targets will be met and should be based on hazard identification and assessment.

Identification and implementation of control measures need to be based on a multi-barrier principle so that if one barrier fails, the remaining barriers will still operate, thus minimizing the likelihood of contaminants passing through the entire system and being in sufficient amounts to cause harm to consumers.

Some control measures are actions at specific points in the system and are referred to as control points. Defining control points is an important component of the water safety plan and provides water utilities with information regarding where specific actions need to be taken to ensure water safety. Control points should not be the only focus of water utilities to ensure water supply as a holistic and preventative approach is required.

The prioritization of control measures and points must be related to the severity of the potential risk. Control points identified as being of higher priority are therefore monitored more frequently to ensure that the situation is under control.

For each control measure, critical limits should be defined. Critical limits are the performance targets that, when exceeded, compromise the quality of water being supplied. Critical limits define when the control measure is out of compliance and action is required. It is essential that critical limits be directly or indirectly measurable. National legislation or international guidelines (e.g. WHO[2]) provide critical limits for various constituents in the water matrix.

Limits will be indicators that can be readily interpreted at the time of monitoring and where actions can be taken in response to non-compliance. Critical limits are defined in such way that they do not automatically lead to a breakthrough of chemical contaminants or pathogens into the water supply, but represent the signal that actions are required urgently to prevent an unacceptable level of risk occurring.

Control measures should be identified for each hazard found within the whole system of water supply. Some important factors that need to be considered are listed in Table 4 (WHO[2]).

Table 4: Factors for consideration

RESOURCE AND ENVIRONMENT PROTECTION	ABSTRACTION POINTS AND CATCHMENTS	WATER ABSTRACTION AND STORAGE SYSTEM EQUIPMENT	WATER TREATMENT SYSTEM	DISTRIBUTION SYSTEMS
▪Developing a catchment management plan which includes control measures to protect surface and ground waters ▪Ensuring that planning regulations include protection of water resources from potentially polluting activities (e.g. industries) ▪Promoting awareness in communities of the impact of human activities on water quality	▪Designated and limited uses ▪Registration of chemicals used in the catchments ▪Specific protective requirements (e.g. containment) for a chemical industry or refueling stations ▪Control of human activities within the catchment area ▪Control of wastewater effluents ▪Regular inspection of catchment area ▪Land use planning procedures – use of planning and environmental regulations to regulate potential water polluting developments ▪Diversion of storm water flows ▪Run-off interception	▪ Use of available water storage during and after periods of heavy rainfall ▪ Appropriate location and protection of intake ▪ Appropriate choice of off-take depth from reservoirs ▪ Proper well protection systems ▪ Storage areas and reservoirs should contain roofs ▪ Access to storage areas should be restricted from animals/birds, etc.	▪ Coagulation/flocculation /sedimentation/filtration ▪ Alternative treatment ▪ Use of approved water treatment chemicals and materials ▪ Control of water treatment chemicals ▪ Process controllability of equipment ▪ Availability of back-up systems ▪ Water treatment process optimization including: chemical dosing, filter backwashing, flow rate, minor infrastructure modifications ▪ Use of tank storage in periods of heavy rainfall	▪Distribution system maintenance ▪Availability of back-up systems ▪Maintaining an adequate disinfectant residual concentration ▪Cross connection and back-flow prevention devices implemented ▪Fully enclosed distribution systems and storage facilities ▪Appropriate repair procedures including subsequent disinfection of water mains ▪Maintaining adequate system pressure

4.2 Chemicals used for treatment or disinfection

The strategy for options reducing the risk of hazardous events due to chemicals which are used in the water treatment process, is based strongly on the application of the water safety plan concept. If this is applied and a multi-step water safety plan is conducted, the options are very efficient in reducing the probability of hazardous events like use of expired chemicals, inadequate storage of chemicals, problems at manufacturing/transport of chemicals.

4.3 Filtration technologies

The filtration technologies summarized here, describe the removal of relatively large solids and particles with screens and rakes, low and rapid sand filtration as well as membrane filtration.

4.3.1 Solid removal - screens and rakes

The application of screens and rakes means the mechanical removing of particles which are bigger than the meshes. Hence the selection of sufficient screen or rake size and geometry is the important factor to removal certain particles. Risk reduction options which mean an optimisation and the prevention of failures of this barrier are e.g. the installation of an appropriate cleaning schedule and the adjustment of the screen/rake geometry to the size and shape of potentially hazardous particles. The removal of particles is necessary to provide a sufficient drinking water quality, but in many cases it is also important as pre-treatment to ensure the effectiveness of other processes like membrane filtration or disinfection.

4.3.2 Slow sand filtration

Slow sand filtration represents a relatively simple technology where the water flows from top to bottom through a layer of sand, usually with a thickness of 0.9-1.5 m (Crittenden 2005). Examples for important risk reduction options are presented in Table 4 of Appendix C. Regarding the maintenance, important actions are to clean the filter with sufficient time intervals, a regular partly refill of the filter material and a complete renewal if necessary. To support this and to be able to guarantee the drinking water quality, monitoring of raw water and of the filter head-loss are necessary. The observation of the head loss is a simple and low-cost option to observe the filter load and can indicate effectively the cleaning schedule. The cost of concentration measurement in the effluent depends significantly on the amount of different components for which the concentrations have to be measured. Nevertheless this action is very important and effective to observe the filter effectiveness and therefore prevent the existence of hazardous substances in the produced drinking water.

Risk reduction options addressing the hazardous event of reduced filtration performance are the conduction of pre-testing and an appropriate development of start up concept (see table C2: B6.8.2a, B6.8.2b, B6.8.2c). The strategy of pre-testing is to estimate the efficiency, filtration properties and behaviour during the ripening phase of the full scale filter using a pilot plant.

The pilot plant consists usually of a cylinder container which is significantly smaller than the full scale plant but which nevertheless uses the same raw water. The efficiency of a pilot study which means the quality of the results depends on its elaborateness and exactness. E.g. taking into account several seasons increase the exactness of a study. Costs include here the experimental work as well as the acquisition of the pilot plant. Examples for costs are given in Hendricks 2006 (page 706, based of projects in 1992) and vary between 76,800 and 123,300 US$. Estimated equivalent of 60,000 to 95,000 €.

The development of an appropriate starting up concept should be based on results of a pre-testing. The target of the start-up phase is to increase the growth of microorganisms which are situated in the filtration material and which are important for the filtration efficiency. The duration can be several weeks during which the water should not delivered as drinking water. Beneficial concepts are to reduce the volume flow during the start up phase and to mix the new with already used sand (DVGW 2005 (b)).

Further options regarding filter blockage or other kind of damages to the filter are the implementation of raw water monitoring and an appropriate concept of filter material changes. Methods for the last mentioned options are to regenerate the media by draining and removing the top filtration material (in a range of 1-2 cm). In Crittenden (2005) and Hendricks (2006) it is mentioned that this can be sensible to apply in a period of weeks or month. After the same material has been used for several years a complete exchange of the material can prevent of filtration efficiency loss.

The installation of redundant filter lines is an important risk reduction option which prevents the unavailability of filtered water in the case that the other line(s) are occupied for cleaning, ripening phase, filter material exchange or are out of operation due to other reasons.

4.3.3 Rapid sand filtration

Rapid sand filtration is technologically more complex than slow sand filtration. Both the design and the operation of this kind of filters are more challenging. The filter works with the hydrostatic pressure as driving force interrupted by regular backwashing. The backwashing water is pressurized by pumps and flows from bottom to top.

Some risk reduction options have been identified which addresses the design filtration plants. These options are most effective and cost efficient if they are taken in the planning and construction phase of a rapid sand filter before it is in operation. One example for such a risk reduction option is the installation of sufficient buffer capacities or the increasing of the buffer capacities to reduce the risk of an insufficient filtration due to a too high hydraulic load. With the installation of appropriate buffer capacities it is possible to ensure an equal flow and therefore velocity in the filter media.

Furthermore the installation of a high number or the increasing of the number of redundant filters ensures the availability of filtered water also if the operation of some filters has to be interrupted (DVGW 2005 (a)). The appropriate installation and dimensioning of connections, valves, flumes and pipes reduces the risk of filter failure. For this action expected changing of the hydraulic conditions has to be taken into account. Methods for dimensioning are to use Darcy's law and Forcheimer relation (for high filtration rates) (Hendricks 2006 p. 617). The change of permeability which happens when particles start to clog in the filter has to be taken into account (Hendricks 2006 p. 617).

The choice and correct installation of the hydraulic operation is the most basic and important risk reduction option to ensure a proper filtration result and prevent e.g. channel forming. Generally the three methods – constant rate and constant head water filtration, constant rate and rising head water filtration and declining rate filtration – are possible (Hendricks 2006 page 618, Cleasby 1981, Cleasby 1989, Kawamura, Babbitt 1939 p. 564). All three methods are simple and effective, nevertheless the constant filtration mode is the most common, the declining rate has the disadvantage of higher initial filtration velocity (Hendricks 2006 page 618). The costs for this option are mainly the training of the operating staff.

The efficiency of the removal during the rapid sand filter (which is mainly due to adsorption) depends on the properties (concentration, size, chemical properties) of the particles in the incoming flow. This depends strongly on the pre-treatment (which is mostly coagulation and sedimentation). Therefore the design and optimisation of the rapid filtration has to be done in combination with the pre-treatment. A proper and stable design of the pre-treatment is an important measure to prevent the risk of malfunctioning filtration.

Experimental investigations in a smaller scale are an important and effective method to understand and operate a rapid filtration system. The adsorption depends on filtration velocity, average size of flock particles, temperature of water, zeta-potential of the particles and ambient water organic acids (these factors are influenced by: ambient water particles, ambient water ionic strength, coagulant species, coagulant dosage, pH). To study these mechanisms, pilot experimentation in combination with the theory of filtration is the most effective way to design this process, since the theoretical models alone are not able to predict the process efficiency without experimental findings (Hendricks 2006). Nevertheless it is important to include the pre-treatment in experimental studies (Hendricks 2006, DVGW 2005 (a)). In Hendricks (2006) it is stated that in all known cases the costs for a pilot plant study have been paid back within 10 years. Costs for investigations depend on the number/ duration/ scale of experiments and can vary extremely, e.g. from only short-time lab-experiments to long-time pilot scale experiments. Costs for the conduction of pilot plant studies can be $10000 to $2 million, costs for the pilot plant itself range between $1000 to $1 million. (Hendricks 2006 page 599).

An important set of risk reduction options relates to backwashing. Rapid filtration includes four different operational phases, which are: filter ripening, steady state filtration, breakthrough and backwash. The backwash should not take place later than the early beginning of the breakthrough phase. The purpose of backwashing is to prevent:

- aggregation of flocculated particles
- the build-up of mud-balls
- accumulation
- formation of crusts
- compaction of filter material (which would lead to surface cracks and hydraulic short-circuits)
- biological contamination.

The backwash can be initiated by controlling the head-loss, the effluent quality or time. It is recommended to have the filter backwashed until it is completely clean, since a shorter period of backwashing could increase the risk of the formation of mud-balls. The shear stress on the filter media during backwashing has to be sufficient to remove particles from the filter media. The characteristics of the filtration cycle (the three first phases) are specific for any system, therefore a site specific operation should be adopted.

Two different backwash methods are possible - surface wash or air wash, the latter one is more widespread in Europe and is getting increasing application also in USA (Kawamura 1996). The first one is not competitive for very deep filters. According to Amintharajah (1984) the most effective procedure is concurrent air and water backwash with water at subfluidization velocity to induce a collapse pulsing mode. The duration depends on the media but is in the magnitude of 10-15 minutes. The installation of turbidity meters is useful to define the period of backwashing and to monitor the backwash procedure in general.
The combined cleaning with air and water-backwash is recommended as option to reduce the risk of blockage is recommended by Babbitt (1939 p. 564). The air wash causes turbulence and physical agitation so that the media is cleaned from agglomerated particles. The air is introduced equally over the whole width with air nozzles. According to Kawamura (1996) only fluidizing with backwash water is not sufficient for an effective filter material cleaning. Extra costs for this option include the equipment with an air piping system and with air nozzles. The maintenance costs are often not increased since the improved backwash concept leads to longer life time of the filter media.

An appropriate backwash frequency and duration is important to achieve effective filtration whereas ineffective backwashing may lead to a reduced effluent quality. In this perspective also the manifold system under the filter plays an important role. A well-known problem is the formation of crusts. Once crusts have been formed, it is not possible to remove them.

The backwash frequency and the water volume used for backwashing is an economical factor, since the amount of water used for this purpose reduces the amount of produced drinking water. A rule of thumb is a maximum water use for back-washing of 5-15% of the total amount of produced water.

Related to backwashing is the risk of contaminates passing the air-cleaning systems. To prevent this, the cleaning air should filtered properly. The compressor has to be chosen and installed appropriately, to ensure that the air is free of contaminates, like oil. Pressurized air pipes should be installed higher than the maximal water level (DVGW 2005 (a)).
With these risk reduction options the contamination path cleaning air can be controlled effectively.

To prevent malfunction of the cleaning procedure the following measures are important:

- prevention of scourer-/nozzle-blockage by regular examination and cleaning (Hendricks 2006)
- ensuring an uniform distribution (prevention of short-circuiting)
- installation of a support layer at the ground of the filter (improvement of uniform water and air distribution)

Some risk reduction options, connected to the filter media that can prevent filter damage or insufficient filtration are presented below.

The choice of appropriate filter media is an important factor for a good working filter. The best choice is made if the combined results are used of a pilot plant study and a theoretical analysis of characteristics of the media and water to be treated. One possible approach for filter media selection is given by Monk (1987). It is possible to shorten the ripening phase and to improve the filtration efficiency by adding polymers, e.g. 15-25 µg/L non-ionic polymer (Kawamura 1991, p. 215).

It is recommended to investigate relevant properties of the filter media like the zeta-potential of filter grains, the 10%-smaller-size of filter media particles, the spherity of filter particles, the porosity of the filter bed and the amount of filter material (Hendricks 2006).
The choice of the appropriate filter material is crucial and is a very effective risk reduction option. The effectivity of the filtration media depends on the local conditions, meaning that testing by using a pilot plant will probably be beneficial (Hendricks 2006, DVGW 2005 (a)).

The cost of filtration material depends on the kind and the filter size. According to Kawamura (1996) the costs for garnet and illumenite is >10 times higher than for anthracite (which costs app. $300/m^3$).

To ensure the filter effectiveness, to detect blockages early and to support an correct timing of backwashing, a regular and frequent monitoring of the filter medium (over the whole filter-height) and of operational parameters (e.g. head-loss, effluent quality) is recommended.

Appropriate operation requires sufficiently trained staff, which leads to extra costs for training. An advanced monitoring scheme also causes extra costs.
In Ref P6.1 2001 it is recommended to perform a detailed filter medium inspection and chemical cleaning at least annually (Hendricks 2006).
Costs connected with these actions are caused since the design of the filter has to be changed (or initially planned) in a way that allows inspections (e.g. including manholes). Hence there are additional costs for inspections but which are cost-effective if conducted in a reasonable way.

If monitoring shows that the quality of the filtration media or of the filtration effluent is decreasing an effective risk reduction option is to exchange the filter material partly or complete (DVGW 2005 (a)). An example for partly exchange is to concentrate on especially contaminated or crusted areas.

To reduce the risk of unacceptable effluent quality after the changing the filter bed, it is recommended to place the new media in at least two phases. After each phase cleaning and subsequent removal of undersize particles (which are floating on the top of the filter layer) has to take place. After cleaning of the final layer the filter material has to be disinfected, e.g. according to DVGW (2005 (a)).

An important pre-condition for numerous risk reduction options is the monitoring of the filtrate quality by selecting the relevant and harmful parameters and establishing an appropriate scheme for sampling, analysis and observation of time dependent behaviours. This enables a robust operation procedure based on the four phases of ripening, steady state, start of filter breakthrough and backwash. The discard of water produced during the ripening phase reduces significantly the risk of supplying customers with drinking water of insufficient quality (DVGW 2005 (a), Hendricks 2006).

Air bubbles in rapid sand filters can be caused by improper backwashing, negative pressures or algae bloom and can result in filter blockage and hydraulic short-circuiting (Babbitt 1939, p. 564 and 614). These risks can be reduced by designing appropriate de-aeration devices (e.g. self-purging air cushion, DVGW 2005 (a)). Additional costs consist of the investment for additional valves and of training for the staff to operate the devices.

4.3.4 Membrane Filtration

Membrane filtration offers the possibility to eliminate specific groups of contaminants depending on what kind of membranes are used out of the types microfiltration, ultrafiltration, nanofiltration and reverse osmosis membranes. Furthermore the membrane filtration plants can be built very compact in comparison to sand filtration.

An important group of risk reduction options to reduce the risk of malfunction during a membrane filtration are options preventing damage of the membrane module. Here the risks have to be distinguished between damage of the membrane material itself and the damage of the remaining parts of the module, which is mainly the housing and the o-rings. A sub-group of these options are the actions to detect membrane module damage which is the pre-condition to further repairing actions. Examples of methods are particle counting, particle monitoring, turbidity monitoring, bubble-point testing, air-pressure-hold testing, pressure decay test, diffusive air test, acoustic sensor method, liquid porosimetry, surrogate challenge test and sonic sensing (Adham 1995; Guo 2010). Integrity tests, detection of damages and exchange of damaged membranes are principally efficient actions to prevent the delivery of low quality drinking water. The precision and efficiency of detection varies between the different methods and measurement devices. The additional costs which are connected with these methods consist mainly of the investment to by the required devices and to train the staff to conduct the tests efficiently.

Integrities which might occur in membrane modules and which are addressed by the risk reduction options can be damage in the membrane material, discontinuities in the glue lines, inadequately sealing of the edges of membrane leaves, broken fibres, damage of the module housing and short circuiting due to non-tight o-ring.

Preventive actions against membrane module damage are appropriate pressure controlling, identification and elimination of adverse chemicals in the water (if necessary, implementation of pre-treatment), regular checking electronic dosage instruments, identification and elimination of adverse particles in the water (pre-treatment) and protection against intentional damage or contamination.

To reduce the consequence of membrane damage the installation of redundant filters is a very effective risk reduction option. This allows the change or reparation of damaged membrane modules without risking the delivery of influenced drinking water or the occurrence of drinking water unavailability. The options cause additional investment costs and higher membrane exchange costs.

One important risk reduction option which is an essential part of many membrane processes to ensure a stable permeate flow, is the regular membrane cleaning. The aim of the cleaning is to remove blockage, layers of particles (fouling) or crystallised layers (scaling) from the membrane surface. Possible actions are regular membrane backwash, chemical cleaning and disinfection.

In some cases an elaborate pre-treatment can be an efficient option to prevent fouling or scaling; in case of fouling by particle elimination and in case of scaling by reducing the concentration of the critical components.
The cleaning activities - especially disinfection - reduce the risk of bacteria transfer to the permeate and therefore to the drinking water. Nevertheless disinfection can also increase some risks, like the formation of disinfection by products (DBP) which are partly hazardous substances. Hence optimising the disinfection procedure is a risk reduction option. Laboratory experiments, an

elaborate automatic control system and trained staff are risk reduction options which lead to a minimum of required disinfection chemicals and therefore a reduced probability of occurrence of high levels of DBP. Further important options are the discard of the first water after disinfection and to check if used chemicals are not harmful for membrane module damage.

Since the membrane process is a relatively complex process, failures of numerous additional elements like pumps, air supply system, compressor, chemical storages, valves and monitoring devices are possible and would impact negatively on the quality and availability of drinking water. Examples of risk reduction options preventing these problems are the use of redundant systems (additional basin around the chemical storage to avoid spillage, existence of emergency compressors, generators and monitoring devices), regular maintenance and checking of the different parts of the system.

4.4 Coagulation/ flocculation

An important part of risk reduction options for the treatment processes of coagulation and flocculation is represented by the implementation of sampling and maintenance plans. The risk of malfunction can be significantly decreased through regular application of the plan´s provision. These options address especially hazardous events connected with the mechanical parts of process like the clarifier rake system and the air release nozzles.

Further important risk reduction options are connected directly with the chemical reaction of coagulation and flocculation. They reduce the risk of insufficient chemical conversion. Important aspects are the mixing time and intensity, coagulant dosing, retention time and pH. The risk reduction options follow mainly the strategy of the multi-step WSP and represent corrective actions according to the WSP (Freese 2004, Bartram 2009, Thompson 2009).

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Appendix A: Strategy, efficiency and associated costs for RROs by barriers for generic hazards

Table A1: Treatment - generic hazards: risk reduction options by barriers. Strategy, efficiency and associated costs

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.1.7	E.g. not adequate coagulants or oxidants are used, improper pH value is maintained, no proper dose of coagulant or oxidants is used, lack of specific knowledge due to outsourcing, etc.		Improve treatment post-chlorination; increase in-house human capacity		Treatment processes and staff skills improvement.	Utilisation of training materials (van der Walt et al., 2009)	Dependent on ability of staff to implement improved processes.	Dependent on local training costs	Information not found
6.1.8	Flow meter is not calibrated		Calibrate flow meter		Calibrate flow meter	Obtain equipment manual and train staff to calibrate flow meter regularly	Dependent on ability of staff to implement improved processes.	Dependent on local training costs	Information not found
6.1.10	Main leak of pipe, burst of wall		Employ leak detection equipment and staff		Utilise leak benchmarking (McKenzie & Seago, 2007)	Leak detection performed regularly and economic repair point determined.	Information not found	Software; equipment; staff training	Information not found
6.1.12	Inappropriate maintenance scheme		Implement preventive maintenance plan		Start Water Safety Plan, which will include this aspect.	Multi-step WSP (Bartram et al., 2009; Thompson & Majam, 2009)	Excellent if WSP completed properly	Information not found	Information not found

Appendix B: Strategy, efficiency and associated costs for RROs by barriers for chemicals used for treatment or disinfection

Table B1: Treatment - chemicals used for treatment or disinfection: risk reduction options by barriers. Strategy, efficiency and associated costs

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.2.1	Problems at manufacturing and/or transport of chemicals; used of expired chemicals.		Audit and remediate chemicals procurement, turnaround, storage and handling methods.		Start Water Safety Plan, which will include this aspect.	Multi-step WSP (Bartram et al., 2009; Thompson & Majam, 2009)	Excellent if WSP completed properly	Information not found	Information not found
6.2.3	Inadequate storage of chemicals		Audit and remediate chemicals procurement, turnaround, storage and handling methods.		Start Water Safety Plan, which will include this aspect.	Multi-step WSP (Bartram et al., 2009; Thompson & Majam, 2009)	Excellent if WSP completed properly	Information not found	Information not found

Appendix C: Strategy, efficiency and associated costs for RROs by barriers for filtration technlogies

Table C1: Treatment - solid removal and screens: risk reduction options by barriers. Strategy, efficiency and associated costs

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.3.1	Incorrect screen size or inadequate cleaning		Install correct screens and rakes / cleaning schedule		Install correct screens and rakes / cleaning schedule	Install correct screens and rakes / cleaning schedule	Should be 100% if correct screen and rake are used	Screen and rake; staff time	Information not found

Table C2: Treatment - slow sand filtration: risk reduction options by barriers. Strategy, efficiency and associated costs

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.8.1	During cleaning process or maintenance or repair in combination with only one existing filtration-line	B6.8.1	Installation of redundant sand filter lines	P	Include redundancies due to the necessity of filter cleaning, sand replacement or higher volume flows				
6.8.2	Inappropriate filtration speed, filter material, running time, cleaning, layer thickness, filter adjustment, insufficient removal of the top layer, inappropriate adjustments during start up phase, absent or insufficient monitoring of pressure differences and operational pressure	B6.8.2a	Pretesting plant experiments to get to the right filtration parameters	P	Estimating of efficiency and filtration properties by pilot studies with the real water (Hendricks 2006 page 661 ff.)	Pilot studies can be performed using cylinders containing the sand and gravel. Several aspects can be studied (e.g. head-loss over time, removal efficiency) (Hendricks page 661 ff.)	The efficiency is influenced by the duration and elaborateness of the studies	Acquisition of the pilot plant	The whole costs for a pilot study were in 1992 between 76800 and 123,300 US$ (Hendricks 2006 page 706)
6.8.2		B6.8.2b	Pretesting plant experiments to get to the right filtration parameters for the start up phase	P	Estimating of the ripening phase by pilot studies with the real water (Hendricks 2006 page 661 ff.)	The build up of the microorganisms in the filter, the schmutzdecke and the effect on the filtration efficiency is studied (Hendricks 2006 page 661 ff.)	The efficiency is influenced by the duration and elaborateness of the studies	Acquisition of the pilot plant	Performance of the experiments.
6.8.2		B6.8.2c	Developing concept for the procedure of the start up phase	P	Basis for the filtration are the microorganism growth in the filter material. A new filter or new filter material need a ripening time until it reaches the full filtration efficiency (DVGW 2005 (b))	This procedure takes up to some weeks. The effluent can not delivered as drinking water in this time. To reduce the amount of wastewater the flow rate can be reduced in this phase. It is recommended to mix new with already used sand to fasten this procedure. (DVGW 2005 (b))		No	Time consuming procedure, water loss, but no additional costs

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.8.2	Inappropriate filtration speed, filter material, running time, cleaning, layer thickness, filter adjustment, insufficient removal of the top layer, inappropriate adjustments during start up phase, absent or insufficient monitoring of pressure differences and operational pressure	B6.8.2d	Implementation of a monitoring of the pressure difference and operational pressure	P	Being able to observe the head-loss and time when cleaning is necessary	Installation of pressure sensors		Acquisition of the relevant measurement devices	
6.8.3	Due to quality of incoming water	B6.8.3d	Implementation of a monitoring of the raw water and according to the monitoring implementation of pre-treatment	P	Identification and monitoring of possible water components which can disturb the filtration process (DVGW 2005 (b))	Water components can lead to a fast crusting and blockage of the filter (so that part of the filter material has to be removed) or to a reduction of the filtration efficiency			Increased costs due to monitoring measurements
6.8.4	Deterioration, erratic hydraulic stress, due to quality of incoming water, rumpling of the filtration layer by small animals or insects, disturbance of microbial fauna in the filter	B6.8.4a	Regular exchange of filter media and additional exchange in case of damages	P+C	Head-loss limit (typically 0.9-1.5 m) indicate the necessity of filter regeneration (Crittenden 2005 page 876 ff.)	Regular filter regeneration by hydraulical cleaning (duration of a cycle typically several weeks or month) . The material can be used for several years until it has to be removed finally. (Crittenden 2005 page 876 ff.)	This method prevents efficiently the usage of crusted and overloaded filtration material and therefore filter breakthrough.		Costs for hydraulically cleaning, replacement of filtration material as well as time in which filter is not operating (including the ripening time after the cleaning procedure)

Table C3: Treatment - rapid sand filtration: risk reduction options by barriers. Strategy, efficiency and associated costs

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.5.5	Inappropriate filtration speed, filter material, running time, layer thickness, insufficient elimination of flocs and/or flocculants, high hydraulic load or variations, high particle load in incoming water	B6.5.5a	Increasing the buffer capacities (new buffer, increased volume)	P+C	Determination of sufficient buffer capacity and realisation	A higher number of redundant filter should be installed so that it can be ensured (by operating only a part of the filters) that the velocity can be kept equally (DVGW 2005(c))	With sufficient size the risk reduction option can be 100% efficient	Investment costs for the building depend on the required buffer size	
6.5.5		B6.5.5b	A slowlier change of the flow	C	Controlling of the hydraulic conditions in the filter even in situations with increased volume flows				
6.5.5		B6.5.5c	A higher number of redundant filters	P+C	Design of the filtration process and determination of the sufficient number of parallel filters according to possible increase of volume flow and guidelines (DVGW 2005 (a), Hendricks 2006)			Investment costs if installation of additional filter lines are necessary	
6.5.5		B6.5.5d	Realising of an appropriate equalisation and hydraulic control (pumps, buffers and valves)	P	Design of an effective flow equalisation and an effective hydraulic control/ appropriate underdrain system				

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.5.5	Inappropriate filtration speed, filter material, running time, layer thickness, insufficient elimination of flocs and/or flocculants, high hydraulic load or variations, high particle load in incoming water	B6.5.5e	Optimisation of the coagulation and sedimentation treatment step	P	Efficiency of the removal during the rapid sand filter depends on the properties of the particles in the incoming flow and hence on the pre-treatment. The design and optimisation of the filtration has to be done in combination with the pre-treatment.	Coagulation has to be designed according guidelines (DVGW 1987, DVGW 1998)			
6.5.5		B6.5.5f	Investigations taking into account the interaction between the pre-treatment and the filter	P	Since the efficiency of the removal during the rapid sand filter depends strongly on the pre-treatment. the design and optimisation of the rapid filtration has to be done in combination with the pre-treatment.	The adsorption depends on filtration velocity, average size of floc particles, temperature of water, zeta-potential of the particles and ambient water organic acids (these both factors are influenced by: ambient water particles, ambient water ionic strength, coagulant species, coagulant dosage, pH)	Piloting in combination with the theory of filtration is the most effective way to design this process, since the theoretical models alone are not able to predict the process efficiency without experimental findings (Hendricks 2006).	Costs for pilot plant studies can be 10000 $ to 2 million $, costs for the plant range between 1000 $ to 1 million $. (Hendricks 2006 page 599)	Repeating of experiments in case of important changes

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.5.1	Poor construction or operation of backwashing concept, poor performance of air scourers, blocked nozzles, uneven distribution of water and air	B6.5.1a	Design and implementation of a frequent backwashing concept	P	Target of the backwash is to prevent aggregation of flocculated particles and the building up of mudballs, as well as the accumulation, crusting and compaction of filter material and the prevention of biological contamination. The backwash can be initiated by means of controlling the head-loss, the effluent quality or time.	Two different methods are possible - surface wash or air wash, the latter one is more important in Europe and is getting increasing importance also in USA (Kawamura 1996). According to Amintharajah (1984) the most effective procedure is concurrent air and water backwash with water at subfluidization velocity to induce a collapse pulsing mode.	A sufficient frequent backwash can ensure the maximal possible filter efficiency whereas an insufficient concept may lead to reduced effluent quality. The efficiency depend on the proper determination of the backwash duration and the installation of the manifold system under the filter.		The backwash frequency and the water volume used for backwash are additional costs. A rule of thumb in the practise is a maximal water consumption of 10-15% of the produced water
6.5.2	Sand not replaced when required	B6.5.2a	Design and implementation of a concept to regular and appropriate filter media removal with the monitoring of the filtrate quality as control parameter	P	Removal and substitution of crusted or contaminated filtration media. Monitoring of effluent quality to detect the quality decrease. (DVGW 2005 (a))	Installation of filtration media in at least two phases. After each phase a cleaning and a subsequent removal of the undersize particles has to take place. After the cleaning of the final layer the filter material has to be disinfected (DVGW 2000; DVGW 2005 (a)) Approach for filter media selection: given by Monk (1987)..	The efficiency of the filtration media depends on the conditions in each case. Due to this a testing phase using a pilot plant is recommended (Hendricks 2006, DVGW 2005 (a))	The cost of filtration material depends on the kind and the filter size.	According to Kawamura (1996) the costs for garnet and illumenite is >10 times higher than for anthracite (which costs app. 300$/m3).

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.5.2	Sand not replaced when required	B6.5.2b	Monitoring of the filter medium over the whole filterhight	C	Inspection of the filter medium (and chemical cleaning) at least annually. (Ref P6.1 2001)	Testing if the relevant properties are appropriate: zeta-potential of filter grains, 10%-smaller-size of filter media particles, spherity of filter particles, porosity of filter bed, ,amount of filter material (Hendricks 2006)	With this measure it can be ensured that the filtration effectiveness of the filtration medium is (still) effective	Design of the filter in a way that the inspection can be done	extra costs for the sampling, filter stop and analysis
6.5.1	Poor construction or operation of backwashing concept, poor performance of air scourers, blocked nozzles, uneven distribution of water and air	B6.5.1b	Regular control of the air scourers and nozzles	C	Ensure the uniform distribution of water and air in the backwash procedure by prevent the clogging of scourers and nozzles under the filter (Hendricks 2006)	Regular examination and cleaning (Hendricks 2006)	Ensure the maximal possible cleaning efficiency and therefore the prevention of short-circuiting	Include in the design the possibility of an easy and fast inspection of the nozzles and scourers	Low costs if fast inspection is possible
6.5.1		B6.5.1c	Support layer on the ground of the filter for the improvement of the evenness of the water and air distribution	P	Ensure the uniform distribution of water and air in the backwash procedure by realising a appropriate support layer on the bottom of the filter (Hendricks 2006)				
6.5.3	Operation during the early stage of rapid filtration although the filter needs ripening time to achieve full removal efficiency	B6.5.3	Monitoring of the filtrate quality and discharge of the first water until the quality is sufficient according to the monitoring	C	Selecting the relevant parameters/ harmful substances and analyse the effluent for it.	Determination of time dependent behaviours (e.g. concentration, turbidity). Identification of the end of the ripening phase and the start of the steady state phase. After this time point, water can be delivered. (DVGW 2005 (a), Hendricks 2006)	Prevent very efficiently the delivery of the effluent which is produced during filter ripening and which has a worse quality.		

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.5.4	Deterioration, erratic hydraulic stress, filter blockage, air underneath the filter bed, reduced cleaning performance, pressure in closed filter layers related to hydro mechanical security devises or pressure-transducers, changing of the filter layers	B6.5.4a	Installation of flow equalising measures to reduce erratic hydraulic stress	P	Ensuring an equal and equally distributed filtration flow through the filter media to realise a stable effluent quality	For the hydraulic operation there are three different methods: constant rate and constant head water filtration, constant rate and rising head water filtration and declining rate filtration (Hendricks 2006 page 618, Cleasby 1981, Cleasby 1989, Kawamura, Babbitt 1939 p. 564)	All three methods are simple and effective, nevertheless the constant filtration mode is the most common, the declining rate has the disadvantage of higher initial filtration velocity (Hendricks 2006 page 618)	Proper installation of valves, incoming flumes. No significant extra costs.	Appropriate operation requires sufficiently trained staff, which lead to extra costs for training.
6.5.4		B6.5.4b	Appropriate connections to the filter and appropriate design taking into account expected hydraulic conditions	P	Correctly dimensioning of flumes, connections, filter size, installation of a sufficient number of parallel filters to equalise flow changes (DVGW 2005 (a))	Dimensioning using Darcy's law and Forcheimer relation (for high filtration rates). For clogged filter the change of permeability has to be taken into account (Hendricks 2006 p. 617)		Proper installation of valves, incoming flumes. No significant extra costs.	Appropriate operation requires sufficiently trained staff, which lead to extra costs for training.
6.5.4		B6.5.4c	Regular control of the filter medium and operational parameters to detect a blockage early and inducing of filter backwashing	C	Observation of the effluent quality, head-loss and filter material to detect the duration of the steady state phase and start the backwash phase early	Visual inspection, observation of measurements in the effluent. Investigation of the cycle pattern. It is recommended to use pilot plant studies			Appropriate operation requires sufficiently trained staff (extra costs for training). An advanced monitoring scheme (extra costs).

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.5.4	Deterioration, erratic hydraulic stress, filter blockage, air underneath the filter bed, reduced cleaning performance, pressure in closed filter layers related to hydro mechanical security devises or pressure-transducers, changing of the filter layers	B6.5.4d	Using of air and water for backwash cleaning	P	Air cleaning additionally to backwash with clean water (Babbitt 1939 p. 564) According to (Kawamura 1996) only fluidizing with backwash water is not sufficient for an effective filter material cleaning	Air wash causes turbulence and physical agitation so that the media is cleaned from agglomerated particles. The air is introduced equally over the whole width with air nozzles.	A sufficient frequent backwash can ensure the maximal possible filter efficiency whereas an insufficient concept may lead to reduced effluent quality. The efficiency depend on the proper determination of the backwash duration and the installation of the manifold system under the filter.	Filter has to be equipped with air piping system and air nozzles.	The maintenance costs are effectively not increased since the improved backwash concept leads to longer life time of the filter media.
6.5.4		B6.5.4e	Design of appropriate deaeration devices	P	Removal of air bubbles in the filter media (which might come from the back flush, negative pressure or algae bloom) to prevent filter blockage due to the air and therefore forming of channels (Babbitt 1939 p. 564 and 614)	Installation of appropriate valves (self-purging air cushion, DVGW 2005 (a))	With an effective design the problem can be avoided efficiently	Costs for the relevant valves	Training for the staff to handle the devices. Costs for control and maintenance.
6.5.4		B6.5.4f	Closed cleaning air system, treatment of the cleaning air	P	It has to be prevented that the cleaning air causes contamination (poles, dust, insects, waste gas) to the water. (DVGW 2005 (a))	The compressor has to be chosen and installed appropriate, to ensure that the air is free of oil. Pressurized air pipes should be installed over the maximal water level. (DVGW 2005 (a))	This contamination path can be controlled effectively.	Special requirements during design phase of the filter, but with relatively low costs	Training for the staff to handle the devices. Costs for control and maintenance.

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.5.4	Deterioration, erratic hydraulic stress, filter blockage, air underneath the filter bed, reduced cleaning performance, pressure in closed filter layers related to hydro mechanical security devises or pressure-transducers, changing of the filter layers	B6.5.4g	Regular exchange of filter material in combination with thorough filter media monitoring	P+C	Removal and substitution of crusted or contaminated filtration media. Monitoring of effluent quality to detect the quality decrease. (DVGW 2005 (a)); Inspection of the filter medium (and chemical cleaning) at least annually. (Ref P6.1 2001)	Installation of filtration media in at least two phases. After each phase a cleaning and a subsequent removal of the undersize particles has to take place. After the cleaning of the final layer the filter material has to be disinfected according to DVGW 2005 (a). (DVGW 2005 (a)) Approach for filter media selection: given by Monk (1987).	The efficiency of the filtration media depends on the conditions in each case. Due to this a testing phase using a pilot plant is recommended (Hendricks 2006, DVGW 2005 (a))	The cost of filtration material depends on the kind and the filter size.	According to Kawamura (1996) the costs for garnet and illumenite is >10 times higher than for anthracite (which costs app.. 300$/m3).
6.5.4		B6.5.4h	Choice of appropriate filter media	P+C	The choice should be made as a combination of results of pilot plant study and theoretical analysis of media and water properties	Approach for filter media selection given by Monk (1987). It is possible to decrease the ripening phase duration and improve the filtration efficiency by addition of polymers, e.g. 15-25 µg/L non-ionic polymer (Kawamura 1991, p. 215);	The choice of the appropriate filtration material is crucial	The cost of filtration material depends on the kind and the filter size.	According to Kawamura (1996) the costs for garnet and illumenite is >10 times higher than for anthracite (which costs app.. 300$/m3).

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.5.9	Cleaning media contaminated, not discarding of the first filtrated water after the cleaning, microbiological activity due to insufficient cleaning , chemical contamination downstream of the filter	B6.5.9a	Design and implementation of an appropriate cleaning and operation concept with the discard of the first filtrated water after the back flush	P	Consequent operation of the filter according to the four phases ripening (with discard of the water), steady state, start of filter breakthrough, backwash	Determination of time dependent behaviours (e.g. concentration, turbidity).. Identification of the time point, when the ripening phase is over and the steady state phase starts. After this time point, water can be delivered (with the monitoring methods and a pilot plant study). (DVGW 2005 (a), Hendricks 2006)	Prevent very efficiently the delivery of the effluent which is produced during filter ripening and which has a worse quality.		
6.5.15	Absent or insufficient monitoring of the pressure difference and operational pressure, inappropriate monitoring and sampling concepts, malfunctioning measuring instrument, no manholes existing	B6.5.15a	Implementation of manholes, respectively designing of a filter with manholes when building up a new filter	P	Allow the possibility to observe and revise the filter in different depth	For closed filters at least 3 holes, for open filters at least 2 holes are recommended. A method for the construction is given in DIN 19605. The positions should be: under the bottom (orifices-level), just above the bottom (orifices-level)	The efficiency of the observation and possibilities of revising is increased with the number of manholes.	Low extra costs for the construction of the manholes	

Table C4: Treatment - membrane filtration: risk reduction options by barriers. Strategy, efficiency and associated costs

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.7.1	Structural damages, e.g. due to pressure shocks, crossflows, chemical damages or broken fibres, raw water bypass (due to failure of o-ring or glue line)	B6.7.1a	A treatment step for reduction of chemicals	P	Identification of the materials used in the membrane modules and substances which can damage these	Identification of substances in the feed which could destroy the materials of the membrane module (housing, connections, resin, glues, o-rings). Identification of methods to reduce the concentrations.	The efficiency depends on the used treatment method.		
6.7.1		B6.7.1b	Performing of membrane integrity tests to prevent broken fibres	P	Detect structural damages in the membrane material	Like: particle counting, particle monitoring, turbidity monitoring, bubble-point testing, air-pressure-hold testing, pressure decay test, diffusive air test, acoustic sensor method, liquid porosimetry, surrogate challenge test and sonic sensing. (Adham 1995) (Guo 2010)	The detection and exchange of the membrane module is a very efficient method to reduce the problem. The efficiency of the integrity tests varies.	The investment to buy the measurement devices for the integrity tests.	Training for the staff to conduct the tests, maintenance of the measurement devices.
6.7.1		B6.7.1c	barrier to prevent pressure shocks	P	Controlling of the pressure to ensure that remains under a critical value	Installation of pressure control valves and automatic security stops for high pressure	High efficiency	Investment for valves	Maintenance of valves and software for automatic process control
6.7.1		B6.7.1d	Redundant membrane modules so that they can be used when damage is detected	C	Using a design which includes redundancy	Calculation of the required membrane area. Planning of the plant with a higher membrane area realised as parallel lines.	Crucial in cases of membrane damage to allow the change of modules.	A higher membrane area is required, leading to higher investment costs.	Costs for membrane exchange is higher due to the higher total area. Membrane costs are generally decreasing but depend strongly on type (MF, UF, NF, RO, material), they are in the range 12-52 €/m2 for polymeric membranes (Zhu 2009, Brepolds 2010) and 400-730 l/m2 for ceramic membranes (Müller 2008)

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.7.2	Operational fault with automatised process by unqualified staff	B6.7.2	Special control of process parameters to detect the operational faults early	C	Automatic process control systems				
6.7.3	Change in quality of raw water or incoming water, inadequate cleaning methods in combination with high concentration of contaminants	B6.7.3a	Installation of an appropriate pre-treatment	P	Prevention of membrane fouling due to inappropriate water characteristics	For RO/NF membranes a particle removal is necessary for high turbidity (a criteria can be the SDI). In some cases it is useful to use antiscalants, precipitation, ion exchange as pre-treatment to prevent crystallisation on the membrane (Scaling) (Melin 2004)	High efficiency	Installation of the relevant pre-treatment process	Maintenance and operation of the relevant process
6.7.3		B6.7.3b	Controlling of the fouling by adapted cleaning intervals	C	Layers on the membrane and blockage in the membrane pores are released regularly to avoid increase of pressure/decrease of permeate flow (Melin 2004, DVGW 2003)	The fouling rate is highly influenced by the membrane material and the membrane manufacturing process as well as the water properties. The cleaning protocol must be optimised in experiments with the relevant water and membranes. The membrane cleaning can be done by regular backwash without chemicals and chemical cleaning. Cleaning chemicals belong to the groups alkalines, acids, metal chelating agents, surfactants, enzymes, oxidants (Disinfectants) (Melin 2004, Li 2004, Liu) regarding the recommendations of the membrane manufacturer especially about the chemical stability of the membranes for the different cleaning chemicals	Influenced by the optimisation process. In many cases cleaning agents are able to remove fouling effective so that the filtration flux can be kept stable	Installation of the backwash (pumps, storage, pipes)	Costs for chemicals, checking and maintenance of backwash system

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.7.3	Change in quality of raw water or incoming water, inadequate cleaning methods in combination with high concentration of contaminants	B6.7.3c	Reducing the high concentration of contaminants with a pre-treatment	P	Prevention of membrane fouling due to inappropriate water characteristics	see: B6.7.3a	High efficiency	Installation of the relevant pre-treatment process	Maintenance and operation of the relevant process
6.7.4	Erratic hydraulic stress, deterioration, wear, inappropriate membrane material, exceeding the maximum pressure, chemicals in the incoming water being harmful for the membranes, incorrect dosage of chemicals for cleaning	B6.7.4a	Redundant membrane modules so that they can be used when damage is detected	C	Using a design which includes redundancy	Calculation of the required membrane area. Planning of the plant with a higher membrane area realised as parallel lines.	Crucial in cases of membrane damage to allow the change of modules.	A higher membrane area is required, leading to higher investment costs.	see B6.7.1d
6.7.4		B6.7.4c	Physical barriers, e.g. fencing, around catchment areas	P	Protection against intentional damage or contamination	Make it difficult to enter the site (fences), installation of control cameras etc.	100% protection is not possible, efficiency depends on the quality of the installations, presence of staff and also profile of potential committer	Installation of protection devices and control measures	Maintenance and repairing of the devices as well as controlling done by the staff
6.7.4			Regular control and check of electronic dosage instruments		Prevention of membrane damage by inappropriate chemical dosage of cleaning chemicals	Automatical dosing systems during cleaning procedure			Maintenance and testing of the functionality

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.7.5	Large particles due to inadequate pre-treatment, pressure of the backflush is too high	B6.7.5b	Prefilter before membrane to prevent too large particles on the membrane		Additional pre-treatment	Installation of a filter with larger pores than the relevant membrane process	Efficiency can vary due to water quality and quality/ fitting of the pre-treatment process	Installation of the additional process	Maintenance and operation of the relevant process
6.7.5		B6.7.5b	Automised back flush program		Correct operation of the back flush	Automatical control system for the backwash program with attention to the maximal possible pressure to prevent membrane damage	Damage can be prevented effectively		Operation and maintenance of the automatical control system
6.7.6	Manufacture deficiencies: faulty barrier layer coating + polymerisation, glue line discontinuities, inadequately sealing the edges of membrane leaves	B6.7.6	Membrane integrity test before application	P	Detect structural damages in the membrane material (barrier layer coating + polymerisation, glue line discontinuities, inadequately sealing the edges of membrane leaves)	see: B6.7.1b	The detection and exchange of the membrane module is a very efficient method to reduce the problem. The efficiency of the integrity tests varies.	The investment to buy the measurement devices for the integrity tests.	Training for the staff to conduct the tests, maintenance of the measurement devices.
6.7.1	Structural damages, e.g. due to pressure shocks, crossflows, chemical damages or broken fibres, raw water bypass (due to failure of o-ring or glue line)	B6.7.1e	Integrity test for/of the module before use	P	Detect structural damages in the membrane module material (o-ring or glue-line caused by e.g. cuts, cracks, leaks from improper installation and shimming)	see: B6.7.1b	The detection and exchange of the membrane module is a very efficient method to reduce the problem. The efficiency of the integrity tests varies.	The investment to buy the measurement devices for the integrity tests.	Training for the staff to conduct the tests, maintenance of the measurement devices.

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.7.7	Bacterial growth on permeate side or internal surfaces	B6.7.7a	Appropriate cleaning procedure	P	The growth of biofouling is released with special cleaning concepts (Melin 2004, DVGW 2003)	see: B6.7.3b	Influenced by the optimisation process. In many cases cleaning agents are able to remove biofouling effective so that the growth of bacteria can be reduced to a very low amount	Installation of the backwash (pumps, storage, pipes)	Costs for chemicals, checking and maintenance of backwash system
6.7.7	Bacterial growth on permeate side or internal surfaces	B6.7.7b	Regular disinfection of membrane module	P/C	Regular usage of disinfection chemicals (Melin 2004 Membranbuch, dvgw W213-5)	Recommendations of the membrane manufacturer especially about the chemical stability of the membranes for the different cleaning chemicals should be taken into account			Costs for chemicals
6.7.4	Erratic hydraulic stress, deterioration, wear, inappropriate membrane material, exceeding the maximum pressure, chemicals in the incoming water being harmful for the membranes, incorrect dosage of chemicals for cleaning	B6.7.4c	Integrity tests of membranes	C	Detect structural damages in the membrane material	see: B6.7.1b	The detection and exchange of the membrane module is a very efficient method to reduce the problem. The efficiency of the integrity tests varies.	The investment to buy the measurement devices for the integrity tests.	Training for the staff to conduct the tests, maintenance of the measurement devices.
6.7.4		B6.7.4d	Change of membranes at an appropriate time point	P	Prevention of the usage of deteriorated membranes	Paying attention to the expected running life of membranes (given by the manufacturing company) and performance of integrity tests; conduction of pilot/ laboratory studies	Difficult to predict/ detect the max. possible life time		

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.7.9	Disinfection of the membrane	B6.7.9a	Using as little as possible amount of chemicals for disinfection	C	Optimisation of disinfection concept to minimize the amounts of used chemicals	Experiments in lab and pilot scale with the actual water and membrane combination	Depending on the elaborateness of the optimisation	Costs for lab/pilot study	Even decreasing costs since the amount of chemicals and therefore the costs for chemicals decrease
6.7.9	Disinfection of the membrane	B6.7.9b	Through away the first filtered water after disinfection	C		Integrate this process phase in the automatical control system / train the staff to perform this step properly			Training of the staff
6.7.8	No discard of the first filtrated water after the cleaning, stored chemicals released into the water downstream of the filter	B6.7.8a	Building up an additional basin or other barrier around the chemical storage	P	Prevention of the entering of stored chemicals into the drinking water	Additional basin		Installation of the basin (low investment costs)	Checking the functionality (low costs)
6.7.10	Power failure, leakage in the air supply system	B6.7.10a	emergency generator	P	Prevention of adverse effects of possible power failures	Installation of an independent generator	High efficiency	Depending on size	Regular checking of functionality

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.7.10	Power failure, leakage in the air supply system	B6.7.10b	Regular testing of the air supply system	C					Additional task during operation (additional requirement on the number/ qualification of the staff)
6.7.10		B6.7.10c	emergency generator	P	Prevention of adverse effects of possible power failures	Installation of an independent generator	High efficiency	Depending on size	Regular checking of functionality
6.7.11	Plugging due to algal bloom, artefacts, accumulation, wear, wrong design	B6.7.11a	Pre-treatment	P					
6.7.11		B6.7.11b	Regular Disinfection to prevent algae bloom	P					
6.7.12	No particle counter or bubble test, pressure decay test	B6.7.12	Installation of these monitoring devices	P	Detect structural damages in the membrane material	see: B6.7.1b	The detection and exchange of the membrane module is a very efficient method to reduce the problem. The efficiency of the integrity tests varies.	The investment to buy the measurement devices for the integrity tests.	Training for the staff to conduct the tests, maintenance of the measurement devices.

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.7.13	Inappropriate monitoring and sampling concepts, malfunction of measuring instruments	B6.7.13a	Regularly testing the measuring instruments for their functionality	P/C	Prevention of measurement mistakes due to malfunctioning or mistakes in the calibration				Maintenance and training of staff
6.7.13		B6.7.13b	emergency generator	P	Prevention of adverse effects of possible power failures	Installation of an independent generator	High efficiency	Depending on size	Regular checking of functionality
6.7.13		B6.7.13c	an emergency set of the monitoring instruments with batteries	C	Prevention of adverse effects of possible power failures	Purchase of the instruments	High efficiency	Relatively low costs	Regular checking of functionality, training of staff to utilise the instruments
6.7.13		B6.7.13d	Implementation of a statistical profound sampling concept	P	Choosing an appropriate frequency (based on time or flow, constant or changing) and amount			No	Eventually extra costs to train the staff and/or to take additional samples

Appendix D: Strategy, efficiency and associated costs for RROs by barriers for coagulation and flocculation

Table D1: Treatment - chemicals used for treatment or disinfection: risk reduction options by barriers. Strategy, efficiency and associated costs

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.4.1	Clarifier rake systems (scrapers) are not regularly maintained		Implement preventive maintenance plan		Start Water Safety Plan, which will include this aspect.	Multi-step WSP (Bartram et al., 2009; Thompson & Majam, 2009)	Excellent if WSP completed properly	Information not found	Information not found
6.4.2	Too low or too high coagulant dose		Correct dosing either through adjusted manual procedure or installation of dosing equipment		Start Water Safety Plan, which will include this aspect.	Multi-step WSP (Bartram et al., 2009; Thompson & Majam, 2009)	Excellent if WSP completed properly	Possible requirmenet for dosing pumps (	Information not found
6.4.3	Improper coagulant mixing and/or flocculation; inappropriate flocculant or flocculation agent; improper pH control.		Corrective action (Freese et al., 2004)		Start Water Safety Plan, which will include this aspect.	Multi-step WSP (Bartram et al., 2009; Thompson & Majam, 2009)	Excellent if WSP completed properly	Information not found	Information not found
6.4.11	Retention time too short; mechanical failure of the stirrer; up flow velocity too high; weir overflow rate too high; insufficient sludge draw-off; retention time too short; reaction zone and/or clarification zone not sized correctly; wrong media specifications; poor bubble formation; etc.		Correction of retention time; etc (Freese et al., 2004)						

Hazardous event (ref. from THDB)		Risk reduction option/Barriers			Strategy and some examples on methods from the literature			Costs (reference)	
(no.)	(description)	Ref.	Option	Type	Strategy (reference)	Method (reference)	Efficiency (reference)	Investment	Operation and maintenance
6.4.12	Air release nozzles not kept clean or blockages not cleared; floc carry-over takes place		Implement preventive maintenance plan		Start Water Safety Plan, which will include this aspect.	Multi-step WSP (Bartram et al., 2009; Thompson & Majam, 2009)	Excellent if WSP completed properly	Information not found	Information not found
6.4.13	Insufficient sampling frequency at control point; inappropriate monitoring program; malfunction of measuring instruments due to construction, operation system or maintenance		Implement sampling programme and preventive maintenance of instrumentation and control		Start Water Safety Plan, which will include this aspect.	Multi-step WSP (Bartram et al., 2009; Thompson & Majam, 2009)	Excellent if WSP completed properly	Information not found	Information not found