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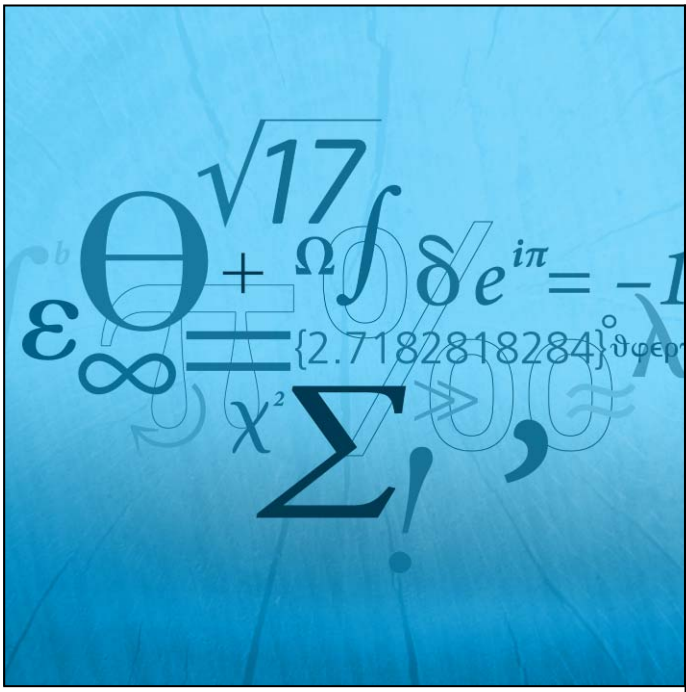

Vurdering af renseeffekt for metoder til lokal rensning og afledning af regnevand

Assessment of removal efficiency for stormwater Best Management Practices

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Kgs. Lygnby
10 Maj 2009

Preface

This report has been prepared at DTU Environment as background documentation for the assessment of the removal performances for stormwater Best Management Practices (BMPs). This work was performed within part 2, 3 and 4 of the Lokal Afledning af Regnvand (LAR) projekthåndbog project (hereafter called LAR-projekthåndbog), coordinated by Rambøll Danmark A/S and Orbicon A/S. The project was financed by the Center for Park og Natur at the Københavns Kommune.

The language of this report is English, but results (tables and graphs) are presented in Danish, in order to harmonize the report with the main document of the catalogue (in Danish).

To simplify the reading of the results for a Danish audience, LAR metoder and rensemetoder names are listed in the report in Danish. Below a list of Danish terms with the corresponding English translation is presented.

Dansk	**English**
Grønne tage	*Green roofs*
Opsamling og anvendelse	*Collection and reuse*
Permeable belægninger	*Permeable pavement*
uden nedsivning	*without infiltration*
med nedsivning	*with infiltration*
Strømning	*Flow*
over græsflader	*over turfed areas*
over stenflader	*over rocky surface*
Regnbede (bioretentionsbed)	*Rain gardens (bioretention sysytems)*
Bassiner	*Basins*
Sandfang + lukket betonbassin uden nedsivning	*Settling tank + closed concrete basin without infiltration*
Sandfang + åbent græsklædt tørt bassin med infiltration	*Settling tank + open turfed dry basin with infiltration*
Sandfang + åbent tørt græsklædt bassin uden infiltration	*Settling tank + open dry turfed basin without infiltration*
Sandfang + åbent vådt bassin	*Settling tank + open wet basin*
Render og grøfter	*Trenches and ditches*
Naturlige lavninger i terræn med nedsivning (swales)	*Natural depression in the terrain with infiltration (swales)*
Gravet rende med filtermateriale af sand/grus og nedsivning	*Infiltration trenches with sand/gravel*
Gravet rende med sand/grus samt fordelerrør eller opsamlingsrør (Wadi eller mulden-rigole)	*Swale-trench (Wadi or infiltration system)*
Tætte kanaler eller render udført i beton eller lign uden nedsivning	*Channels or ditches without infiltration (concrete)*
Faskiner	*Soakways/infiltration trenches*
Infiltrationsbrønde	*Infiltration shafts*
Drosling af afløb	*Throttling of runoff*

Dansk	**English**
Kantstene og forsinkelse på befæstede arealer	*Kurbstones or detention on paved areas*
Sandfang	*Settling tank (sand trap)*
Olieudskiller	*Oil separator*
Filtre og sier	*Filters and sieves*
Adsorptionsanlæg	*Adsorption filters*
Forbassiner	*Basins*
Bassiner med membran og uden beplantning	*Basins with membrane and without plants*
Bassiner med membran med beplantning	*Basins with membrane and plants*
Adsorption til substrat	*Adsorption to substrate*
Akkumulering	*Accumulation*
Eksempel på fjernet stoffer	*Example of removed compounds*
Filtrering	*Filtration*
Fordampning	*Volatilization*
Fotolyse	*Photolysis*
Høj	*High*
Ikke Anvendelig	*Not Applicable*
Ja	*Yes*
Lokal Afledning af Regnvand (LAR) metoder og rensemetoder	*Stormwater Best Management Practices (BMPs)*
Lav	*Low*
Medium	*Medium*
Mikrobiel nedbrydning	*Microbial degradation*
Nedbrydning	*Degradation*
Nej	*No*
Optag i planter	*Plant uptake*
Processer i jord og grundvand	*Processes in soil and groundwater*
Renseproces	*Treatment process*
Sedimentation	*Sedimentation*
Vigtighed af processen	*Importance of the process*

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1. Introduction

This report describes a methodology which has been developed and applied to assess the potential removal efficiencies of stormwater pollutants for different Best Management Practices (BMPs). These units are described within the LAR projekthåndbog, which aims to provide a complete description of BMPs and thus allow a wide application of these methods in urban areas. The significant lack of field monitoring data (e.g. Scholes et al., 2005b) prevents a quantitative estimation of removal performances for all the considered units and therefore traditional approaches (e.g. based on the mass balance of the considered system) cannot be applied.

A qualitative and comparative assessment of the different structural BMPs removal efficiencies was performed by extending the ranking methodology developed in the EU-research projects DayWater and ScorePP (Scholes et al., 2005a; 2008a,b) with a new "model-unit".

This assessment is based on the available knowledge in the scientific world and it provides a reliable framework for decision-making. It is based on the identification and assessment of the various removal processes taking place in the units. The physico-chemical properties of each specific pollutant are considered and combined to achieve an overall index, which reflect the removal potential of the considered unit. The various BMPs are then ranked according to their index, showing the order of preference for the use of BMPs for each pollutant.

The chosen methodology provides a preference order between different BMP units. According to the water quality parameter of major concern, decision-makers can use the provided order of preference to select the most appropriate unit. It is important to stress that the chosen methodology is based on qualitative assessments and cannot be directly used to gain quantitative information about the removal efficiency of the selected units.

1.1. Outline of the report

The main aim of this report is to provide a support for selection of the most appropriate BMPs for a specific compound (or substances group). The results show a preference order for a general situation. However, site specific characteristics can modify the preference order for different BMPs. In this report a conservative approach regarding groundwater protection was furthermore applied, but this might be regarded as excessive in areas where groundwater protection is not an issue. Thus results discarding groundwater protection are also presented in the report.

In the first section of the report (Chapter 2) the ranking procedure is described with the help of a simplified example. The procedure described in Chapter 2 is then applied in the following sections of the report. In Chapter 3 the relevant stormwater pollutants are selected as indicators and the relevant fate processes are identified. Chapter 4 present the assessment of the various stormwater pollutant processes that contribute to pollutant removal in BMPs. In Chapter 5 the ranking procedure is concluded and the results for each single unit (both with and without groundwater protection) are listed.

2. Ranking of stormwater treatment methods

The BMP ranking procedure (Scholes et al., 2008a) consists of four main steps:

1. *Identification of main removal processes in BMPs*: the relevant processes for removal of stormwater pollutants are identified. The parameters and units that can be used to quantify each process are also listed.
2. *Identification and assessment of pollutants removal potential*: selected stormwater pollutants are evaluated according to their physico-chemical properties and thus the removal potential for each process (identified in step 1).
3. *Assessment of processes relevance in BMPs*: the physical characteristics of each BMP are analyzed and the significance of the processes taking place in each unit are assessed.
4. *Calculation of the BMP rank*: for each unit and pollutant (or group thereof), the results of the assessment performed in step 2 and 3 are combined and a performance index is calculated. The different BMPs are then ranked, providing the order of preference for the considered compound

The new methodology developed and applied here follows the same steps. Compared to the original formulation, groundwater removal processes are included in the assessment (steps 1 and 3) and in the mathematical formulation used to rank the units (step 4). Also, further information on the fate of the pollutant is extracted from the information that is elaborated during the ranking procedure.

A simplified example is presented in the following section, to illustrate step-by-step the ranking procedure.

2.1. Identification of removal processes

The main removal processes for stormwater pollutants in the water phase are listed in Scholes et al. (2005b). These processes include a combination of physical, chemical and biological processes (Figure 1).

Pollutants can be removed from the water column directly (e.g. settling) or indirectly (e.g. adsorption to suspended solids). Indirect pollutant removal processes are dependant on other processes taking place in the unit (e.g. adsorption to suspended solids/filtration influence the importance of settling). Indirect processes are used to estimate the importance of the related processes, but they are not included in the final removal potential assessment. Precipitation and adsorption, for example, are used to estimate the importance of settling removal, but they are not considered in the final assessment of the BMP.

The original approach considers only the pollutant fate processes that are removing pollutants from the water phase. To achieve a better understanding of the dynamics inside the system, these processes can be differentiate between processes that cause an accumulation of pollutant inside the considered system (water and sediments) and those that transfer the pollutant outside the system or modify it. This subdivision can also be useful for managing purposes, as it provides information on the fate of the considered compound.

In the first category are listed all the processes that remove pollutants from the water phase but “store” the pollutant inside the system (e.g. accumulation of pollutants in sediments). Although these processes are improving the water quality, they have an impact on the BMP maintenance. In fact, the accumulated pollutant should be removed from the unit at defined intervals, with further problems linked to the disposal of the process byproduct (e.g. handling of contaminated sediments).

In the second category are included all the processes that cause the pollutant to disappear from the considered system (i.e. water and sediments). This can be due to transfer to other environmental compartments outside the system (e.g. atmosphere) or the modification of the structure of the pollutant itself. These processes are hereafter referred as “degradation processes”, with a terminology that included also transfer processes (e.g. volatilization). Infiltration is also considered as transfer to another compartment outside of the system (i.e. groundwater), but it’s not included among the processes that removes the pollutants from the water phase.

Figure 1 and Table 1 list the stormwater pollutant removal processes in BMPs that were identified and described in Scholes et al. (2005b).

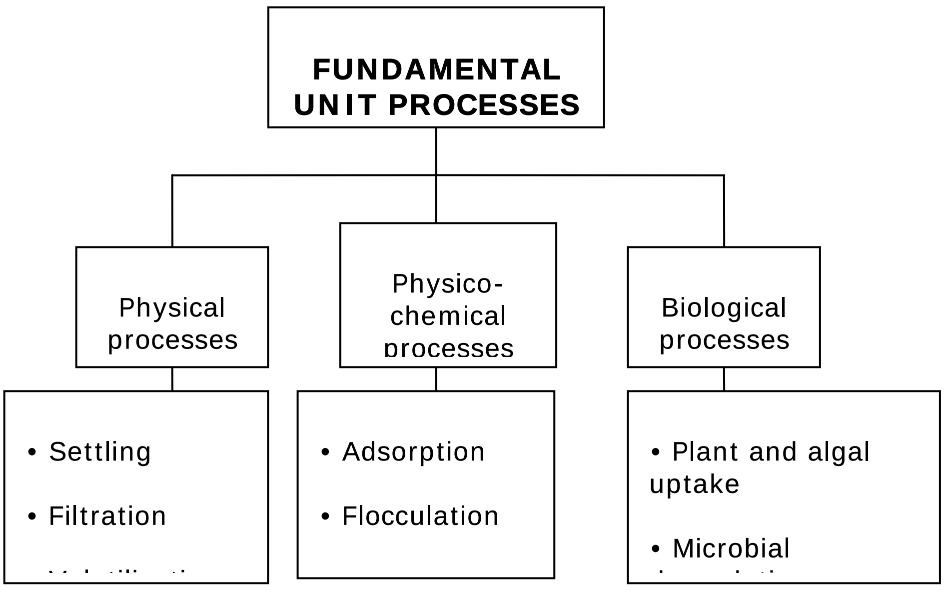


Figure 1 - Fundamental removal processes in the water phase in BMPs (adapted from Scholes et al., 2008b).

Table 1 – Removal processes in BMPs and relevant parameters (adapted from Scholes et al., 2005a) – indirect processes are in the grey boxes.

Degradation Processes	*Relevant Measurements and units*
Microbial degradation	Rate of biodegradation [$^1/_2$ life in days]
Photolysis	Rate of photodegradation [$^1/_2$ life in days]
Plant uptake	Bioaccumulation [K_{ow}]
Volatilisation	K_h [atm-m^3/mole]
Accumulation Processes	
Adsorption to substrate	K_{oc} [L/g];associated chemical fraction
Adsorption to suspended solids	K_{oc} (L/g); chemical fraction with which the pollutant is mainly associated.
Filtration	Function of K_d [L/g] and precipitation [mg/l]
Precipitation	Water solubility [mg/l]
Settling	Settling velocity [m/s]
Processes in the Soil beneath BMP	
Biodegradation	Rate of biodegradation [$^1/_2$ life in days]
Adsorption	K_{oc} [L/g];associated chemical fraction
Volatilisation	K_h [atm-m^3/mole]

K_{oc} = organic carbon-water partitioning coefficient = partitioning of a substance between the organic carbon and dissolved phases at equilibrium = ratio of the concentration of a pollutant associated with the organic phase to its concentration in the dissolved phase at equilibrium

K_h = Henry's Law constant (based on the relationship that at a constant temperature the mass of gas dissolved in a liquid at equilibrium is proportional to the partial pressure of the gas)

K_{ow} = octanol-water partition coefficient = a measure of the potential for organic compounds to accumulate in lipids = ratio of the concentration of a pollutant in octanol to that in water at equilibrium

Degradation processes

In this category are included all the processes that causes a disappearence of the pollutant from the system, by transferring it outside the system or modifying its structure.

- *Microbial degradation*: is important in the fate of several stormwater pollutants. For example, biological activity is involved in degradation of organic matter, removal of nitrogen, precipitation and binding of metals, breakdown of organic compounds. These processes can be either aerobic or anaerobic, and they are characterizd by different rates (often expressed as half-life).
- *Photolysis*: is the breakdown of a chemical due to the expusore to light. Although photolysis is mainly affeecting atmospheric pollutants, this process can affect compounds in the first layer of the water column.
- *Plant uptake*: aquatic vegetation can uptake pollutants from both sediments and the water column. The amount of pollutant potentially available for uptake is defined as the bioavailable fraction, which may quantified by appliying the water-octanol partition coefficient (K_{ow}). This value indicates the potential for a pollutant to be bioaccumulated in the plant tissues during its vegetative cycle. The organic content of

the biomass (i.e. vegetation) in the unit was not taken into consideration, given the massive amount of information needed for such evaluation.

- *Volatilization*: the mass transport between the water phase and the atmosphere affects all the stormwater pollutants. The importance of this process for the removal of a pollutant is related to the inherent properties of the analyzed compound (e.g. Henry's law coefficients). Volatilization tends to be more important for organic substances, with a preference for lighter and more soluble substances.

Accumulation processes

In this category are included all the processes that remove the pollutant from the water phase but accumulate it inside the system.

- *Adsorption:* includes different physical and chemical processes that lead to the binding of dissolved or particulate compound onto the surface of a substrate. The adsorption substrate can be suspended solids, micro-organisms, vegetation, settled sediments, filter material, etc. When the pollutant is adsorbed to particles that remain in the water phase (e.g. sorption to suspended solids) the removal process is considered as indirect, as the direct removal process is the further removal of the substrate. When the pollutant is bounded to a surface outside the water phase (e.g. adsorption to sediments, to a component ot the BMP structure, etc.), the process is considered as a direct removal process. The tendency of each pollutant to sorb is related to the inherent properties (e.g. solid/water partition coefficient – K_d) and to the characteristics of the substrate (e.g. organic content, f_{oc}). The adsorption to suspended solids (indirect process) and the consequent removal due to settling of the substrate particles by sedimentation (direct process) represent one of the more important pollutant removal processes in BMPs.
- *Filtration*: refers to the solid-water separation caused by the passage of stormwater across a porous media (e.g. porous asphalt, gravel, etc) or vegetation (biofiltration). Filtration rates depend on the filter medium characteristics, the size of the considered pollutant, the stormwater flow velocity, etc. The potential of filtration across porous media can be estimated by combining the importance of adsorption and precipitation, while biofiltration potential can be assessed by considering the possible presence of vegetation.
- *Sedimentation*: is the removal of suspended particles frow the water column due to the action of the gravity force and the direction of the water flow. This process is commonly described by the Stokes' law (valid for discrete partcle) and has a different importance according to the size of the investigated pollutant.

– *Precipitation* is caused by the creation of insoluble compounds, which are then settling. It is strongly dependant on chemical paramters (e.g. pH, water hardness and presence of competing ions).

Groundwater processes

The original methodology developed during the DayWater project does not consider the final fate of the considered pollutant when infiltration is concerned. Here, the approach was expanded by including the potential impact on the soil and groundwater beneath the BMP-unit.

Various processes can affect pollutants in soil and groundwater (Kjeldsen and Christensen, 1996). Some processes are strongly linked to the site characteristics (e.g soil characteristics, redox potential, etc.) and the removal potential of these processes cannot be generalized. In the assessment only the soil and groundwater processes that are also taking place in the water phase are considered:

– *Biodegradation*: microbial population in soil and groundwater can degradate different pollutants. These processes can be both aerobic and anaerobic.

– *Adsorption*: compared to the water column, soil offers a significantly wider surface where pollutants can bind. Thus this process is considered to be one of the most relevant removal process by comparison with the processes in the soil and in the water phase

– *Volatilization*: the soil porosity ensures the presence of a gas phase, where pollutants can migrate according to their properties. This process might be significant for highly volatile compounds, but it is sensibly less important than volatilization from the water phase (i.e. from surfaces with direct contact to the atmosphere).

2.2. Stormwater pollutants identification and removal assessment

Selected stormwater pollutants are identified as indicators for stormwater quality. The pollutant relevant properties are retrieved from existing databases (for example the Hazardous Substance DataBank (HSDB), and the European chemical Substances Information System (ESIS)) and they are used to assess the removal potential for the processes listed in Table 1.

As an example, three different imaginary compounds are used in this section. The characteristics of these examples are chosen (and exaggerated) to include a wide spectrum of stormwater pollutants. The three example compounds are:

– *Compound α*: is volatile, highly biodegradable and it is not significantly affected by photodegradation. It is commonly present in the soluble phase, with a low sorption capacity and a medium-low uptake by plants and vegetation. This compound represent substances that are mainly affected by degradation removal processes (see Table 1)

- *Compound β*: is low volatile, with a low biodegradability and it is not significantly affected by photolysis. It has high sorption capacity and it is mainly removed by accumulation removal processes (see Table 1).
- *Compound γ*: is a conservative pollutant, which is not significantly affected by any removal processes in the BMP.

The removal potential for these compounds is qualitatively assessed by assigning a value ranging from high to low. When a compound is not affected by one of the processes listed in Table 1, the qualitative assessment is not applicable (N/A).

The processes taking place in the soil are evaluated by comparison with the other removal processes taking place in the water column. The values assigned for a process in water is usually increased/decreased accordingly to the process characteristics:

- Volatilization and biodegradation are less significant in soil than in water. In fact, it is assumed that a limited air exchange in pores might affect volatilization rates (e.g. saturation of gas phase). Also, biological degradation rates in soil are assumed to be lower than in the water column, where aerobic processes are likely to prevail.
- Adsorption is significantly more important in soil, as soil offers a significantly wider surface where pollutants can bind. Thus the removal potential for this process in soil and groundwater is considerably higher than adsorption processes in the water phase.

The removal potential for the three example compounds is listed in the Table 2:

Table 2 – Potential for removal of three example compounds by the removal processes listed in Table 1.

Removal process	**Compound**		
Degradation	*α*	*β*	*γ*
Microbial degradation	High	Low	N/A
Photolysis	Low	Low	N/A
Plant uptake	Medium/Low	Low	N/A
Volatilisation	High	Low	N/A
Accumulation			
Adsorption to substrate	Low	High	N/A
Filtration	Low	High	N/A
Settling	Low	High	N/A
In the Soil beneath BMP			
Adsorption	Medium	High	N/A
Biodegradation	High/Medium	Low	N/A
Volatilisation	Medium	Low	N/A

N/A = Not Applicable

2.3. Assessment of removal processes in BMPs

The relative importance of the removal processes listed in Table 1 is assessed by a classification scale ranging from high to low. The assessment is given by considering the relative importance of each process within the considered BMP and the relative importance compared the other units. For example, the predominant process in a unit is also compared with the same process in other units: the final assessment is thus including all this information.

The removal efficiency for different units can vary according to different factors, such as location, design details, age of the system, local climate and environmental conditions. The units are assumed to operate at their maximum design potential.

To illustrate this concept, three typical example BMPs are assessed in this section (Figure 2). The three examples are created to have an overview of the wide range of BMPs assessed in the report:

- *Method A* is characterized by a permanent water volume and no infiltration to groundwater
- *Method B* is similar to Unit A, but it is characterized by a permeable bottom, which allows infiltration of stormwater into the soil.
- *Method C* is characterized by a vegetated channel for transporting stormwater, with negligible infiltration to soil

The relative significance of the removal processes in the water column for the three example units are listed in Table 3. Note that unit A and B are characterized by the same removal processes in the water column and the relative importance is similar for the degradation processes. Accumulation processes have a higher importance in unit B than in unit A as the stormwater infiltration flow enhances the removal of particles (and thus sorbed pollutants).

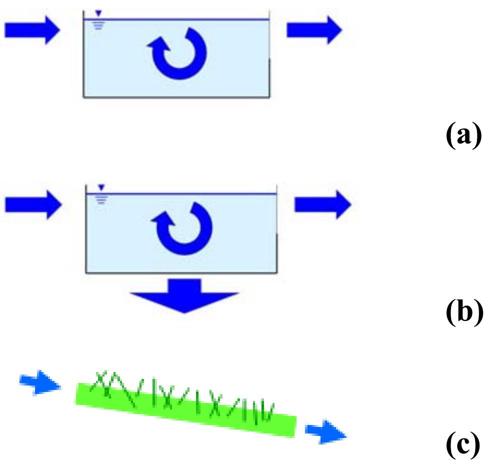


Figure 2 – Schematic representation of stormwater fluxes in the three example BMPs.

Table 3 – Relative importance of the removal processes in the water column for the three different BMPs.

Removal process	BMP		
Degradation	*A*	*B*	*C*
Microbial degradation	High	High	Medium/Low
Photolysis	Low	Low	Medium/Low
Plant uptake	Low	Low	Medium
Volatilisation	Medium	Medium	Medium
Accumulation			
Adsorption to substrate	Medium	High	Medium
Filtration	Medium	High	Medium/Low
Settling	High	High	Medium/Low

Table 4 – Interaction of example BMPs with soil and groundwater.

	LAR metode		
	A	*B*	*C*
Interaction wit soil/groundwater	No	Yes	No

The assessment of the removal processes in the soil cannot be performed. In fact, the variability due to the location of the BMPs (e.g. soil porosity, consistence and texture; groundwater level; soil organic content; etc.) does not permit the relative assessment of the pollutant removal processes. To include groundwater processes in the final assessment, a logical variable is used to define if stormwater interacts with soil and groundwater (Table 4).

2.4. Calculation of BMPs' rank

The methodology developed in the DayWater project (Scholes et al., 2005a) is based on the combination of the relative assessments that were presented in the two previous sections. The approach is based on the conversion of the high-low scale into numerical values (Table 5).

Table 5 – Conversion of classification values into numerical values.

Relative classification	Numerical value
High	3
Medium	2
Low	1
Not Applicable	0

The importance of the a removal process *i* in the treatment unit *M* (Table 3) is converted into the numerical value $I_{M,i..}$ Similarly, the importance of the process *i* for the compound *S* (Table 2) is converted into the numerical value $I_{S,i.}$ The multiplication of the two values $I_{M,I}$ and $I_{S,i}$ gives a numeric value that expresses the importance of the removal process *i* in unit *M* for the compound *S*, and these values are calculated for all the p_w processes affecting the water column listed in Table 1. To obtain a numeric value expressing the overall removal potential for the unit *M* and the compound *S*, these values are summed according to the following equation:

$$RP_{M,S} = \sum_{i=1}^{p_w} \left(I_{M,i} \cdot I_{S,i} \right) \qquad \text{Eq. (1)}$$

This value is then used to compare and rank the different units. Treatment units with infiltration enhance the importance of some of the considered removal processes (e.g. filtration, adsorption to filter material, etc.): these BMPs are thus likely to obtain high values of $RP_{M,S}$ for a wide range of substances (see for example the results in Scholes et al., 2005a; 2008b). These results can be judged as biased when considering groundwater protection, as the $RP_{M,S}$ value calculated by using Eq. 1 does not include potential negative effects on the groundwater compartment. The original formulation presented in Scholes et al. (2005a) has therefore been extended to consider also the potential impact of stormwater infiltration in soil.

This new approach privileges the units that avoid contact between stormwater and soil and groundwater. The assessment of the pollutant removal potential in soils requires however a level of information that can seldom be obtained. Also, local characteristics (e.g. soil texture, soil composition, etc.) do not allow a general assessment of removal processes in soil. To overcome these limitations, a conservative approach was adopted: any potential contact of stormwater with groundwater (i.e. where stormwater infiltration is present) is considered as a negative factor in the unit ranking. Units with no infiltration score better than units that allow infiltration of stormwater. If stormwater is infiltrated, compounds with high removal potential in soil will score better than compounds that are not (or to a low extent) affected by removal processes in soil.

Mathematically, these considerations are obtained by subtracting the influence of potential groundwater contamination from the value of the removal potential $RP_{M,S}$. Thus, the higher the potential impact on groundwater is, the lower the removal potential will be. The value of $RP^*_{M,S}$ including the potential effect on groundwater is calculated by the following equation:

$$RP^*_{M,S} = \sum_{i=1}^{p_w} \left(I_{M,i} \cdot I_{S,i} \right) - \Phi_{M,\inf} \cdot \left(4 \cdot p_g - \sum_{i=p_w}^{p_w+p_g} I_{S,i} \right) \qquad \text{Eq. (2)}$$

where $I_{M,i}$ is the numerical value assigned to importance of process *I* in the unit *M*; $I_{S,i}$ is the removal potential for the compound *S* by the process *I*; p_w is the number of removal processed in the water column and p_g is the number of removal processes in soil and groundwater.

The presence/absence of interactions with groundwater is expressed by a logical variable (Table 4), which is converted in a numeric value $\Phi_{M,inf}$ (potential interaction with groundwater=1; no interaction with groundwater=0). When no infiltration is present ($\Phi_{M,inf}$ =0), the second term of Eq. 2 is null and the formula becomes equal to Eq. 1.

The value 4 in the second term of Eq. 2 is used to be consistent with the conservative assumption that absence of infiltration is preferable. In fact, for a system with a single soil removal process (p_g=1) and a compound *S* with high removal potential in soil due to the process *i* (i.e. $I_{S,i}$=3), the second term of Eq. 2 is:

$$-\Phi_{M,\inf}\cdot\left(4\cdot p_g-\sum_{i=p_w}^{p_w+p_g} I_{S,i}\right)=-1\cdot(4-3)=-1$$

For a similar unit with exactly the same removal process importance in the water phase (i.e. the same values for $I_{M,i}$) but no infiltration, the second term of equation 2 is void. The latter unit has therefore a higher value for $RP^*_{M,S}$ and it is ranked in a higher position, i.e. units with no infiltration score better than units that allow infiltration of stormwater.

As can be noticed by inspection of Eq. 2, the chosen approach is the very conservative and privileges groundwater protection rather than other factors. The second term in Eq. 2, in fact, can play an important role in the final estimation of $RP^*_{M,S}$. As this approach could be judged as excessive in areas where groundwater protection is not an issue, both the ranking performed by using Eq. 1 and 2 are listed in Chapter 5. This allows the user to choose between two different rankings according to the characteristics of the study area.

Table 6 – Removal potentials estimated for unit B.

Removal process	**Compound**		
Degradation	*α*	*β*	*γ*
Microbial degradation	9	3	0
Photolysis	1	1	0
Plant uptake	1,5	1	0
Volatilisation	6	2	0
Accumulation			
Adsorption to substrate	3	9	0
Filtration	3	9	0
Settling	3	9	0
Overall removal potential in the water column ($RP_{M,S}$ - from Eq. 1)	26,5	34	0
*Processes in the soil beneath the BMP**			
Adsorption	2	3	0
Biodegradation	2,5	1	0
Volatilization	2	0,5	0
*Groundwater impact term***	-5,5	-7,5	-12
Overall removal potential ($RP^*_{M,S}$ - from Eq.2)	21	26,5	-12

* *For volatilization in soil the numerical conversion values listed in Table 5 are lowered by 0,5 (e.g. low=0,5), due to the relative low importance of this process in soil when compared with the water phase*

** *The second term of Equation 2, calculated with p_g=3*

Table 7 – Overall removal potentials and rank (in brackets) for example units and compounds.

Treatment Unit (Fig. 2)	Stof		
	α	*β*	*γ*
Overall removal potential in the water column ($RP_{M,S}$)			
A	24,5 (2)	28 (2)	0 (1)
B	26,5 (1)	34 (1)	0 (1)
C	20 (3)	22 (3)	0 (1)
Overall removal potential ($RP^{*}_{M,S}$)			
A	24,5 (1)	28 (1)	0 (1)
B	21 (2)	26,5 (2)	-12 (3)
C	20 (3)	22 (3)	0 (1)

The removal potentials for the different example compounds listed in Section 2.2 for unit B are listed in the Table 6. The overall removal potentials for all the three units are shown in Table 7. It is important to remember that these values are only used to rank the different units according to the qualitative assessment previously described.

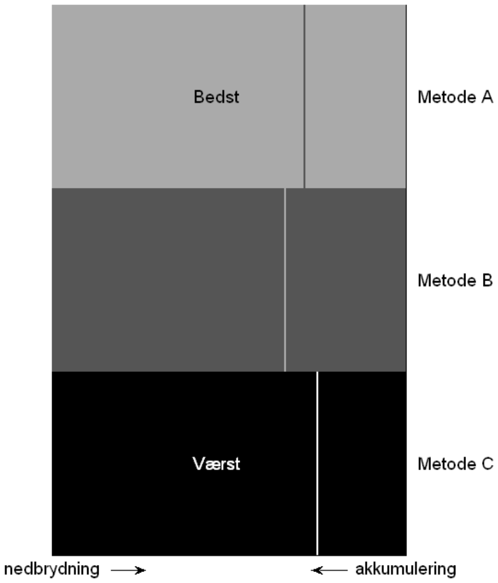
The units are then ranked according to their overall removal potential for each compound. The final results of the example assessment procedure are shown in Figure 3. A similar procedure can be adopted for family of compounds (e.g. heavy metals, PAHs, etc.): the ranking of the units is in this case performed by looking at the sum of the removal potential for each member of the considered family of compounds.

When looking only at the removal from the water phase (i.e. the $RP_{M,S}$ values listed in Table 7), unit B is always performing better than the others for both compound α and β. However, when looking at the results shown in Figure 3 (based on the $RP^{*}_{M,S}$ values), the overall performance of unit B is decreased by the presence of stormwater infiltration. Similarly, units A and B have similar performance for the water column when looking at the removal of compound γ (not reactive). However, unit B is ranked in a lower position due to the potential contamination of groundwater with compound γ.

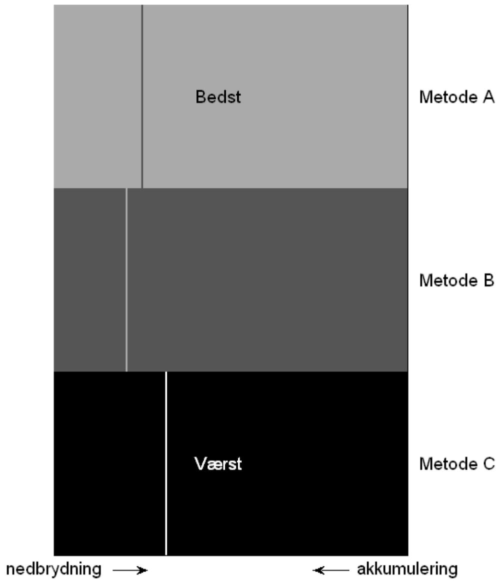
The method also allows displaying the relative importance of degradation and accumulation removal processes for each single unit. This information can provide an additional insight on the potential maintenance requirements (e.g. sediment removal by dredging). For example, units with similar rank might have different ratio accumulation/degradation and the decision-maker might chose the unit with higher importance of degradation processes.

The results shown in Figure 3 highlight that unit B has a higher level of accumulation processes, due to the higher importance of filtration and adsorption processes due to the stormwater infiltration process (see the different assessment between accumulation processes between unit A and B - Table 3). Thus it is likely that unit B will require higher maintenance level than unit A (which has similar geometric characteristics).

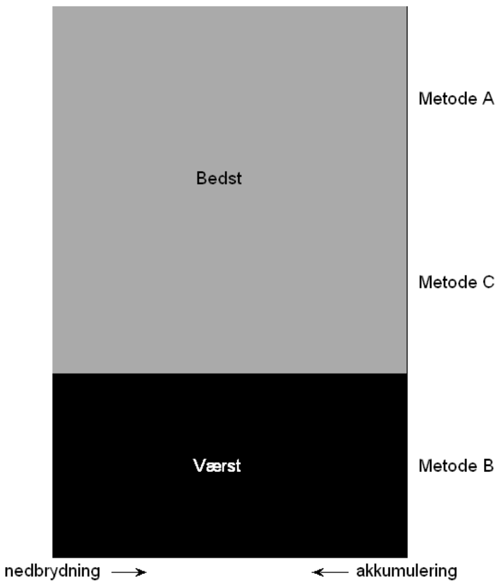
The ranking methodology provides only a preference order, which is based on a qualitative assessment. Thus, the results shown in Figure 3 facilitate the choice between different stormwater treatment options, but cannot be used to calculate actual pollution risks to surface water or groundwater.



(α)



(β)



(γ)

Figure 3 – Ranking of the different example units for compound α, β and γ. The middle line represents the ratio between the significance of degradation and accumulation processes in the unit.

3. Identification and assessment of removal processes for stormwater pollutants

3.1. Selection of stormwater pollutants

Stormwater pollutants can be classified and selected according to their physico-chemical properties and degradability, which define their potential threat to natural waters. A list of selected stormwater pollutants was identified by applying the methodology developed by Eriksson et al. (2005) and combining it with the information available in Scholes et al. (2005a,b). The selected priority pollutants (see Table 8) are grouped in four big families, which are used as indicators for a wider number of water quality parameters:

– *General water quality parameters*: water quality parameters that are commonly used. Only suspended solids (SS) is used in this report. Bacteria can be assumed as suspended particulate matter and they undergo similar removal processes. Else, pH, dissolved oxygen and organic matter may be relevant but they have not been included here.

– *Metals* included in the assessment are cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni) and lead (Pb). These metals have different sorbing mechanisms and behave differently under similar environmental conditions. Therefore their removal potential for similar processes might differ (e.g. adsorption processes).

– *Polycyclic aromatic hydrocarbons (PAHs) indicators*: fluoranthene and pyrene are used to describe the removal potential for PAHs

– *Biocides indicators*: four pesticides (diuron, glyphosate, isoproturon, terbutylazine) are selected to represent biocides that can be identified in stormwater.

Additionally, have two industrial chemicals been selected as urban pollutants, namely di(ethylhexyl) phthalate (DEHP) and methyl tert-butyl ether (MTBE), which are used as softener in plastics and anti-knocking in petrol, respectively. These two (2) substances behave very different in the environment and during treatment. DINP has exchanged DEHP and the knowledge of DINP levels in runoff is very poor. Their sources are relevant for urban areas.

Table 8 – List of selected stormwater priority pollutants used for the assessment of BMP techniques.

General parameters	Justification
SS	Loadings of particulate matter as well as CPH water quality criteria
Metals	
Cd, Cr, Cu, Ni, Pb	Water Framework Directive metals + CPH water quality criteria as well as different fate in BMPs and runoff related sources
PAHs indicators	
fluoranthene and pyrene	Water Framework Directive parameter; scored high for risks in Harrestrup Å (Eriksson et al., 2007) and recently measured in runoff in Copenhagen (Birch et al., 2009). Runoff related sources
DEHP	Sources are relevant for urban areas. It should be noticed that DINP has exchanged DEHP and the knowledge of DINP levels in runoff is very poor.
Biocides indicators	
diuron, glyphosate, isoproturon, terbutylazine	Water Framework Directive parameter; scored high for risks in Harrestrup Å (Eriksson et al., 2007) and recently measured in runoff in Copenhagen by (Birch et al., 2009). Different fate in BMPs and Danish use statistics.
MTBE	

Table 9 – List of selected stormwater pollutants with associated CAS numbers.

General parameters	CAS Number
SS	-
Metals	
Cd	7440-43-9
Cr	7440-47-3
Cu	7440-50-8
Ni	7440-02-0
Pb	7439-92-1
PAHs indicators	
fluoranthene	206-44-0
pyrene	129-00-0
DEHP	117-81-7
Biocides indicators	
diuron	330-54-1
glyphosate	1071-83-6
isoproturon	34123-59-6
terbutylazine	5915-41-3
MTBE	1634-04-4

3.2. Removal processes for stormwater pollutants

The removal potential for the selected stormwater pollutants is evaluated according to their inherent properties. A detailed description of the pollutant fate processes in BMPs is available in (Scholes et al., 2005b; 2008b) and only a short summary is given below.

- *General water quality parameters*: sedimentation and filtration are the major removal processes for suspended particles. Addition of chemicals can enhance flocculation processes and increase the removal rate in BMPs.
- *Metals*: the selected metals are characterized by different binding mechanisms, associated sediment fraction and behaviour under similar environmental conditions. Thus the removal potential for the similar process can vary (e.g. sorption processes). All the metals are bioaccumulated, but the importance of this process is lower when when compared to adsorption to other available substrate for sorption (e.g. sediments, suspended particles). Volatilization and photolysis are not significant for the removal of metals from the water column
- *Polycyclic aromatic hydrocarbons indicators*: the selected organic compounds have high tendency to sorb, due to their generally low solubility and high value of the partition coefficient (K_{oc}). Volatilization plays also a role in the fate of the selected compound in BMPs with aerated surface, while microbial degradation is relatively low both in aerobic an anaerobic condition. The breakdown of PAHs due to photolysis can also be a significant removal process in shallow water BMPs. DEHP has some similar inherent properties as the PAHs (low solubility in water, sorbing, light absorption, high potential for accumulation in fatty tissue etc.) and have, thus, been included.
- *Biocides indicators*: the selected compounds have different inherent properties, thus the removal potential for similar processes will vary. Sorption and related processes (e.g. settling, filtration) is commonly one the major removal processes. Some of the selected compounds are highly biodegradable. Photolysis and volatilization are usually not relevant for the selected pollutants. MTBE is included in this group as it shares common properties with some included biocide indicators (high solubility, low sorption, no light absorption, low potential for accumulation in fatty tissue etc.).

The following tables (Table 10-17) list the relevant parameters for each removal process (see Table 1), along with the overall removal potential assessment, which is summarized in Table 18.

Table 10 – Potential for selected stormwater pollutants removal by microbial degradation (adapted from Scholes et al., 2005b; 2008b).

	Aerobic degradation (half life [d] if available)	Anaerobic degradation (half life [d] if available)	Potential for removal in water*		
			Aerobic	Anaerobic	Overall removal
General parameters					
SS	-	-	Low	Low	Low
Metals					
Cd	N/A	immobilized by sulphate-reducing bacteria	N/A	Low	Low
Cr	N/A	immobilized by sulphate-reducing bacteria	N/A	Low	Low
Cu	N/A	immobilized by sulphate-reducing bacteria	N/A	Low	Low
Ni	N/A	immobilized by sulphate-reducing bacteria	N/A	Low	Low
Pb	N/A	immobilized by sulphate-reducing bacteria	N/A	Low	Low
PAHs indicators					
fluoranthene	2-440	560-5475	Medium	Low	Low/ Medium
pyrene	199-260 (in soil)	**	Low	Low	Low
DEHP	30 (in river water, slower in sediment due to adsorption)	much slower than in aerobic sediments	Medium	Low	Low/ Medium
Biocides indicators					
diuron	70-372	17-995	Low	Low	Low
glyphosate	44 (average in soil)	High	High	High	High
isoproturon	6.5-61	4-15	High	High	High
terbutylazine	30-60	N/A	High	N/A	Medium
MTBE	Low	Low	Low	Low	Low

N/A = Not Applicable

* *Low persistence if half life < 60 d; medium persistence if half life between 60-180 d; high persistence if half-life > 180 d*

** *No field data available, but laboratory data indicates low biodegradability*

Table 11 – Potential for selected stormwater pollutants removal by microbial degradation in water (from Table 10) and soil/groundwater.

	Overall removal in water	Overall removal in soil/groundwater
General parameters		
SS	Low	Low
Metals		
Cd	Low	Low
Cr	Low	Low
Cu	Low	Low
Ni	Low	Low
Pb	Low	Low
PAHs indicators		
fluoranthene	Low/Medium	Low
pyrene	Low	Low
DEHP	Low/Medium	Low
Biocides indicators		
diuron	Low	Low
glyphosate	High	Medium/High
isoproturon	High	Medium/High
terbutylazine	Medium	Low/Medium
MTBE	Low	Low

Table 12 – Potential for selected stormwater pollutants removal by photolysis (adapted from Scholes et al., 2005b; 2008b).

	Half life (range in days)	Potential for removal*
General parameters		
SS	N/A	N/A
Metals		
Cd	N/A	N/A
Cr	N/A	N/A
Cu	N/A	N/A
Ni	N/A	N/A
Pb	N/A	N/A
PAHs indicators		
fluoranthene	21-200	Medium
pyrene	0.68 hr	High
DEHP	Absorbs light > 210 nm, thus can potentially be removed	N/A
Biocides indicators		
diuron	600-1732	Low
glyphosate	Negligible	N/A
isoproturon	1500	Low
terbutylazine	> 40 d	Low
MTBE	does not absorb light with wavelength > 210nm	N/A

N/A = Not Applicable

* *Low if half life > 5 d; medium if half life between 1-5 d; high if half-life < 24 hours*

Table 13 – Potential for selected stormwater pollutants removal by plant uptake (adapted from Scholes et al., 2005b; 2008b).

	Characteristic behaviour (log K_{ow} if available	Potential for removal*
General parameters		
SS	N/A	N/A
Metals		
Cd	Low level of bioaccumulation	Low
Cr	Low level of bioaccumulation	Low
Cu	Low level of bioaccumulation	Low
Ni	Low level of bioaccumulation	Low
Pb	Low level of bioaccumulation	Low
PAHs indicators		
fluoranthene	5.0-5.5	Medium/High
pyrene	5.1	High
DEHP	7.5	High
Biocides indicators		
diuron	2.5-2.7	Low
glyphosate	-4.47	Low
isoproturon	2.5-2.9	Low
terbutylazine	3.1	Medium
MTBE	1.24	Low

N/A = Not Applicable

* *Low bioaccumulation if logKow < 3; medium bioaccumulation if logKow between 3-4.5; high bioaccumulation if logKow > 4.5*

Table 14 – Potential for selected stormwater pollutants removal by volatilization (adapted from Scholes et al., 2005b; 2008b).

	Henry constant (K_H) [atm m^3/mol]	Potential for removal in the water column*	Potential for removal in soil/groundwater*
General parameters			
SS	N/A	N/A	N/A
Metals			
Cd	N/A	N/A	N/A
Cr	N/A	N/A	N/A
Cu	N/A	N/A	N/A
Ni	N/A	N/A	N/A
Pb	N/A	N/A	N/A
PAHs indicators			
fluoranthene	$6.48 \cdot 10^{-6}$-$1.61 \cdot 10^{-5}$	Medium	Low
pyrene	$1.19 \cdot 10^{-3}$	Medium	Low
DEHP	$1.3 \cdot 10^{-7}$-$1.71 \cdot 10^{-5}$	Medium	Low
Biocides indicators			
diuron	$5.05 \cdot 10^{-4}$-$5.1 \cdot 10^{-5}$	Medium	Low
glyphosate	$4.08 \cdot 10^{-19}$	Low	Low
isoproturon	$1.48 \cdot 10^{-10}$-$4.70 \cdot 10^{-9}$	Low	Low
terbutylazine	$3.72 \cdot 10^{-8}$	Low	Low
MTBE	$5.87 \cdot 10^{-4}$	Medium	Low

N/A = Not Applicable

* *Low if $K_H < 10^{-7}$ atm m^3/mol; medium if K_H between 10^{-7}-10^{-3} atm m^3/mol; high if $K_H > 10^{-3}$ atm m^3/mol*

Table 15 – Potential for selected stormwater pollutants removal by adsorption to substrate (direct process) or suspended solids (indirect process) (adapted from Scholes et al., 2005b; 2008b).

	Characteristic behaviour (partition coefficient if available)	Potential for removal in the water column*	Potential for removal in soil/groundwater *
General parameters			
SS	Tendency to flocculate will vary according to existing hydrochemical conditions	Medium	High
Metals			
Cd	predominantly associated with the exchangeable fraction	Low	Medium
Cr	Cr(VI) predominantly associated with the exchangeable fraction	Low	Medium
Cu	Predominantly associated with the organic fraction	Medium	High
Ni	Predominantly associated with the oxide/organic fractions	Medium	High
Pb	Predominantly associated with the oxide/organic/residual fractions	High	High
PAHs indicators			
fluoranthene	K_{oc} = 32359-295121	Medium/High	High
pyrene	K_d = 13060	High	High
DEHP	K_d = 3710	High	High
Biocides indicators			
diuron	K_{oc} = 224-682	Low/Medium	Medium/High
glyphosate	K_d = 24000	High	High
isoproturon	K_{oc} = 124-182	Low/Medium	Medium/High
terbutylazine	K_d = 2.2-20; 103	Low/Medium	Medium/High
MTBE	Low tendency to adsorb	Low	Medium

* *Low adsorption if K_d < 100 or K_{oc} < 100; medium adsorption if K_d between 100-1000 or K_{oc} between 1000-10000; high adsorption if K_d > 1000 or K_{oc} > 100000*

Table 16 – Potential for selected stormwater pollutants removal by precipitation (indirect process) (adapteret fra Scholes et al., 2005b; 2008b).

	Characteristic behaviour (solubility if available [mg/l])	Potential for removal in the water column*
General parameters		
SS	already in solid form	High
Metals		
Cd	1,400,000	Low
Cr	23,000	Medium
Cu	70,600	Medium
Ni	642,000	Low
Pb	6,730	Medium
PAHs indicators		
fluoranthene	0.26	High
pyrene	0.077	High
DEHP	0.041	High
Biocides indicators		
diuron	42	High
glyphosate	12000	Medium
isoproturon	65-70	High
terbutylazine	8.5	High
MTBE	42,000	Medium

** Low solubility if < 100 mg/l; medium solubility if between 100-100,000 mg/l; high solubility if > 100,000. High solubility implies low removal potential and vice versa*

Table 17 – Potential for selected stormwater pollutants removal by settling and filtration (direct processes) due to the combined effect of adsorption to suspended solids and precipitation (indirect process) (adapted from Scholes et al., 2005b; 2008b).

	Characteristic behaviour		Potential for removal
	Tendency to adsorb	Tendency to precipitate	
General parameters			
SS	Medium	High	High
Metals			
Cd	Low	Low	Low
Cr	Low	Medium	Low/Medium
Cu	Medium	Medium	Medium
Ni	Medium	Low	Low/Medium
Pb	High	Medium	Medium/High
PAHs indicators			
fluoranthene	Medium/High	High	High
pyrene	High	High	High
DEHP	High	High	High
Biocides indicators			
diuron	Low/Medium	High	Medium
glyphosate	High	Medium	Medium/High
isoproturon	Low/Medium	High	Medium
terbutylazine	Low/Medium	High	Medium
MTBE	Low	Medium	Low/Medium

Table 18 – Summary of removal potential for the selected stormwater pollutants.

	DEGRADATION				ACCUMULATION			SOIL/GROUNDWATER		
	microbial degradation	**photolysis**	**plant uptake**	**volatilization**	**adsorption to substrate**	**filtration**	**settling**	**adsorption**	**microbial degradation**	**volatilization**
General parameters										
SS	Low	N/A	N/A	N/A	Medium	High	High	High	Low	N/A
Metals										
Cd	Low	N/A	Low	N/A	Low	Low	Low	Medium	Low	N/A
Cr	Low	N/A	Low	N/A	Low	L/M	L/M	Medium	Low	N/A
Cu	Low	N/A	Low	N/A	Medium	L/M	L/M	High	Low	N/A
Ni	Low	N/A	Low	N/A	Medium	Medium	Medium	High	Low	N/A
Pb	Low	N/A	Low	N/A	High	M/H	M/H	High	Low	N/A
PAHs indicators										
fluoranthene	L/M	Medium	M/H	Medium	M/H	High	High	High	Low	Low
pyrene	Low	High	Medium	Medium	High	High	High	High	Low	Low
DEHP	L/M	N/A	High	Medium	High	High	High	High	Low	Low
Biocides indicators										
diuron	Low	Low	Low	Medium	L/M	Medium	Medium	M/H	Low	Low
glyphosate	High	N/A	Low	Low	High	M/H	M/H	High	M/H	Low
isoproturon	High	Low	Low	Low	L/M	L/M	Medium	Medium	M/H	M/H
terbutylazine	Medium	Low	Medium	Low	L/M	L/M	Medium	Medium	M/H	L/M
MTBE	Low	N/A	Low	Medium	Low	Low	L/M	L/M	Medium	Low

L/M = Low/Medium *M/H = Medium/High* *N/A =Not Applicable*

4. Evaluation of removal processes in stormwater BMPs

In this section the assessment of the different pollutant removal processes in BMPs is presented. Table 19 shows the BMPs that were included in the assessment: some units are subdivided into sub-categories, due to different configurations. In fact, different characteristics required a separate assessment of the fate process potential in the specific unit. Other units are lumped into a single category. Different adsorption filters, for example, can be differentiated according to their adsorption capacity for different pollutants. However, the potential for the assessed removal processes is similar, independently of the sorption material. In this phase of the assessment, in fact, only the importance of a certain process (e.g. filtration) is assessed and no considerations are made on the process affinity with a specific compound (e.g. higher sorption capacity of a certain substrate for a certain compound).

Table 19 – List of assessed BMPs with their removal processes.

LAR metoder og rensemetoder	Primary removal processes
Grønne tage	Biological degradation, photolysis, uptake in plants, filtration though growing layer
Opsamling og anvendelse	Biological degradation, volatilization, sedimentation in container
Permeable belægninger	
uden nedsivning	Adsorption to pavement layer
med nedsivning	Adsorption to pavement layer, adsorption to the support layer and soil
Strømning	
over græsflader	Biological degradation, uptake in plants, photolysis, adsorption to cover layer, adsorption to underlying support layer and soil, filtration through soil
over stenflader	Biological degradation, adsorption to cover layer, photolysis, adsorption to underlying support layer and soil, filtration through soil
Regnbede (bioretentionsbed)	Biological degradation, uptake in plants, photolysis, filtration through root zone an underlying soil layer
Bassiner	
Sandfang + åbent tørt græsklædt bassin uden infiltration	Uptake in plants, filtration through plants, sedimentation and adsorption to sediment
Sandfang +åbent græsklædt tørt bassin med infiltration	Uptake in plants, adsorption and filtration through bottom of the basin and soil layer, filtration through plants, sedimentation and adsorption to sediment
Sandfang + lukket betonbassin uden nedsivning	Sedimentation and adsorption to sediment
Sandfang + åbent vådt bassin	Photolysis, uptake in plants, filtration through plants, sedimentation and adsorption to sediment
Render og grøfter	
Naturlige lavninger i terræn med nedsivning (swales)	Uptake in plants, sedimentation and adsorption to sediment, adsorption and filtration through filter material and soil

LAR metoder og rensemetoder	Primary removal processes
Gravet rende med filtermateriale af sand/grus og nedsivning	Sedimentation and adsorption to sediment
Gravet rende med sand/grus samt fordelerrør eller opsamlingsrør (Wadi eller mulden-rigole)	Uptake in plants, sedimentation and adsorption to sediment, adsorption and filtration through filter material and soil
Tætte kanaler eller render udført i beton eller lign uden nedsivning	Sedimentation and adsorption to sediment
Faskiner	Adsorption and filtration through soil, sedimentation and adsorption to sediment
Infiltrationsbrønde	Adsorption and filtration through soil, sedimentation and adsorption to sediment
Drosling af afløb	None
Kantstene og forsinkelse på befæstede arealer	None
Sandfang	Sedimentation and adsorption to sediment
Olieudskiller	
Filtre og sier	Filtration and adsorption to particles
Adsorptionsanlæg	Filtration and adsorption to particles
Forbassiner	
Bassiner med membran og uden beplantning	Biological degradation, sedimentation and adsorption to sediment
Bassiner med membran med beplantning	Biological degradation, uptake in plants, sedimentation and adsorption to sediment

4.1. Degradation processes

Biological degradation

Biological degradation is assumed to be more important in systems that provide high availability of microbial attachment sites (e.g. root systems, substrate) and a sufficient contact time between stormwater and the substrate material. Infiltration systems provides generally a good substrate for microbial growth, but only some have a sufficient stormwater residence time to ensure high removal due to biodegradation. For further details on the criteria used in the evaluation presented in Table 20 see Scholes et al. (2005b).

Table 20 – Potential for microbial degradation in BMPs.

LAR metoder og rensemetoder	Relative importance of biological degradationr
Grønne tage	Medium
Opsamling og anvendelse	Low
Permeable belægninger	
uden nedsivning	Low
med nedsivning	Medium/Low
Strømning	
over græsflader	Medium/Low
over stenflader	Low

LAR metoder og rensemetoder	Relative importance of biological degradationr
Regnbede (bioretentionsbed)	Medium
Bassiner	
Sandfang + åbent tørt græsklædt bassin uden infiltration	Medium/Low
Sandfang +åbent græsklædt tørt bassin med infiltration	Medium
Sandfang + lukket betonbassin uden nedsivning	Low
Sandfang + åbent vådt bassin	Medium/Low
Render og grøfter	
Naturlige lavninger i terræn med nedsivning (swales)	Medium/High
Gravet rende med filtermateriale af sand/grus og nedsivning	Medium/High
Gravet rende med sand/grus samt fordelerrør eller opsamlingsrør (Wadi eller mulden-rigole)	Medium/High
Tætte kanaler eller render udført i beton eller lign uden nedsivning	Low
Faskiner	Medium/Low
Infiltrationsbrønde	Medium/High
Drosling af afløb	Not Applicable
Kantstene og forsinkelse på befæstede arealer	Not Applicable
Sandfang	Not Applicable
Olieudskiller	Not Applicable
Filtre og sier	Not Applicable
Adsorptionsanlæg	Not Applicable
Forbassiner	
Bassiner med membran og uden beplantning	Medium/Low
Bassiner med membran med beplantning	Medium

Volatilization

Volatilization occurs only in units that ensure a sufficient surface exposure and it can take place within the BMP structure (e.g. infiltration units), providing that it is not filled by stormwater (i.e. there is a significant gas phase). Units with wider contact surface between stormwater and atmosphere ensure higher potential for removal by volatilization. For further details on the criteria used in the evaluation presented in Table 21 see Scholes et al. (2005b).

Table 21 – Potential for volatilization in BMPs.

LAR metoder og rensemetoder	Relative importance of fordamning
Grønne tage	Medium/High
Opsamling og anvendelse	Low
Permeable belægninger	
uden nedsivning	Low
med nedsivining	Low
Strømning	
over græsflader	Low/Medium
over stenflader	Low/Medium
Regnbede (bioretentionsbed)	Medium
Bassiner	
Sandfang + åbent tørt græsklædt bassin uden infiltration	Medium
Sandfang +åbent græsklædt tørt bassin med infiltration	Medium
Sandfang + lukket betonbassin uden nedsivning	Low/Medium
Sandfang + åbent vådt bassin	Medium
Render og grøfter	
Naturlige lavninger i terræn med nedsivning (swales)	Medium
Gravet rende med filtermateriale af sand/grus og nedsivning	Medium
Gravet rende med sand/grus samt fordelerrør eller opsamlingsrør (Wadi eller mulden-rigole)	Medium
Tætte kanaler eller render udført i beton eller lign uden nedsivning	Low/Medium
Faskiner	Low
Infiltrationsbrønde	Low/Medium
Drosling af afløb	Not Applicable
Kantstene og forsinkelse på befæstede arealer	Not Applicable
Sandfang	Not Applicable
Olieudskiller	Not Applicable
Filtre og sier	Not Applicable
Adsorptionsanlæg	Not Applicable
Forbassiner	
Bassiner med membran og uden beplantning	Medium
Bassiner med membran med beplantning	Medium

Photolysis

Photolysis is dependant on the exposure of stormwater to sunlight. This process is not relevant in BMPs that rapidly incorporates stormwater into their structure (e.g. infiltration processes). BMPs ensuring wide surface areas ensure higher potential for removal. Also, stormwater residence time plays a role in increasing the exposure time to sunlight. For further details on the criteria used in the evaluation presented in Table 22 see Scholes et al. (2005b).

Table 22 – Potential for photolysis in BMPs.

LAR metoder og rensemetoder	Relative importance of photolysis
Grønne tage	Low/Medium
Opsamling og anvendelse	Low
Permeable belægninger	
uden nedsivning	Low/Medium
med nedsivining	Low
Strømning	
over græsflader	Low/Medium
over stenflader	Low/Medium
Regnbede (bioretentionsbed)	Low/Medium
Bassiner	
Sandfang + åbent tørt græsklædt bassin uden infiltration	Low/Medium
Sandfang +åbent græsklædt tørt bassin med infiltration	Low/Medium
Sandfang + lukket betonbassin uden nedsivning	Not Applicable
Sandfang + åbent vådt bassin	Medium
Render og grøfter	
Naturlige lavninger i terræn med nedsivning (swales)	Low/Medium
Gravet rende med filtermateriale af sand/grus og nedsivning	Low/Medium
Gravet rende med sand/grus samt fordelerrør eller opsamlingsrør (Wadi eller mulden-rigole)	Low/Medium
Tætte kanaler eller render udført i beton eller lign uden nedsivning	Low
Faskiner	Not Applicable
Infiltrationsbrønde	Not Applicable
Drosling af afløb	Not Applicable
Kantstene og forsinkelse på befæstede arealer	Not Applicable
Sandfang	Not Applicable
Olieudskiller	Not Applicable
Filtre og sier	Not Applicable
Adsorptionsanlæg	Not Applicable
Forbassiner	
Bassiner med membran og uden beplantning	Medium
Bassiner med membran med beplantning	Medium

Uptake in plants

This process can take place only in units characterized by the presence of vegetation. Marginal vegetation might be present in units with a permanent water volume. Pollutant uptake can occur in all the units that provide a substrate for algae growth (e.g. filters in infiltration systems). Higher potential is assigned to the units that ensure a longer contact between stormwater and vegetation. For further details on the criteria used in the evaluation presented in Table 23 see Scholes et al. (2005b).

Table 23 – Potential for plant uptake in BMPs.

LAR metoder og rensemetoder	Relativ vigtighed afuptake in plants
Grønne tage	Medium
Opsamling og anvendelse	Not Applicable
Permeable belægninger	
uden nedsivning	Not Applicable
med nedsivining	Low
Strømning	
over græsflader	Low/Medium
over stenflader	Not Applicable
Regnbede (bioretentionsbed)	Medium
Bassiner	
Sandfang + åbent tørt græsklædt bassin uden infiltration	Low/Medium
Sandfang +åbent græsklædt tørt bassin med infiltration	Medium
Sandfang + lukket betonbassin uden nedsivning	Not Applicable
Sandfang + åbent vådt bassin	Medium
Render og grøfter	
Naturlige lavninger i terræn med nedsivning (swales)	Medium/High
Gravet rende med filtermateriale af sand/grus og nedsivning	Medium
Gravet rende med sand/grus samt fordelerrør eller opsamlingsrør (Wadi eller mulden-rigole)	Medium/High
Tætte kanaler eller render udført i beton eller lign uden nedsivning	Not Applicable
Faskiner	Low
Infiltrationsbrønde	Low
Drosling af afløb	Not Applicable
Kantstene og forsinkelse på befæstede arealer	Not Applicable
Sandfang	Not Applicable
Olieudskiller	Not Applicable
Filtre og sier	Not Applicable

LAR metoder og rensemetoder	Relativ vigtighed afuptake in plants
Adsorptionsanlæg	Not Applicable
Forbassiner	
Bassiner med membran og uden beplantning	Not Applicable
Bassiner med membran med beplantning	Medium

4.2. Accumulation processes

Adsorption to substrate

Adsorption to substrate can be differentiated into three categories:

- *Adsorption to artificial substrate*: e.g. the gravel filter in infiltrationsbrønde
- *Adsorption to natural substrate*: e.g. the vegetation in a swale
- *Adsorption to introduced substrate*: e.g. accumulated sediments on the bottom of a vådt basin.

The units ensuring higher contact surface between stormwater and substrate are assumed to have higher potential for adsorption processes. Different constructive characteristics might affect this process (e.g. offering wider contact surface), thus this assessment is based on general assumption on the BMP structure. For further details on the criteria used in the evaluation presented in Table 24 see Scholes et al. (2005b).

Table 24 – Potential for adsorption to substrate in BMPs.

LAR metoder og rensemetoder	Relative importance of adsorption til substrat
Grønne tage	Medium
Opsamling og anvendelse	Low
Permeable belægninger	
uden nedsivning	Medium
med nedsivining	Medium/High
Strømning	
over græsflader	Medium
over stenflader	Low/Medium
Regnbede (bioretentionsbed)	Medium
Bassiner	
Sandfang + åbent tørt græsklædt bassin uden infiltration	Medium
Sandfang +åbent græsklædt tørt bassin med infiltration	Medium/High
Sandfang + lukket betonbassin uden nedsivning	Low
Sandfang + åbent vådt bassin	Low/Medium

LAR metoder og rensemetoder	Relative importance of adsorption til substrat
Render og grøfter	
Naturlige lavninger i terræn med nedsivning (swales)	Medium/High
Gravet rende med filtermateriale af sand/grus og nedsivning	Medium/High
Gravet rende med sand/grus samt fordelerrør eller opsamlingsrør (Wadi eller mulden-rigole)	Medium/High
Tætte kanaler eller render udført i beton eller lign uden nedsivning	Low/Medium
Faskiner	Medium
Infiltrationsbrønde	Medium/High
Drosling af afløb	Not Applicable
Kantstene og forsinkelse på befæstede arealer	Not Applicable
Sandfang	Low
Olieudskiller	Low
Filtre og sier	Medium/High
Adsorptionsanlæg	High
Forbassiner	
Bassiner med membran og uden beplantning	Medium
Bassiner med membran med beplantning	Medium/High

Filtration

Filtration is the removal of particulate pollutants by the passage of stormwater through a porous substrate or a hydraulic barrier which acts as a sieve. Units characterized by high filtration substrate (e.g. permeable belægninger) have higher score for this process. The grain size is an important criterion in the BMP evaluation, as coarser materials ensure a lower level of filtration. Surface vegetation can provide a hydraulic barrier that can enhance filtration, but the contact time between vegetation and stormwater should be taken into account. Concrete constructions are assumed to have a negligible filtration effect. For further details on the criteria used in the evaluation presented in Table 25 see Scholes et al. (2005b).

Table 25 – Potential for filtering in BMPs.

LAR metoder og rensemetoder	Relative importance of filtrering
Grønne tage	Low/Medium
Opsamling og anvendelse	Not Applicable
Permeable belægninger	
uden nedsivning	High
med nedsivining	High
Strømning	
over græsflader	Low/Medium

LAR metoder og rensemetoder	Relative importance of filtrering
over stenflader	Low
Regnbede (bioretentionsbed)	Medium
Bassiner	
Sandfang + åbent tørt græsklædt bassin uden infiltration	Low
Sandfang +åbent græsklædt tørt bassin med infiltration	Medium
Sandfang + lukket betonbassin uden nedsivning	Not Applicable
Sandfang + åbent vådt bassin	Low
Render og grøfter	
Naturlige lavninger i terræn med nedsivning (swales)	Medium
Gravet rende med filtermateriale af sand/grus og nedsivning	Medium
Gravet rende med sand/grus samt fordelerrør eller opsamlingsrør (Wadi eller mulden-rigole)	Medium
Tætte kanaler eller render udført i beton eller lign uden nedsivning	Not Applicable
Faskiner	Low/Medium
Infiltrationsbrønde	Medium/High
Drosling af afløb	Not Applicable
Kantstene og forsinkelse på befæstede arealer	Not Applicable
Sandfang	Not Applicable
Olieudskiller	Not Applicable
Filtre og sier	Medium
Adsorptionsanlæg	High
Forbassiner	
Bassiner med membran og uden beplantning	Not Applicable
Bassiner med membran med beplantning	Low

Sedimentation

As explained in Section 2.1, the potential for sedimentation of a specific pollutant is estimated by combining the propensity to absorb to particulate material and to precipitate. In BMPs the importance of settling process is dependent on the hydraulic residence time and the permanent water volume. Longer residence time and/or bigger permanent water volume enhances the removal of finer particles. For further details on the criteria used in the evaluation presented in Table 26 see Scholes et al. (2005b).

Table 26 – Potential for sedimentation in BMPs.

LAR metoder og rensemetoder	Relative importance of sedimentation
Grønne tage	Low
Opsamling og anvendelse	Low
Permeable belægninger	
uden nedsivning	Low
med nedsivining	Low
Strømning	
over græsflader	Low
over stenflader	Low
Regnbede (bioretentionsbed)	Medium/High
Bassiner	
Sandfang + åbent tørt græsklædt bassin uden infiltration	Medium/High
Sandfang +åbent græsklædt tørt bassin med infiltration	Medium/High
Sandfang + lukket betonbassin uden nedsivning	Medium/High
Sandfang + åbent vådt bassin	High
Render og grøfter	
Naturlige lavninger i terræn med nedsivning (swales)	Low/Medium
Gravet rende med filtermateriale af sand/grus og nedsivning	Low/Medium
Gravet rende med sand/grus samt fordelerrør eller opsamlingsrør (Wadi eller mulden-rigole)	Low/Medium
Tætte kanaler eller render udført i beton eller lign uden nedsivning	Low
Faskiner	Low/Medium
Infiltrationsbrønde	Low/Medium
Drosling af afløb	Not Applicable
Kantstene og forsinkelse på befæstede arealer	Not Applicable
Sandfang	Medium/High
Olieudskiller	Not Applicable
Filtre og sier	Low
Adsorptionsanlæg	Not Applicable
Forbassiner	
Bassiner med membran og uden beplantning	Medium/High
Bassiner med membran med beplantning	High

4.3. Interaction with soil/groundwater

As explained in Section 2.1, the impact of each BMP on the groundwater cannot be evaluated, as the impact is strongly dependant on site-specific characteristics. Table 27 shows the logical variable used in the final assessment to consider if the BMP is interacting soil/groundwater. Table 28 presents a summary of the relative importance of the various fate processes for each of the considered BMP units.

Table 27 – Interaction of BMPs with soil/groundwater.

LAR metoder og rensemetoder	Interaction with soil/groundwater
Grønne tage	No
Opsamling og anvendelse	No
Permeable belægninger	
uden nedsivning	No
med nedsivining	Yes
Strømning	
over græsflader	Yes
over stenflader	Yes
Regnbede (bioretentionsbed)	Yes
Bassiner	
Sandfang + åbent tørt græsklædt bassin uden infiltration	No
Sandfang +åbent græsklædt tørt bassin med infiltration	Yes
Sandfang + lukket betonbassin uden nedsivning	No
Sandfang + åbent vådt bassin	No
Render og grøfter	
Naturlige lavninger i terræn med nedsivning (swales)	Yes
Gravet rende med filtermateriale af sand/grus og nedsivning	Yes
Gravet rende med sand/grus samt fordelerrør eller opsamlingsrør (Wadi eller mulden-rigole)	Yes
Tætte kanaler eller render udført i beton eller lign uden nedsivning	No
Faskiner	Yes
Infiltrationsbrønde	Yes
Drosling af afløb	No
Kantstene og forsinkelse på befæstede arealer	No
Sandfang	No
Olieudskiller	No
Filtre og sier	No
Adsorptionsanlæg	No
Forbassiner	
Bassiner med membran og uden beplantning	No
Bassiner med membran med beplantning	No

Table 28 – Summary of removal processes potential in BMPs.

Treatment	DEGRADATION				ACCUMULATION		
	microbial degradation	volatilization	photolysis	plant uptake	settling	adsorption to substrate	filtration
Grønne tage	Medium	Medium/High	Low/Medium	Medium	Low	Medium	Low/Medium
Opsamling og anvendelse	Low	Low	Low	N/A	Low	N/A	N/A
Permeable belægninger							
uden nedsivning	Low	Low	Low/Medium	N/A	Low	Medium	High
med nedsivining	Low/Medium	Low	Low	Low	Low	Medium/High	High
Strømning							
over græsflader	Low/Medium	Low/Medium	Low/Medium	Low/Medium	Low	Medium	Low/Medium
over stenflader	Low	Low/Medium	Low/Medium	N/A	Low	Low/Medium	Low
Regnbede (bioretentionsbed)	Medium	Medium	Low/Medium	Medium	Medium/High	Medium	Medium
Bassiner							
Sandfang + åbent tørt græsklædt bassin uden infiltration	Low/Medium	Medium	Low/Medium	Low/Medium	Medium/High	Medium	Low
Sandfang +åbent græsklædt tørt bassin med infiltration	Medium	Medium	Low/Medium	Medium	Medium/High	Medium/High	Medium
Sandfang + lukket betonbassin uden nedsivning	Low	Low/Medium	N/A	N/A	Medium/High	Low	N/A
Sandfang + åbent vådt bassin	Low/Medium	Medium	Medium	Medium	High	Low/Medium	Low
Render og grøfter							
Naturlige lavninger i terræn med nedsivning (swales)	Medium/High	Medium	Low/Medium	Medium/High	Low/Medium	Medium/High	Medium
Gravet rende med filtermateriale af sand/grus og nedsivning	Medium/High	Medium	Low/Medium	Medium	Low/Medium	Medium/High	Medium

Treatment	**DEGRADATION**				**ACCUMULATION**		
	microbial degradation	**volatilization**	**photolysis**	**plant uptake**	**settling**	**adsorption to substrate**	**filtration**
Gravet rende med sand/grus samt fordelerrør eller opsamlingsrør (Wadi eller mulden-rigole)	Medium/High	Medium	Low/Medium	Medium/High	Low/Medium	Medium/High	Medium
Tætte kanaler eller render udført i beton eller lign uden nedsivning	Low	Low/Medium	Low	N/A	Low	Low/Medium	N/A
Faskiner	Low/Medium	Low	N/A	Low	Low/Medium	Medium	Low/Medium
Infiltrationsbrønde	Medium/High	Low/Medium	N/A	Low	Low/Medium	Medium/High	Medium/High
Drosling af afløb	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Kantstene og forsinkelse på befæstede arealer	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Sandfang	N/A	N/A	N/A	N/A	Medium/High	Low	N/A
Olieudskiller	N/A	N/A	N/A	N/A	N/A	Low	N/A
Filtre og sier	N/A	N/A	N/A	N/A	Low	Medium/High	Medium
Adsorptionsanlæg	N/A	N/A	N/A	N/A	N/A	High	High
Forbassiner							
Bassiner med membran og uden beplantning	Low/Medium	Medium	Medium	N/A	High	Medium	N/A
Bassiner med membran med beplantning	Medium	Medium	Medium	Medium	High	Medium/High	Low

N/A = Not Applicable

5 Evaluation of the selected BMPs

In this Chapter all the datasheets and results for each of the analyzed BMPs defined in Table 19 are listed. Each sheet is the results of the combination of the information from Chapter 3 and 4, which is performed according to the methodology described in Chapter 2.

The following graphs show the ranking of the different BMPs for the four compound groups that are described in Section 3.1. This evaluation includes the potential impact on groundwater.

In Sections from 5.1 to 5.25, the ranking position for each single BMP is highlighted, along with a table listing the potential importance for the assessed removal processes. The table also lists some of the pollutants groups with higher potential to be removed in that unit (i.e. the pollutants with higher removal potential for the more important processes of the unit). The ranking position is estimated both considering the impact on groundwater (left column – calculated by using Eq. 2) and without impact on groundwater (right column – calculated by applying Eq. 1).

The presence of a double ranking enables the final user to identify the more appropriate stormwater treatment option according to the groundwater protection requirements that exist in the study area.

Figure 4 – Ranking of BMPs for the removal of TSS.

Figure 5 – Ranking of BMPs for the removal of metals (Cd, Cr, Cu, Ni, Pb).

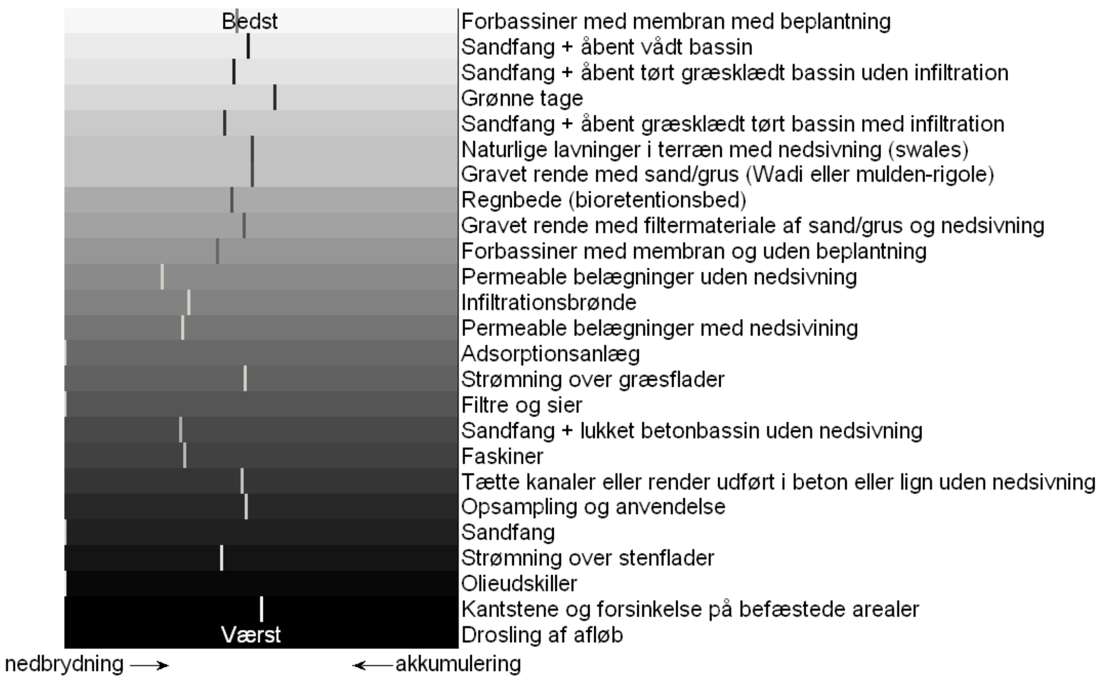


Figure 6 – Ranking of BMPs for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

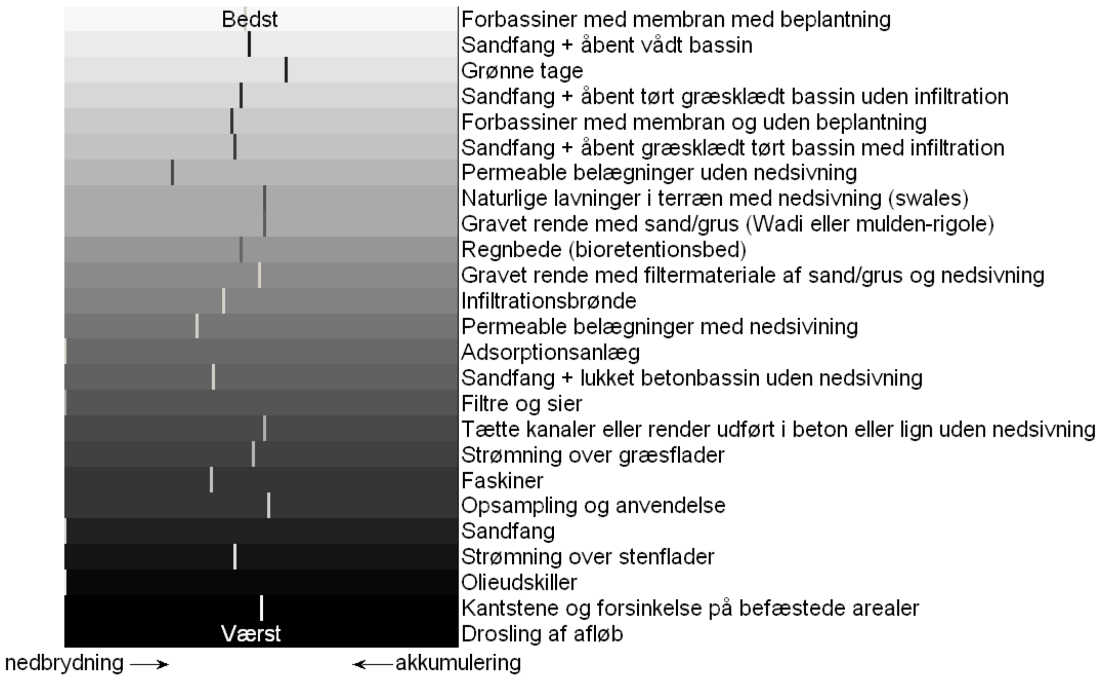


Figure 7 – Ranking of BMPs for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.1 Grønne tage

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Medium	PAHs, Biocides
Fordampning	Medium/Høj	
Fotolyse	Lav/Medium	
Optag i planter	Medium	
Adsorption til substrat	Medium	
Filtrering	Lav/Medium	
Sedimentation	Lav	
Processer i jord og grundvand	Nej	

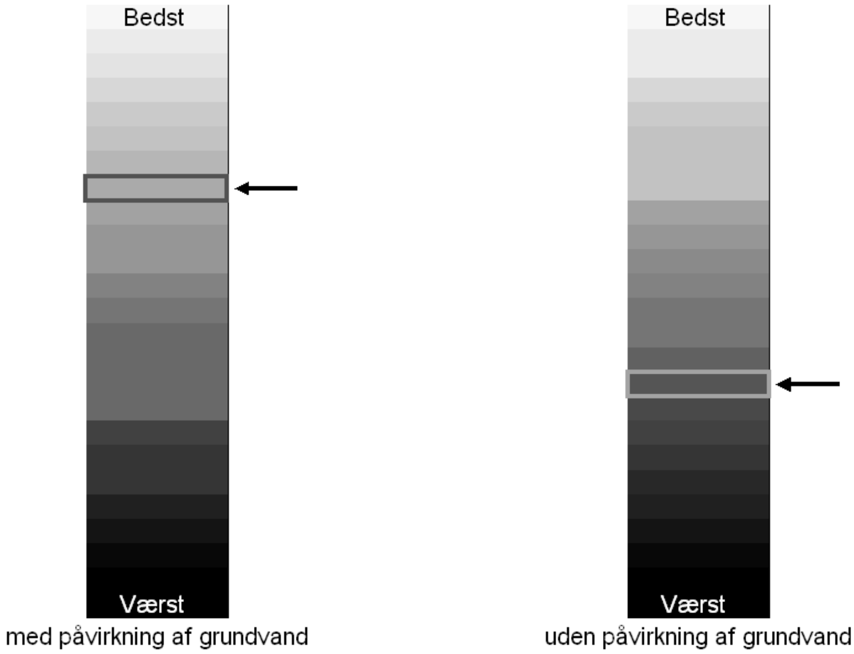


Figure 8 – Ranking for the removal of TSS.

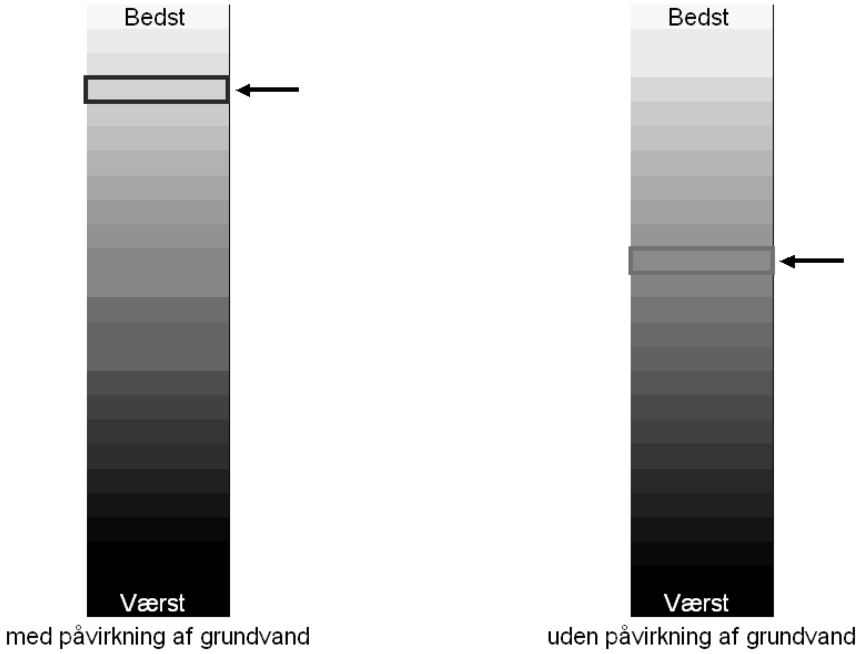


Figure 9 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

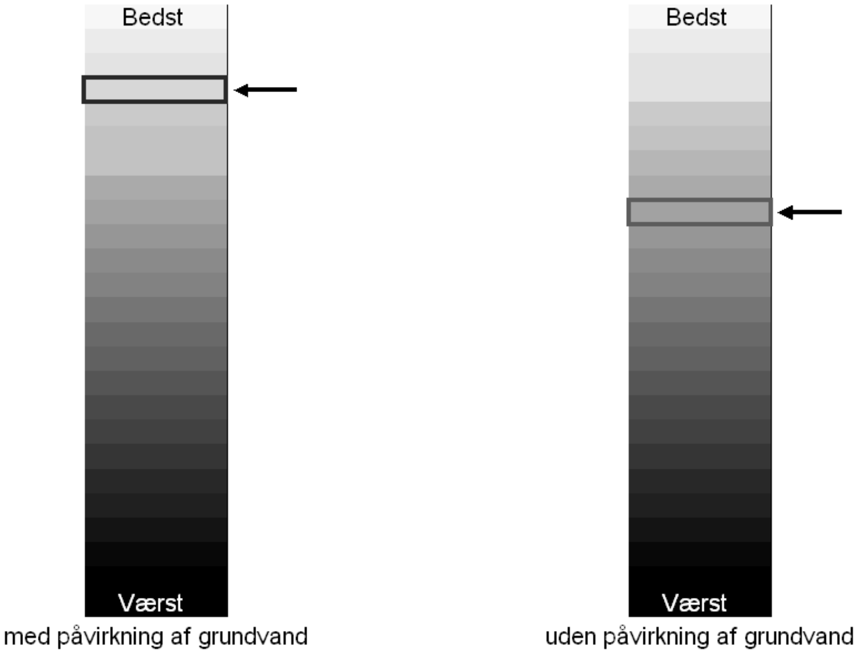


Figure 10 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

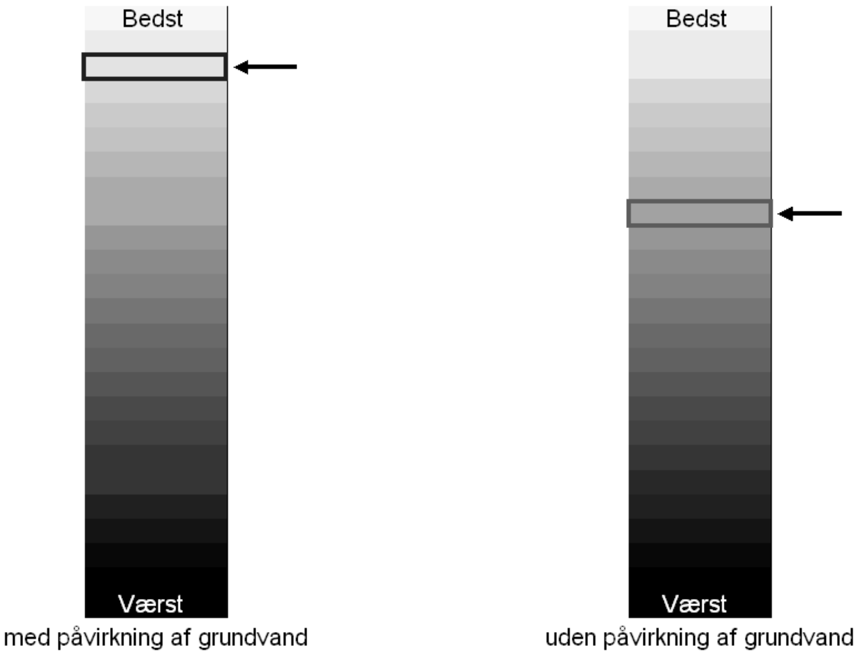


Figure 11 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.2 *Opsamling og anvendelse*

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Lav	Suspended Solids, metals, PAHs, biocides
Fordampning	Lav	
Fotolyse	Lav	
Optag i planter	Lav	
Adsorption til substrat	Lav	
Filtrering	Lav	
Sedimentation	Lav	
Processer i jord og grundvand	Ja	

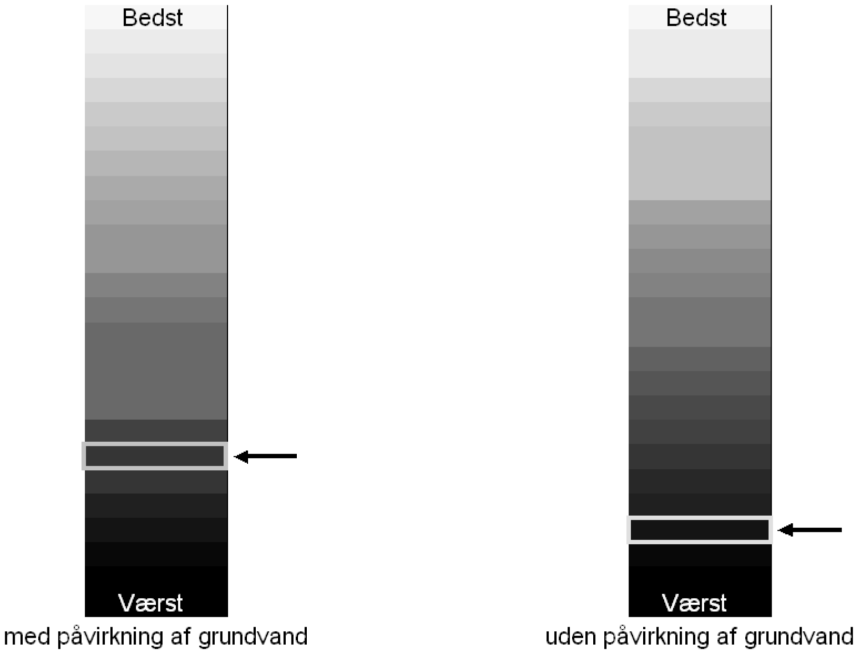


Figure 12 – Ranking for the removal of TSS.

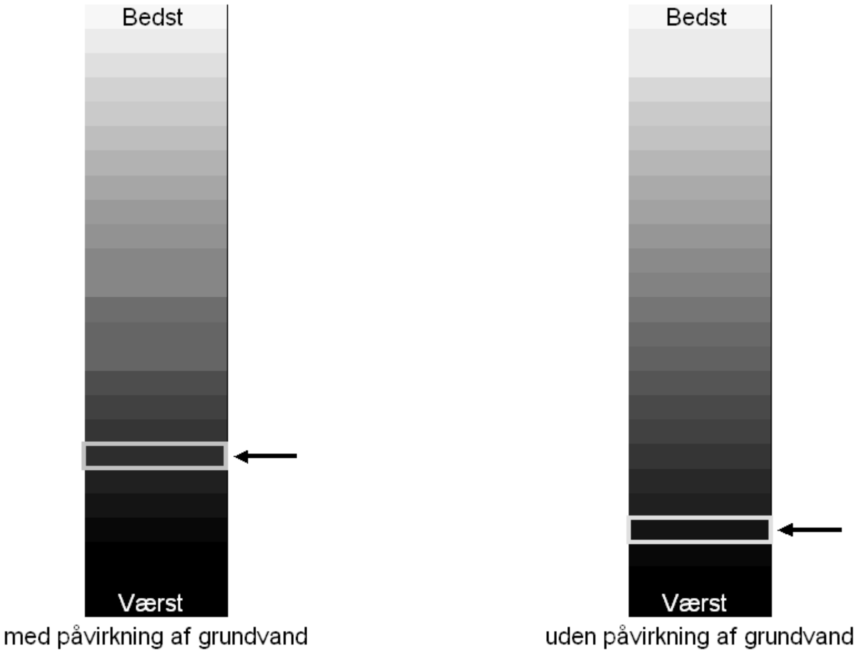


Figure 13 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

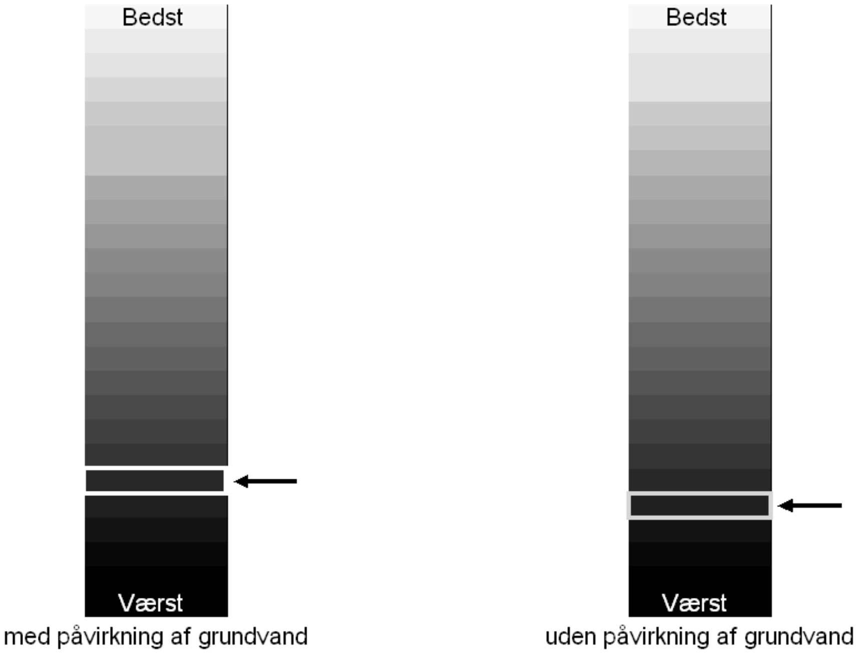


Figure 14 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

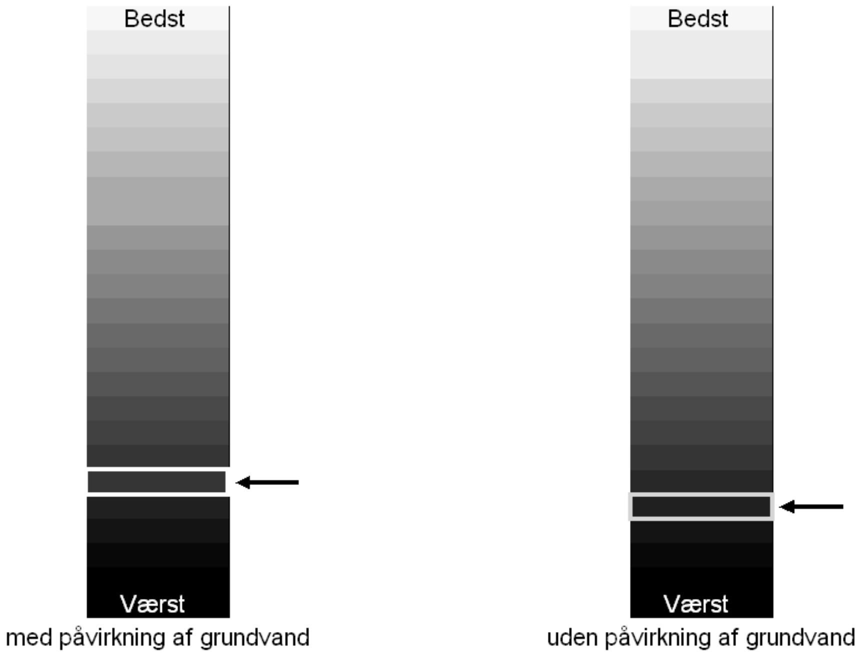


Figure 15 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.3 *Permeable belægninger uden nedvisning*

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Lav	Suspended Solids, PAHs
Fordampning	Lav	
Fotolyse	Lav/Medium	
Optag i planter	Ikke Anvendlig	
Adsorption til substrat	Medium	
Filtrering	Høj	
Sedimentation	Lav	
Processer i jord og grundvand	Nej	

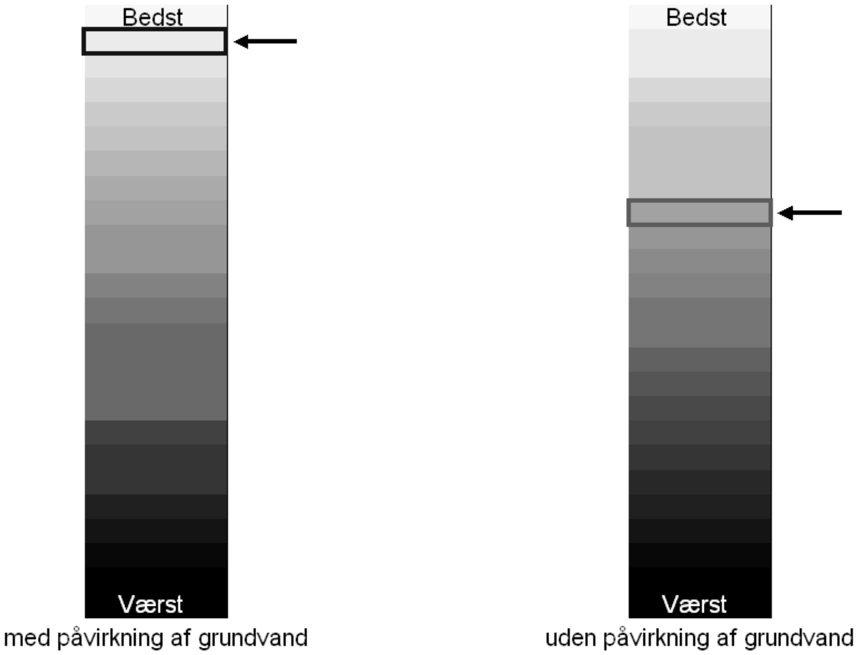


Figure 16 – Ranking for the removal of TSS.

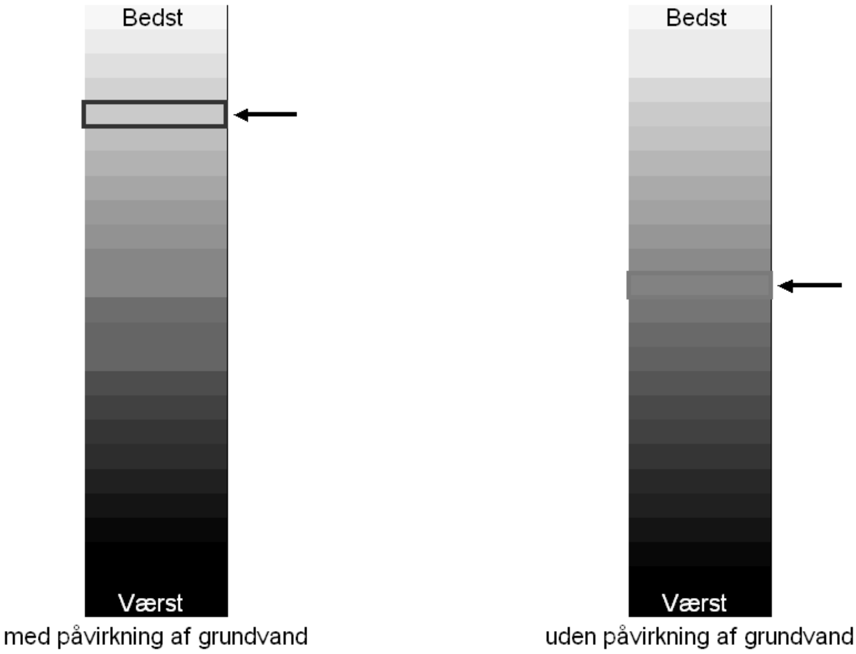


Figure 17 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

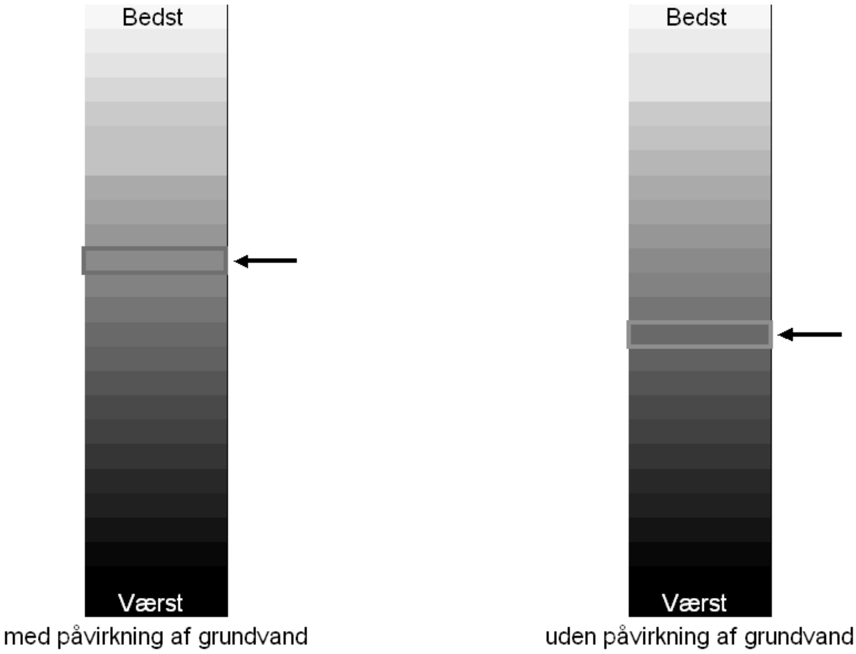


Figure 18 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

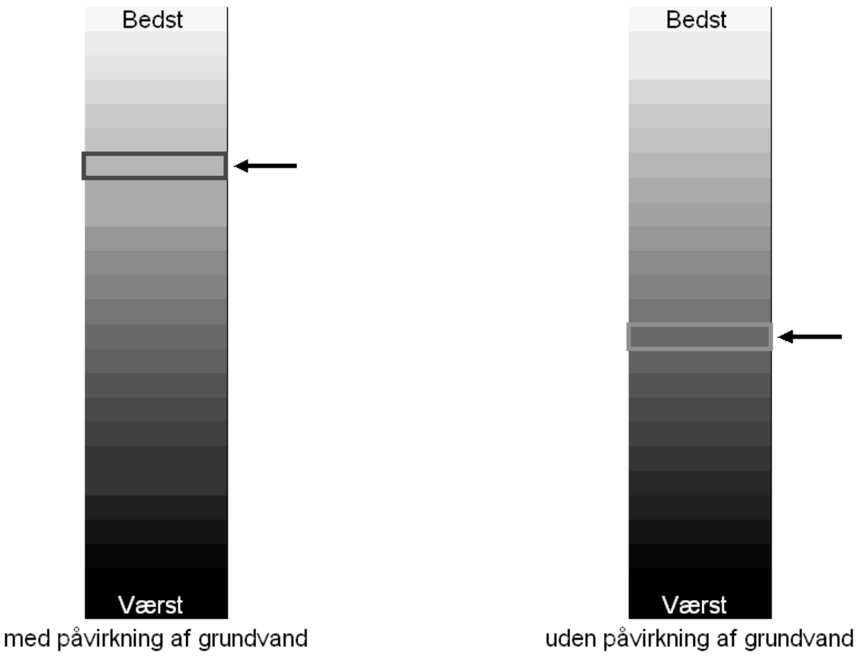


Figure 19 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.4 Permeable belægninger med nedvisning

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Lav/Medium	Suspended Solids, PAHs
Fordampning	Lav	
Fotolyse	Lav	
Optag i planter	Lav	
Adsorption til substrat	Medium/Høj	
Filtrering	Høj	
Sedimentation	Lav	
Processer i jord og grundvand	Ja	

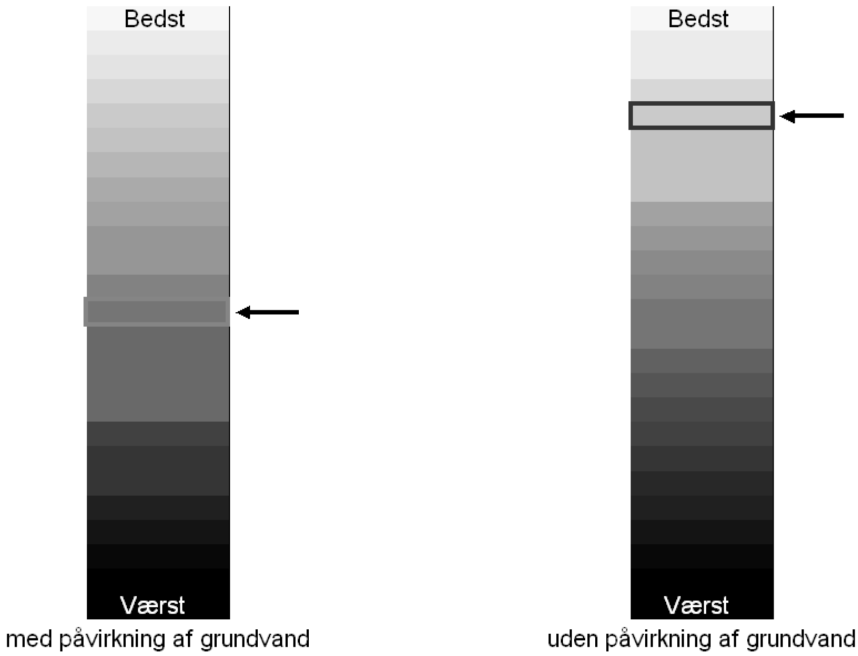


Figure 20 – Ranking for the removal of TSS.

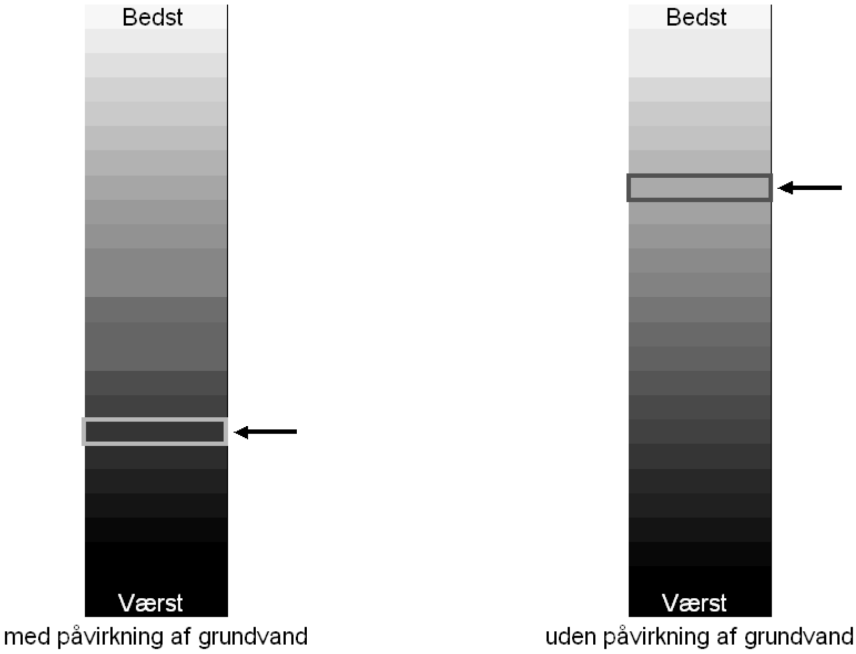


Figure 21 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

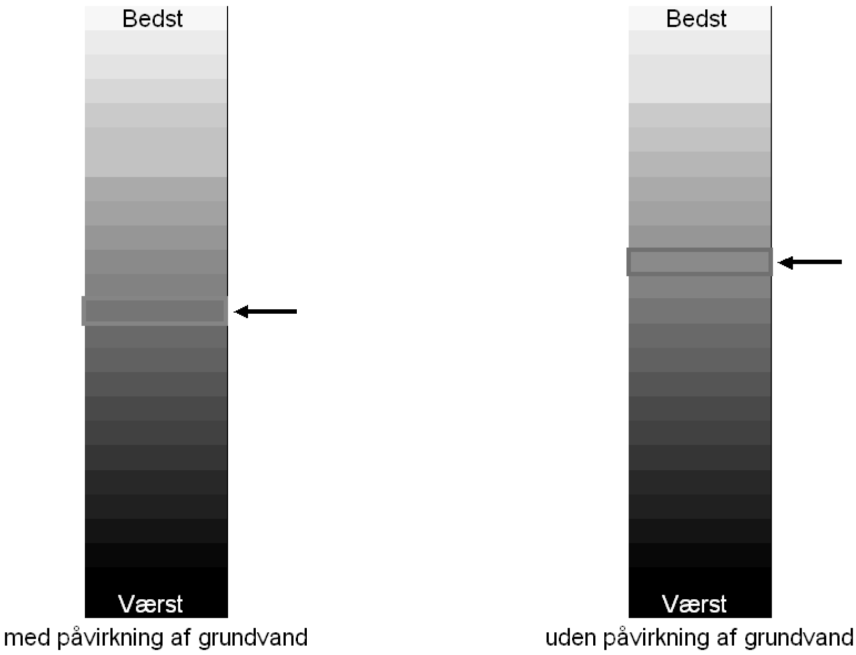


Figure 22 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

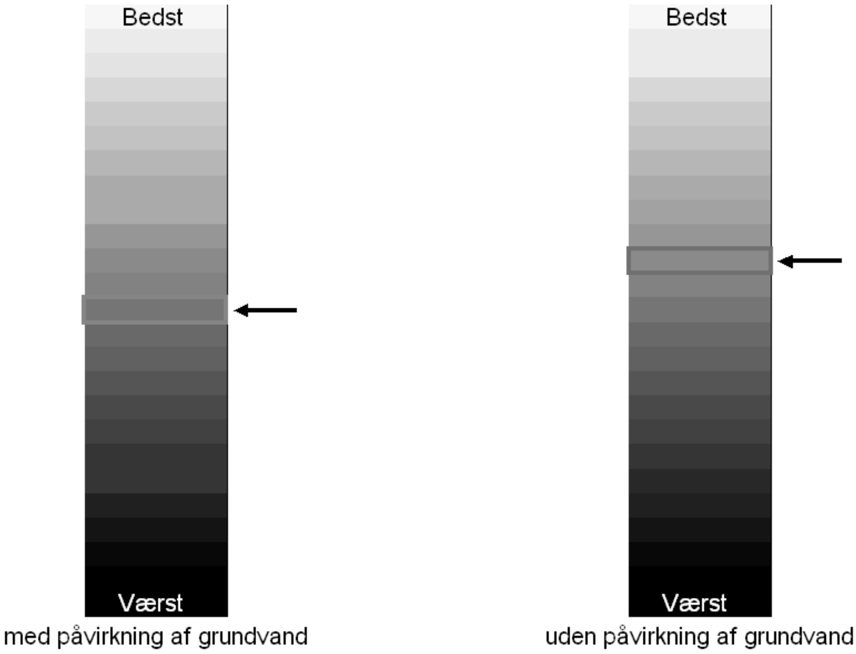


Figure 23 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.5 *Strømning over græsflader*

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Lav/Medium	Metals, PAHs
Fordampning	Lav/Medium	
Fotolyse	Lav/Medium	
Optag i planter	Lav/Medium	
Adsorption til substrat	Medium	
Filtrering	Lav/Medium	
Sedimentation	Lav	
Processer i jord og grundvand	Ja	

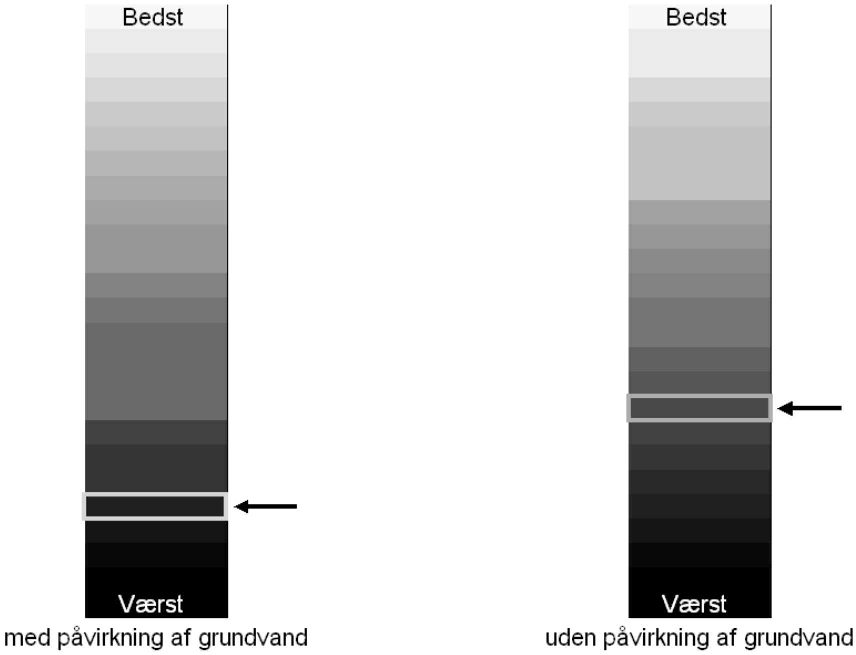


Figure 24 – Ranking for the removal of TSS

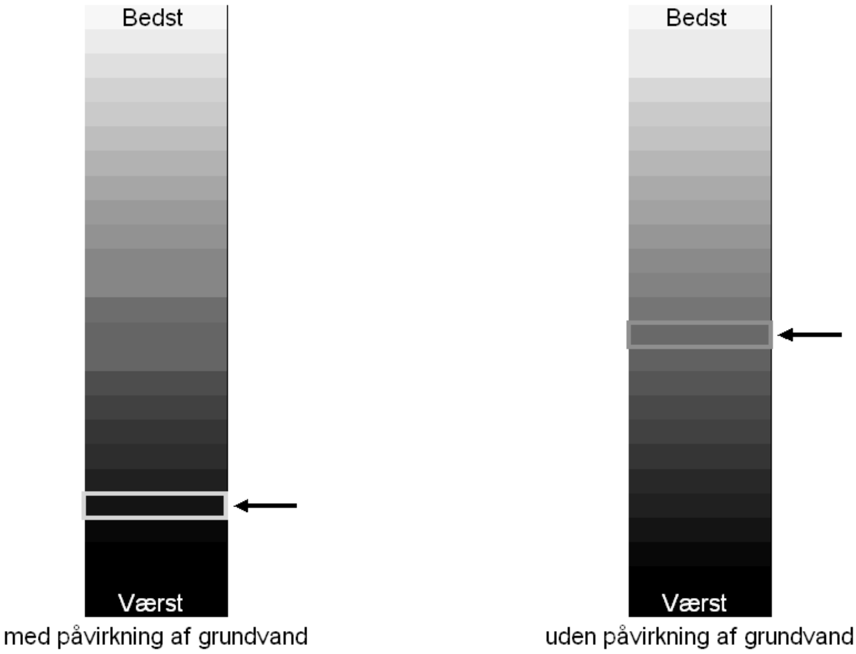


Figure 25 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

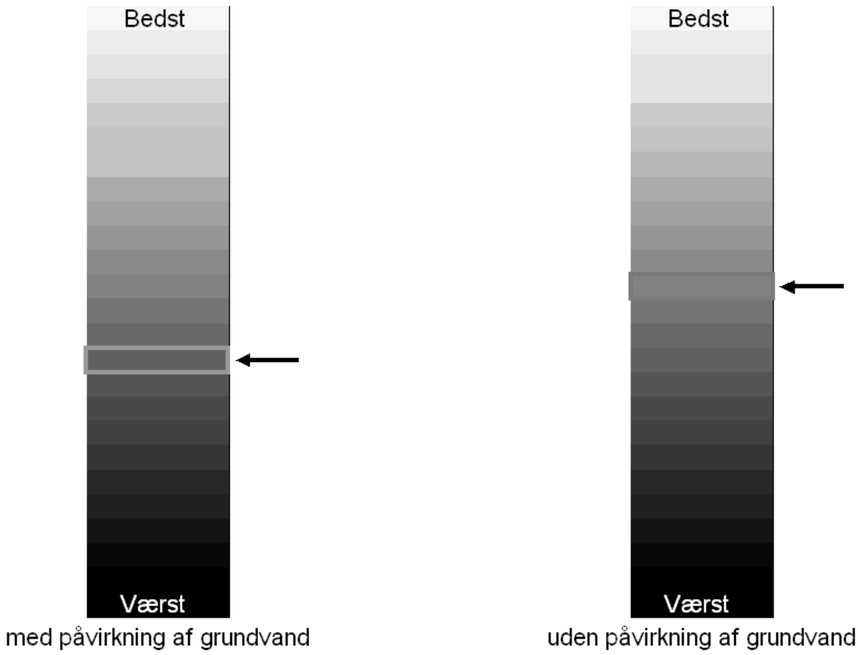


Figure 26 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

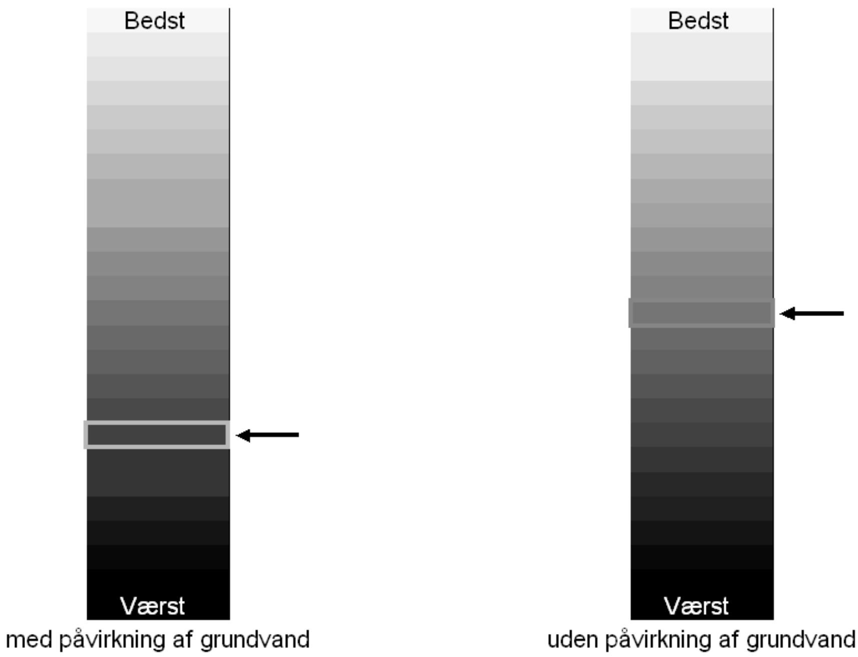


Figure 27 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.6 *Strømning over stenflader*

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Lav	PAH
Fordampning	Lav/Medium	
Fotolyse	Lav/Medium	
Optag i planter	Ikke Anvendelig	
Adsorption til substrat	Lav/Medium	
Filtrering	Lav	
Sedimentation	Lav	
Processer i jord og grundvand	Ja	

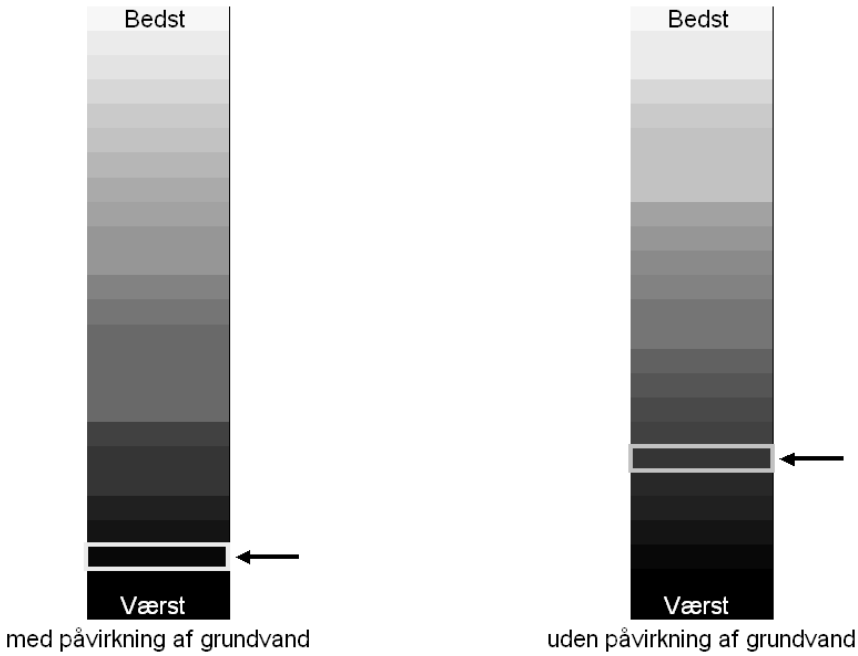


Figure 28 – Ranking for the removal of TSS

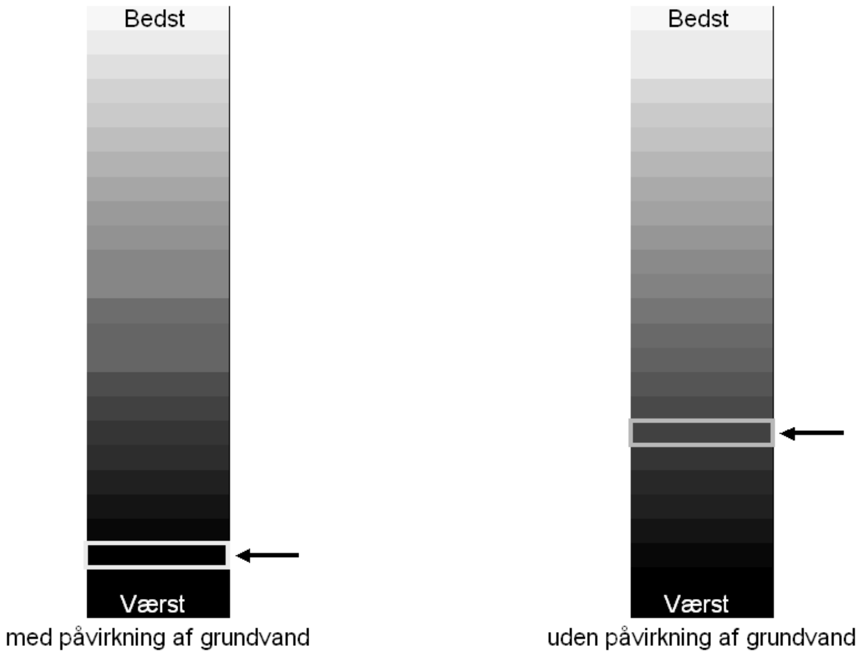


Figure 29 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

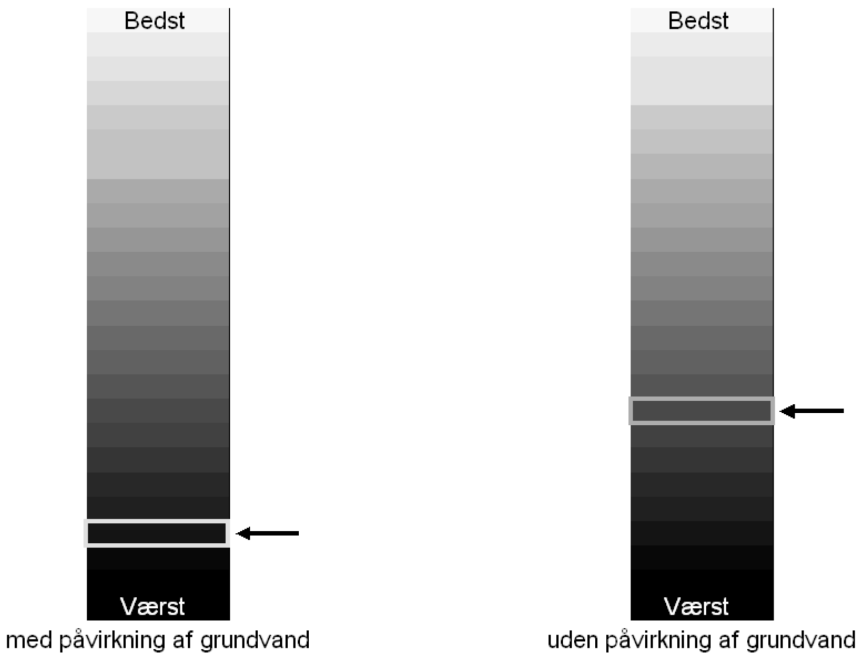


Figure 30 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

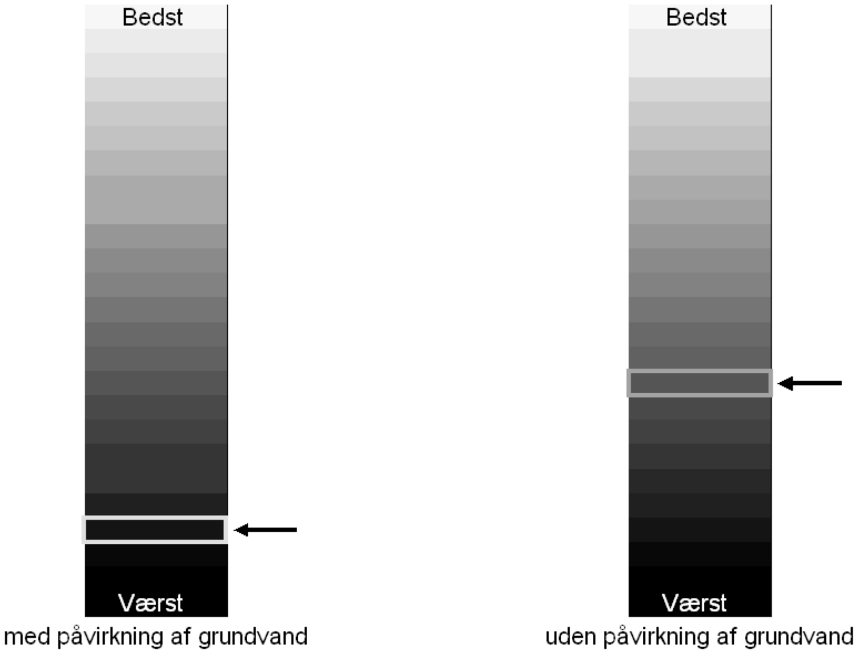


Figure 31 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.7 Regnbede (bioretentionsbed)

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Medium	Suspended Solids, PAH
Fordampning	Medium	
Fotolyse	Lav/Medium	
Optag i planter	Medium	
Adsorption til substrat	Medium	
Filtrering	Medium	
Sedimentation	Medium/Høj	
Processer i jord og grundvand	Ja	

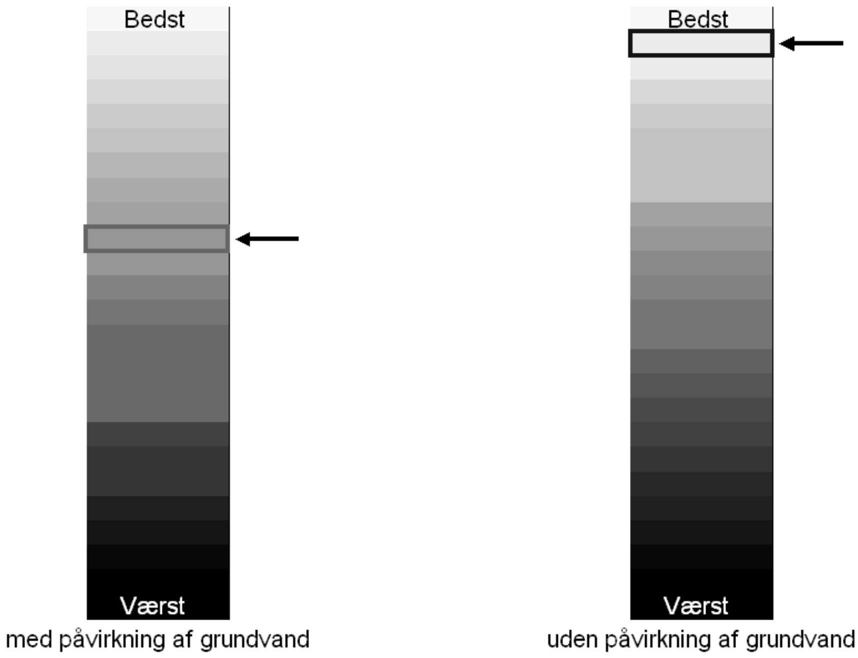


Figure 32 – Ranking for the removal of TSS

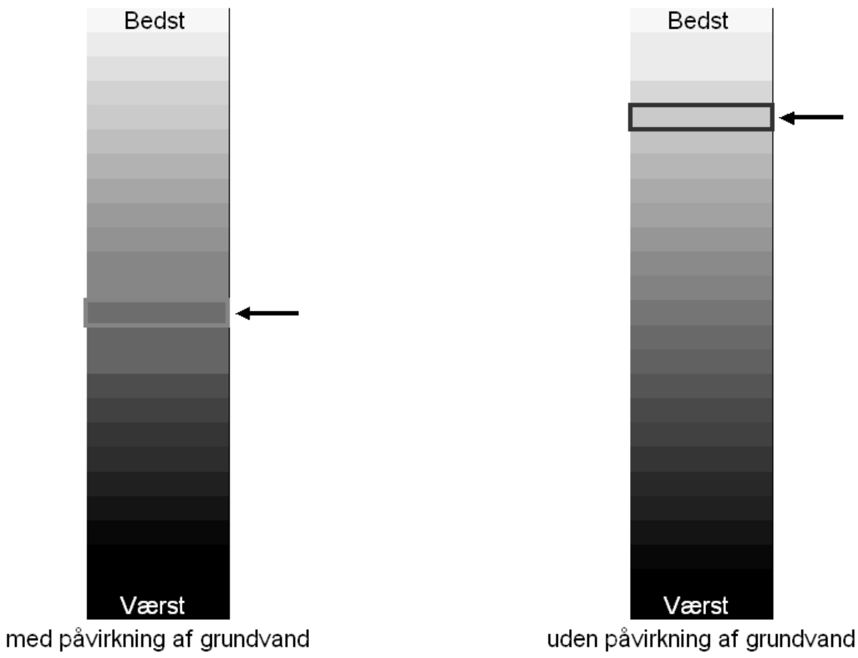


Figure 33 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

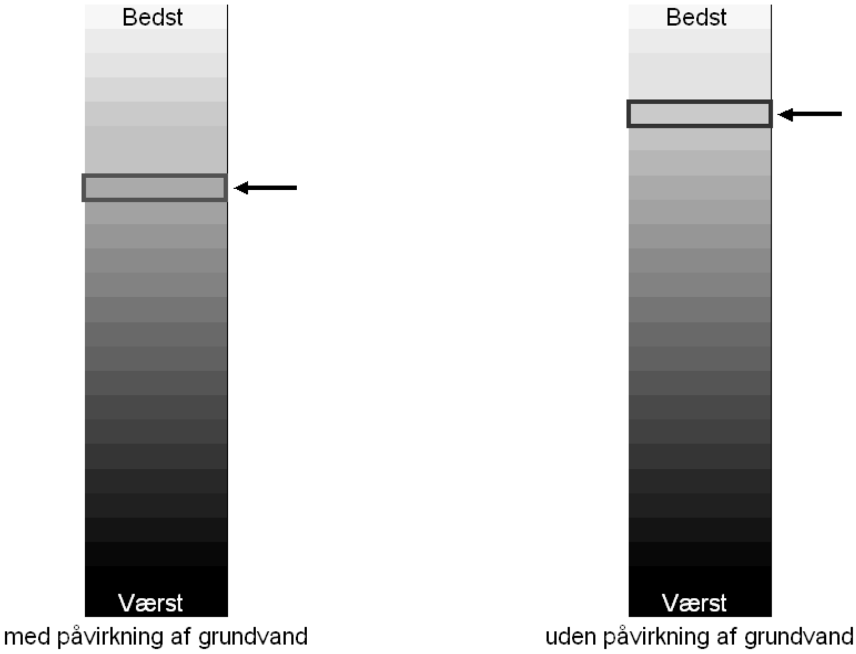


Figure 34 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

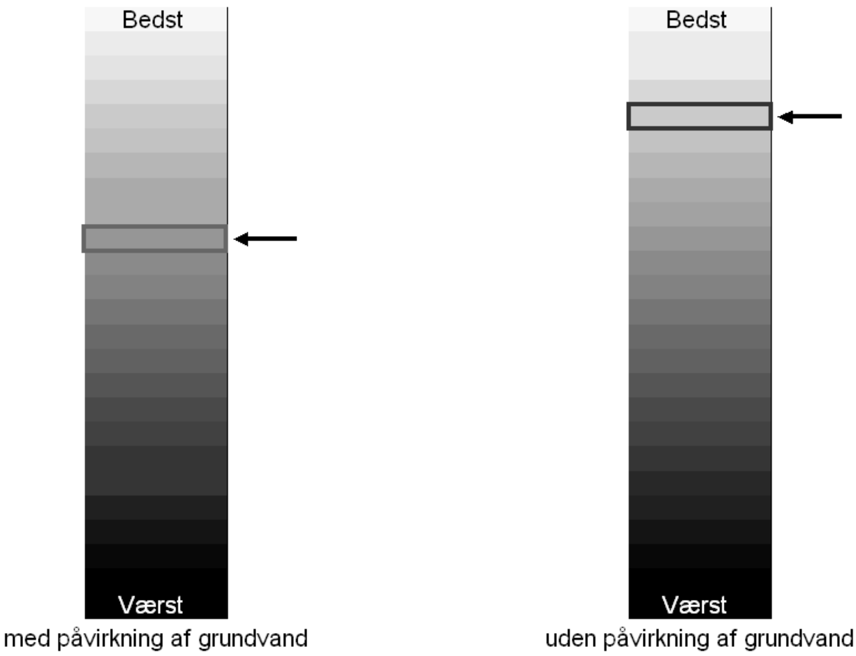


Figure 35 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.8 Bassiner - Sandfang + åbent tørt græsklædt bassin uden infiltration

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Lav/Medium	Suspended Solids, PAH
Fordampning	Medium	
Fotolyse	Lav/Medium	
Optag i planter	Lav/Medium	
Adsorption til substrat	Medium	
Filtrering	Lav	
Sedimentation	Medium/Høj	
Processer i jord og grundvand	Nej	

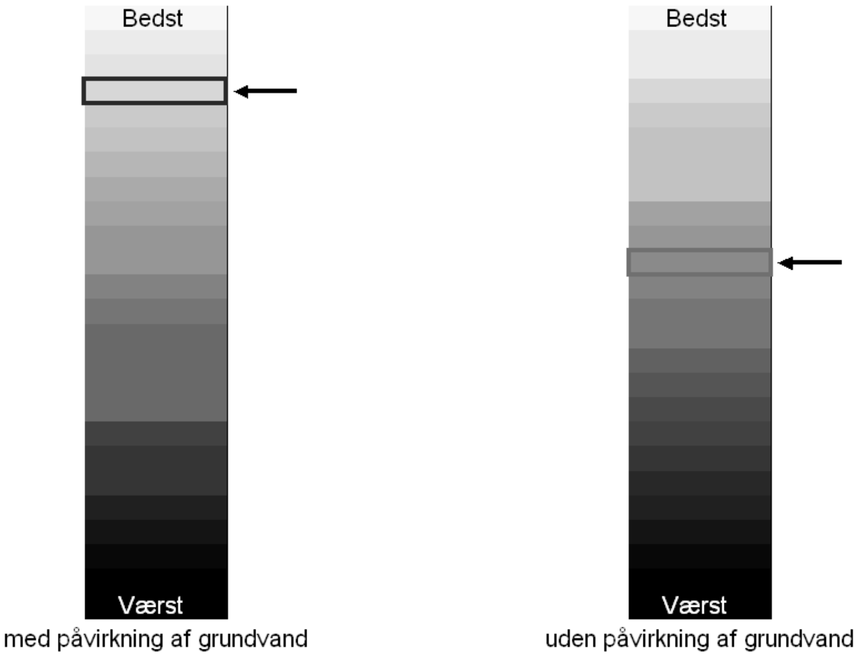


Figure 36 – Ranking for the removal of TSS

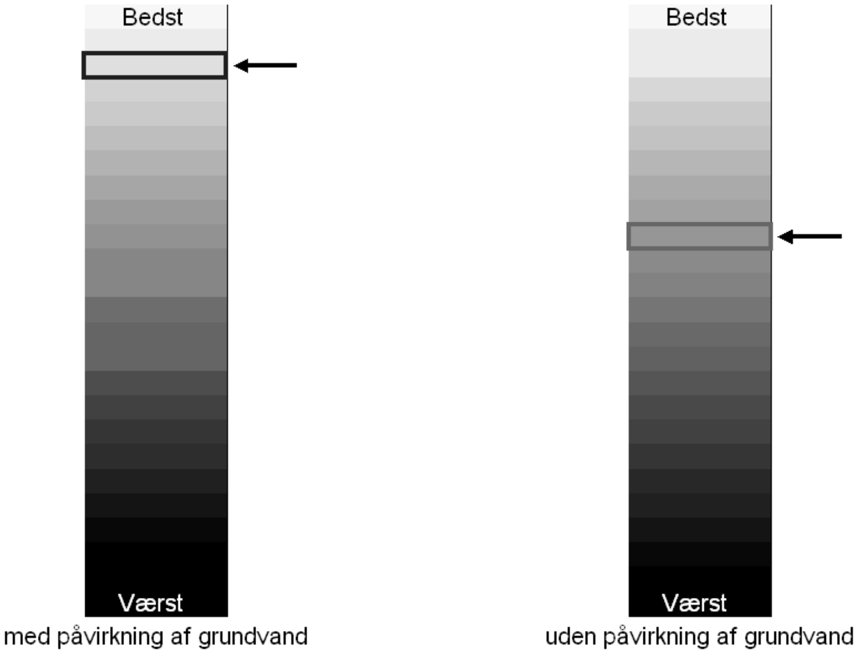


Figure 37 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

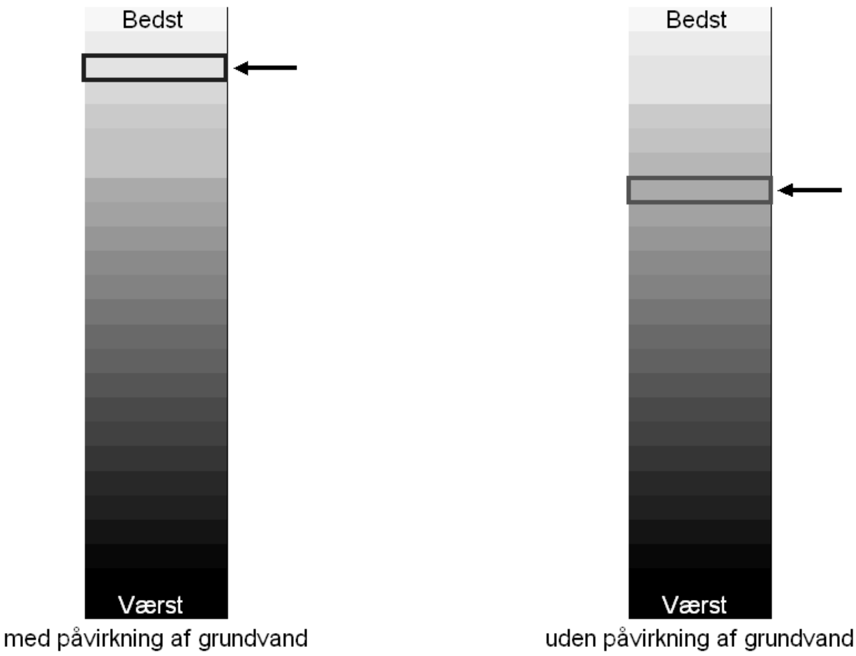


Figure 38 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

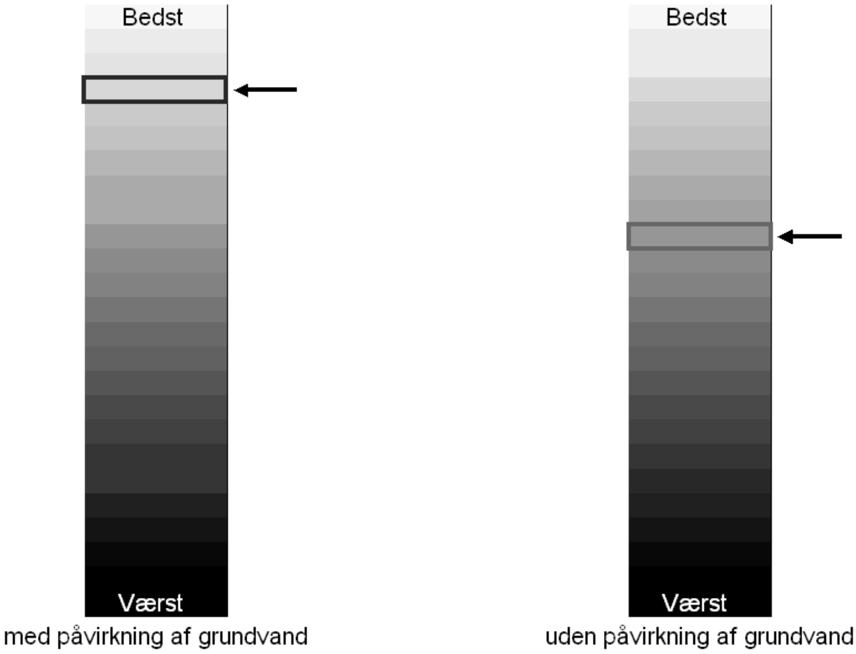


Figure 39 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.9 Bassiner - Sandfang + åbent græsklædt tørt bassin medinfiltration

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Medium	Suspended Solids, PAH
Fordampning	Medium	
Fotolyse	Lav/Medium	
Optag i planter	Medium	
Adsorption til substrat	Medium/Høj	
Filtrering	Medium	
Sedimentation	Medium/Høj	
Processer i jord og grundvand	Ja	

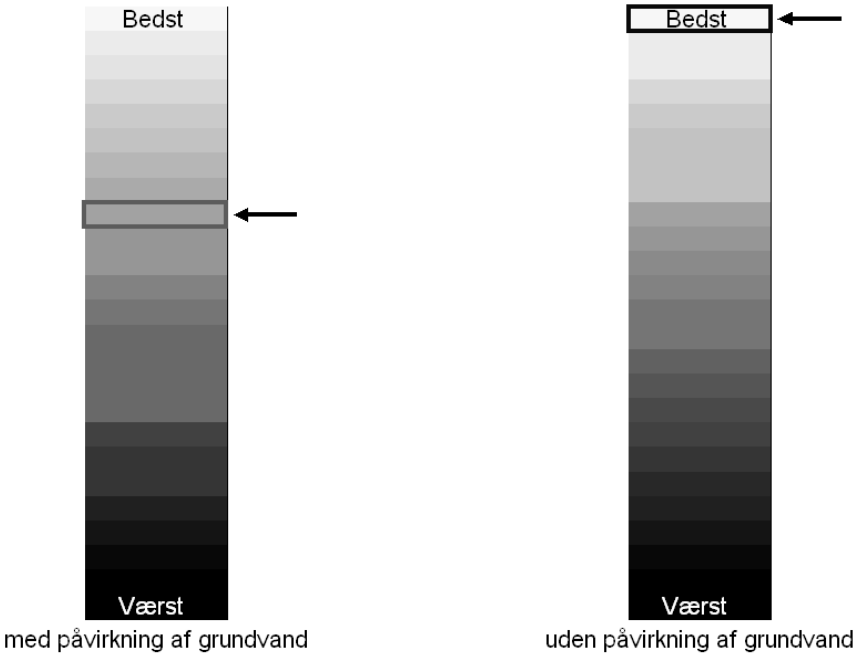


Figure 40 – Ranking for the removal of TSS

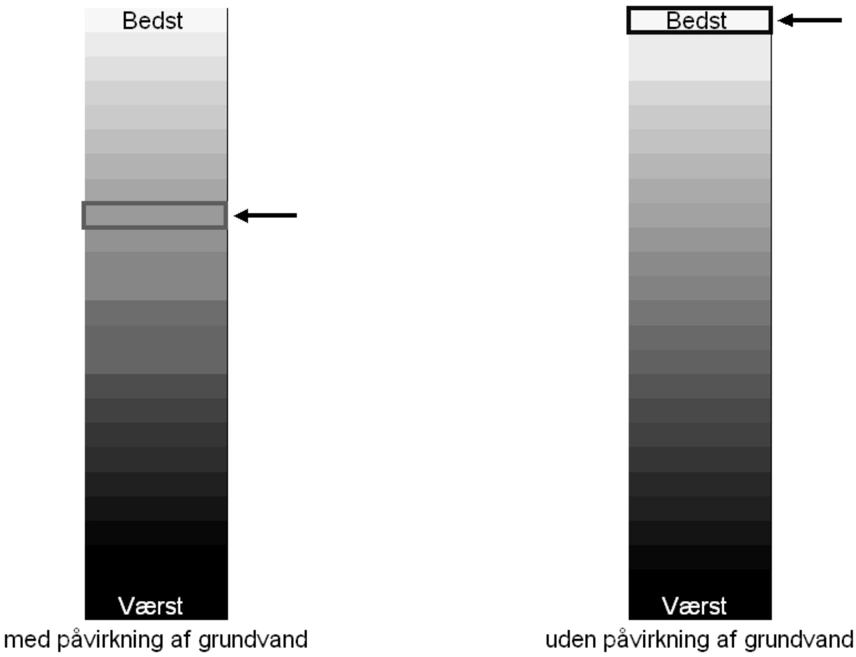


Figure 41 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

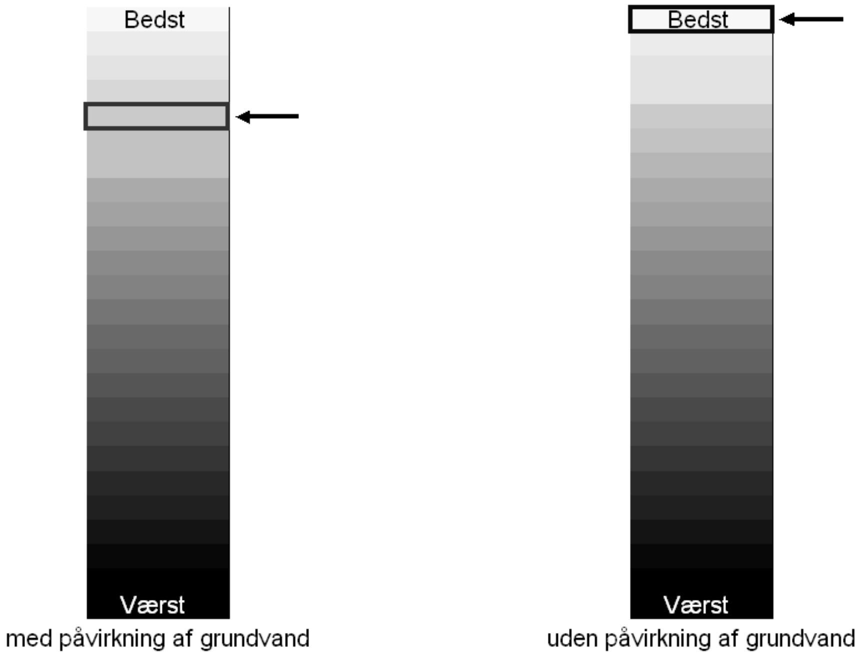


Figure 42 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

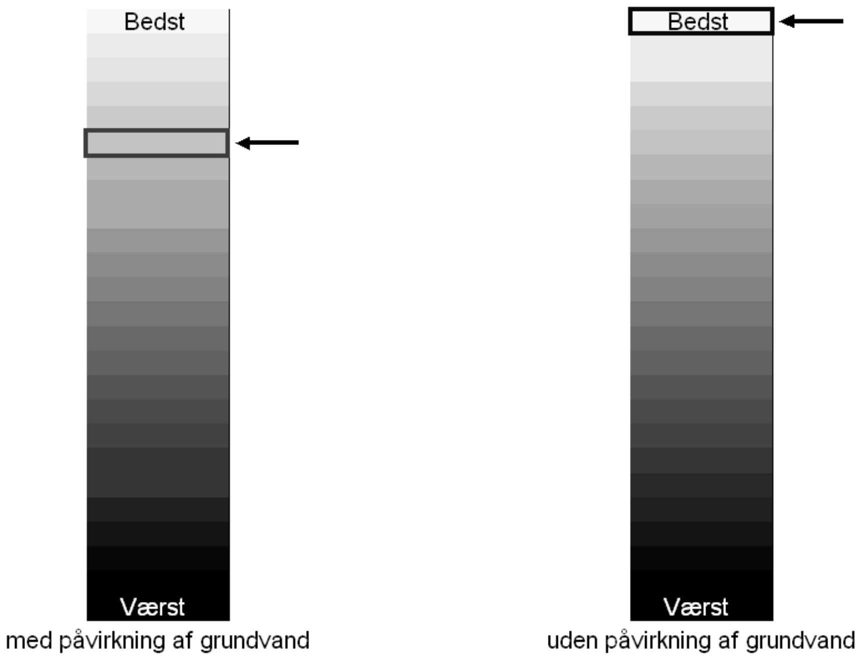


Figure 43 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.10 Bassiner - Sandfang + lukket betonbassin uden nedsivning

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Lav	Suspended Solids, PAH
Fordampning	Lav/Medium	
Fotolyse	Ikke Anvendelig	
Optag i planter	Ikke Anvendelig	
Adsorption til substrat	Lav	
Filtrering	Ikke Anvendelig	
Sedimentation	Medium/Høj	
Processer i jord og grundvand	Nej	

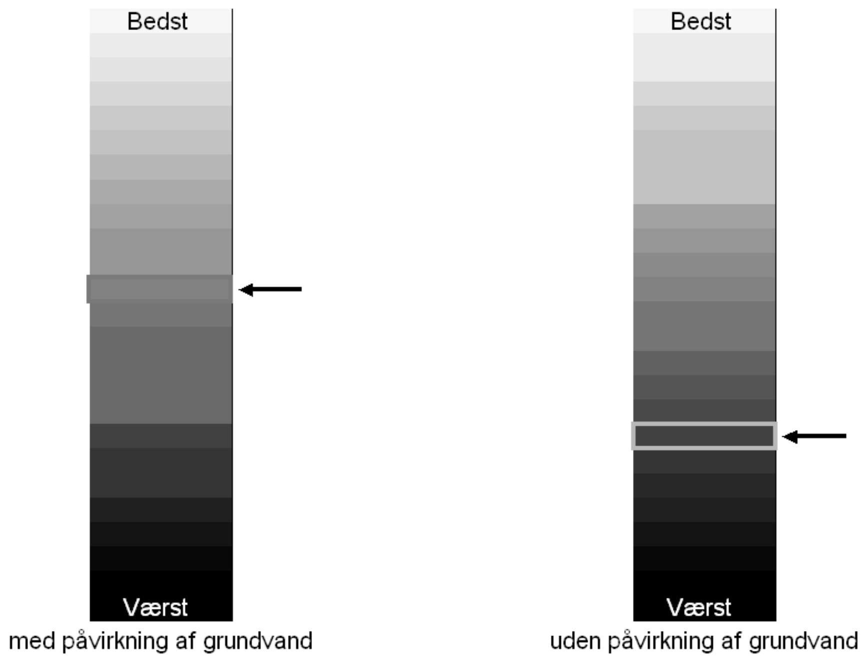


Figure 44 – Ranking for the removal of TSS

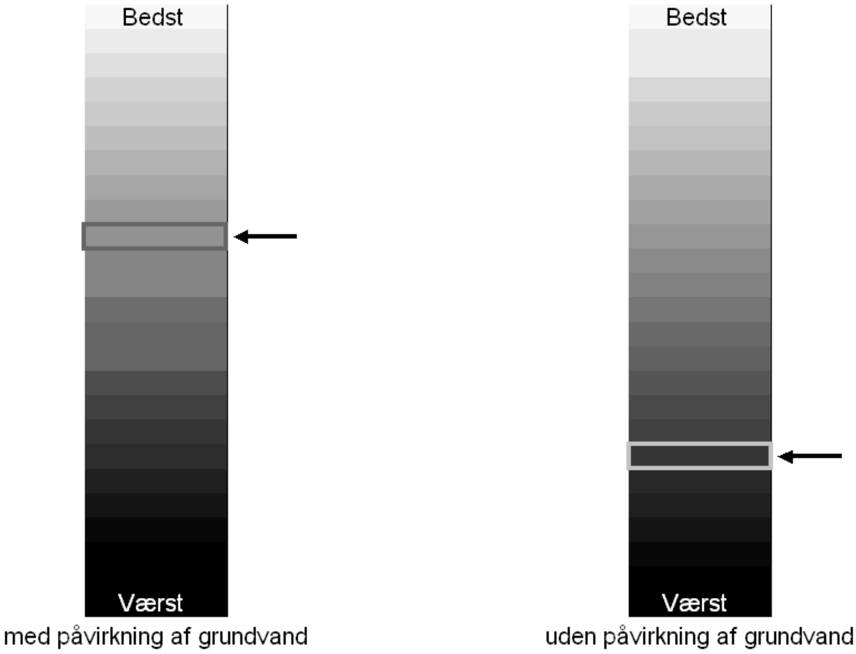


Figure 45 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

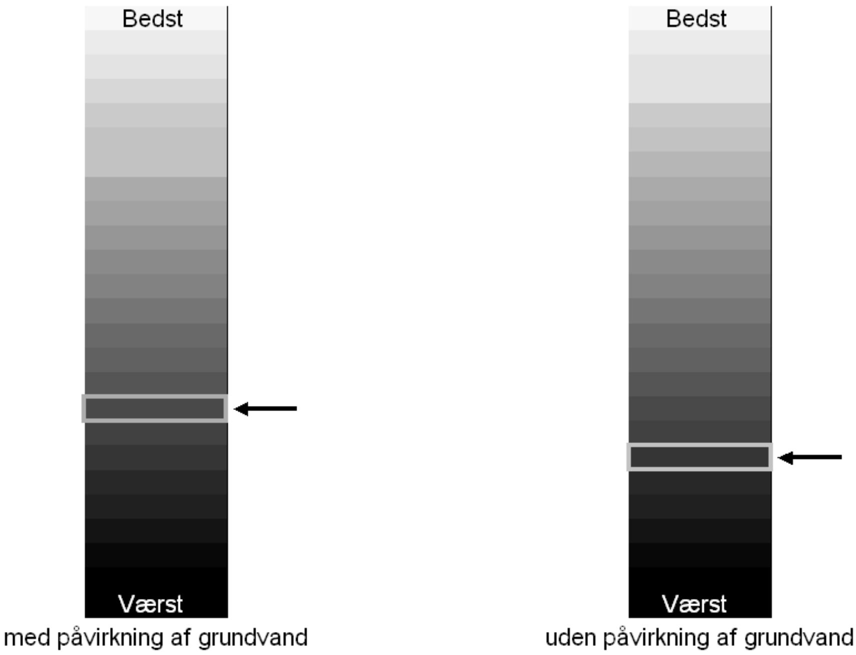


Figure 46 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

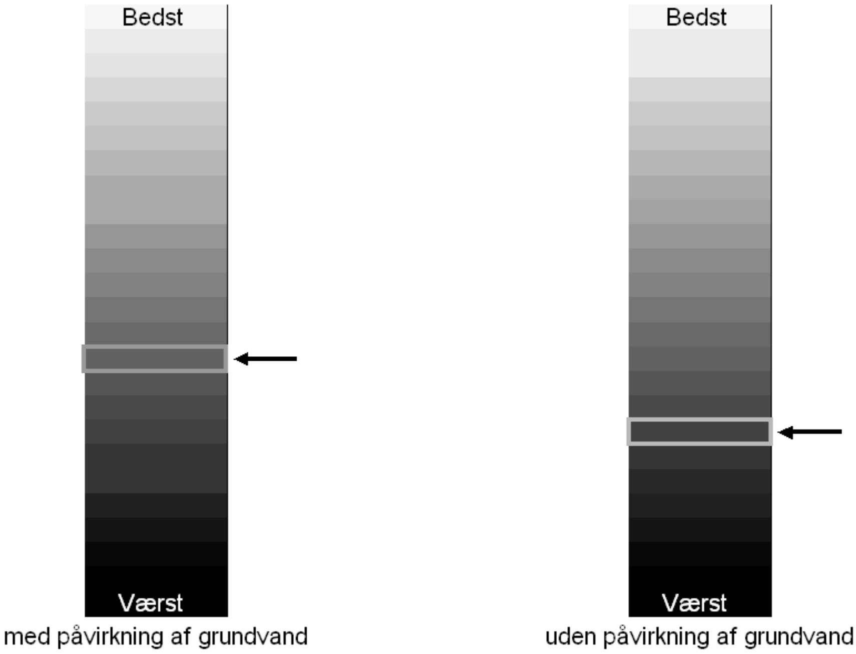


Figure 47 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.11 Bassiner - Sandfang + åbent vådt bassin

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Lav/Medium	Suspended Solids, PAH
Fordampning	Medium	
Fotolyse	Medium	
Optag i planter	Medium	
Adsorption til substrat	Lav/Medium	
Filtrering	Lav	
Sedimentation	Høj	
Processer i jord og grundvand	Nej	

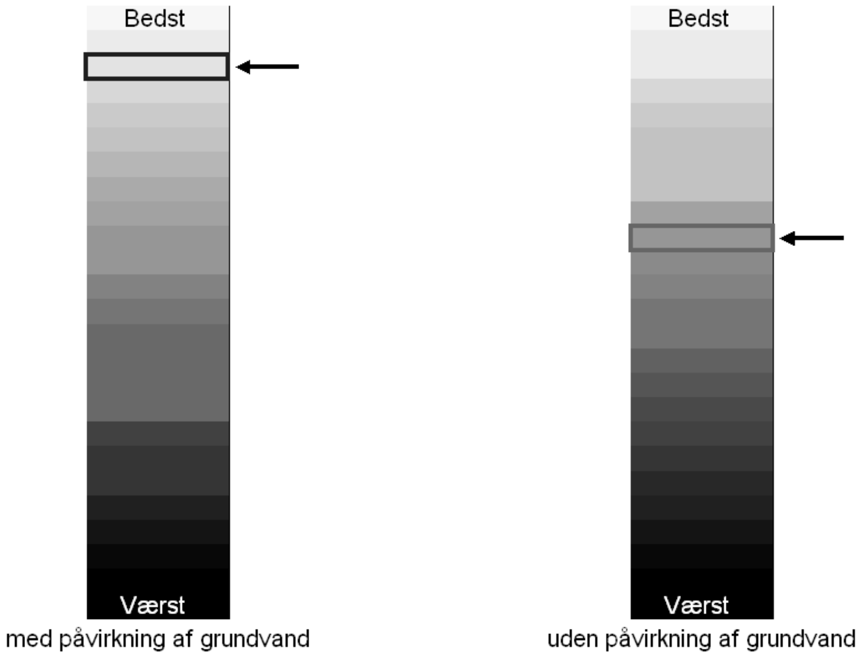


Figure 48 – Ranking for the removal of TSS

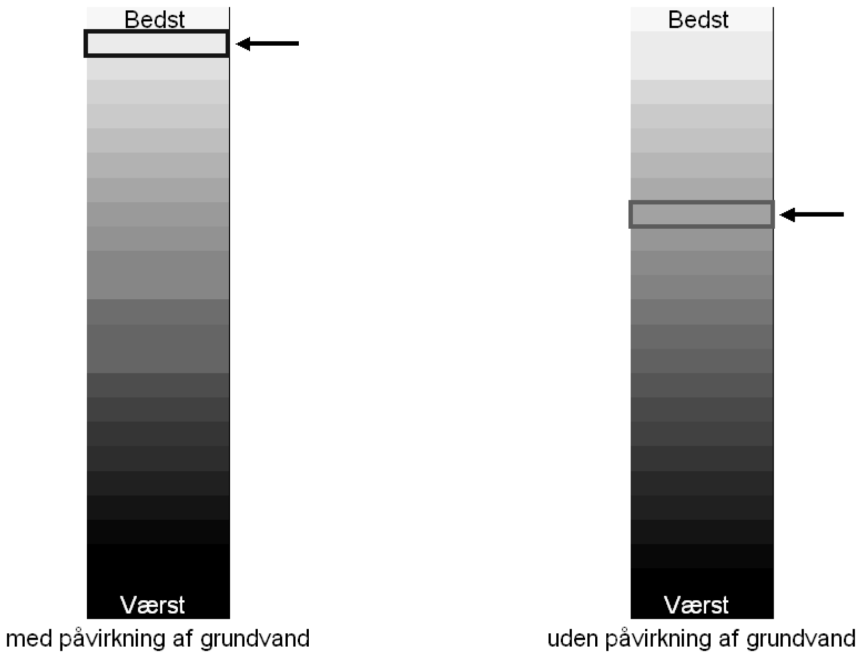


Figure 49 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

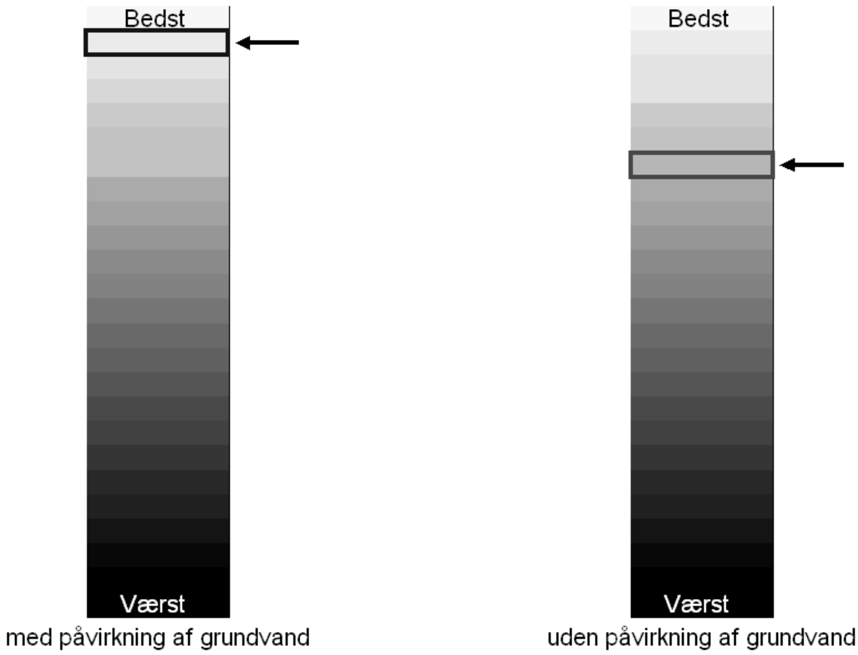


Figure 50 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

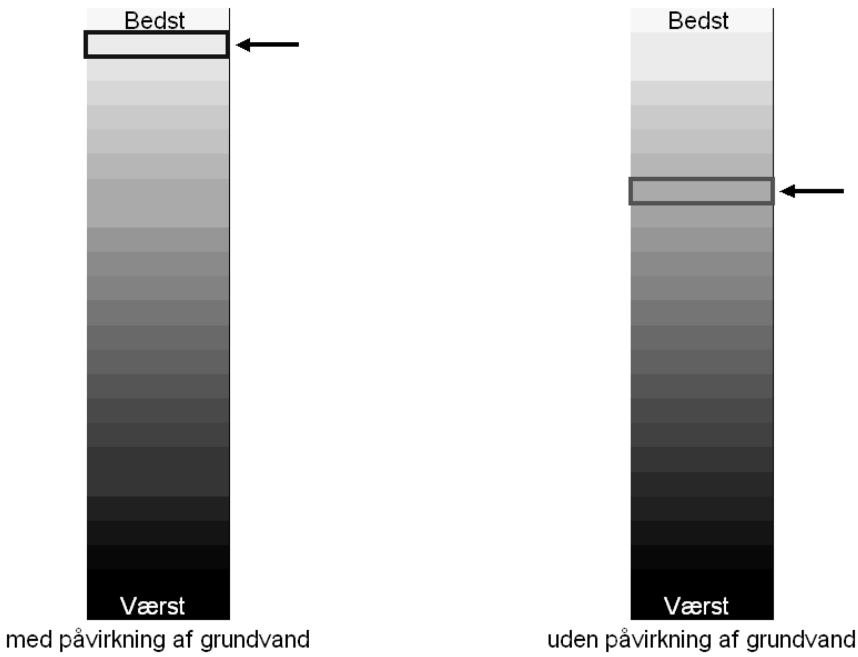


Figure 51 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.12 Naturlige lavninger i terræn med nedsivning (swales)

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Medium/Høj	Biocides, PAH
Fordampning	Medium	
Fotolyse	Lav/Medium	
Optag i planter	Medium/Høj	
Adsorption til substrat	Medium/Høj	
Filtrering	Medium	
Sedimentation	Lav/Medium	
Processer i jord og grundvand	Ja	

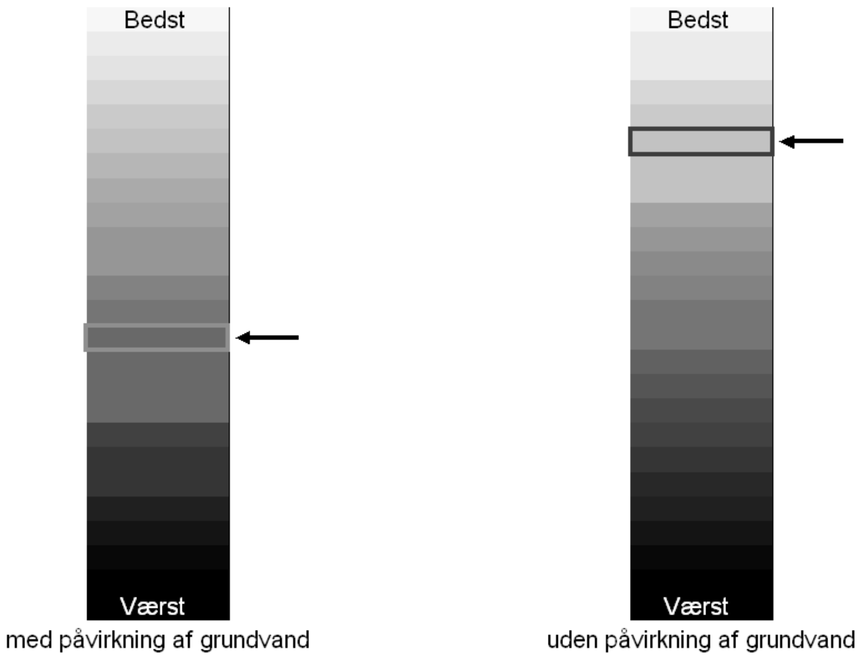


Figure 52 – Ranking for the removal of TSS

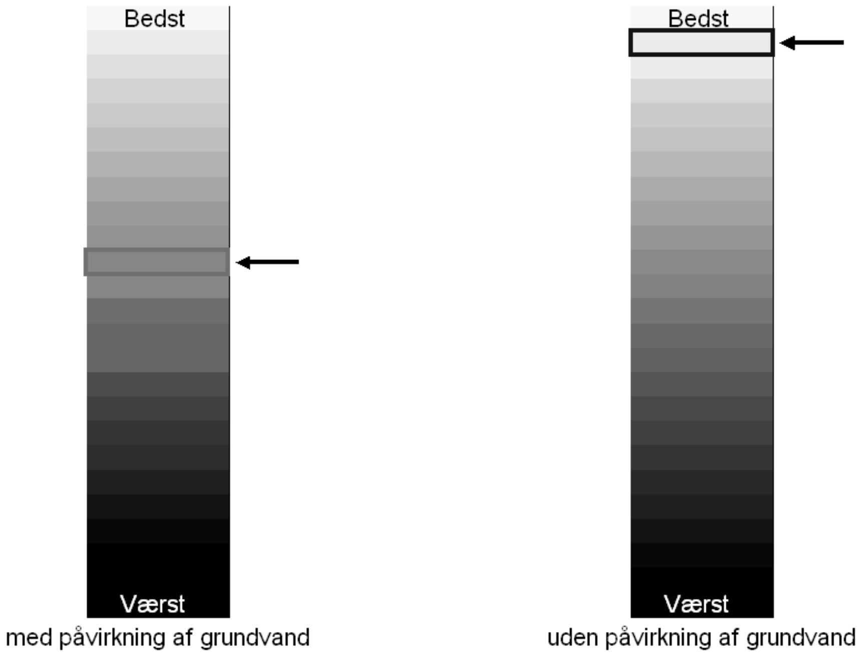


Figure 53 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

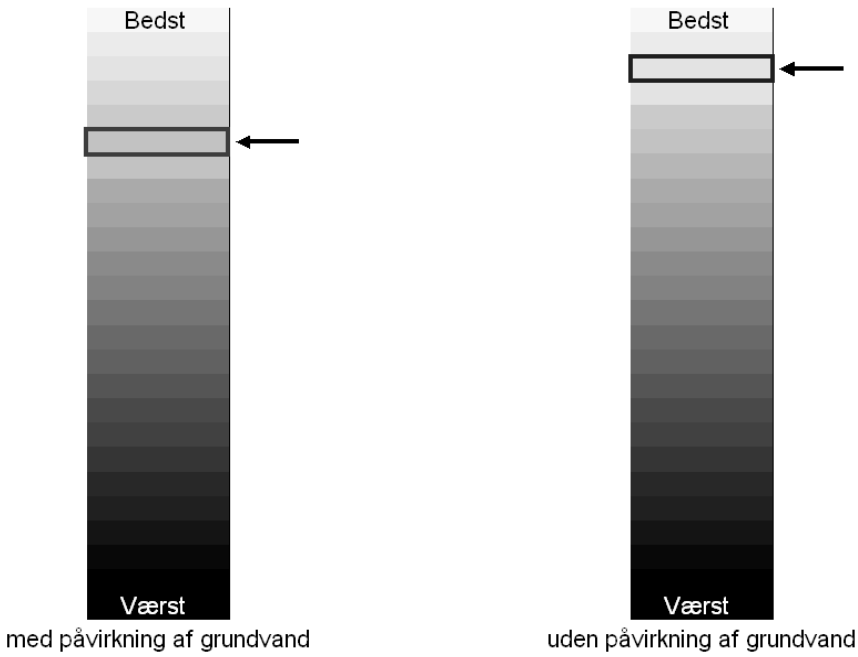
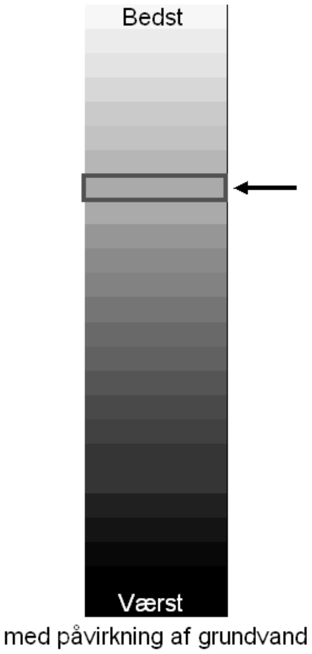


Figure 54 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).



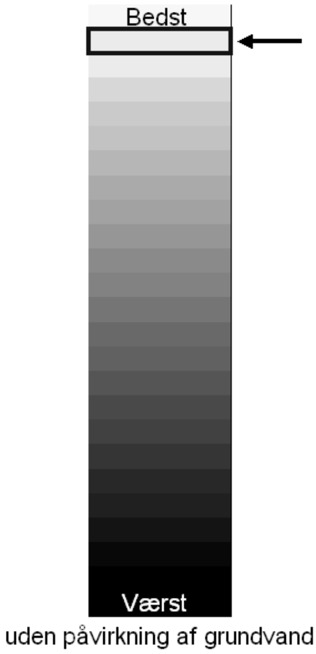


Figure 55 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.13 Gravet rende med filtermateriale af sand/grus og nedsivning

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Medium/Høj	Biocides, PAH
Fordampning	Medium	
Fotolyse	Lav/Medium	
Optag i planter	Medium	
Adsorption til substrat	Medium/Høj	
Filtrering	Medium	
Sedimentation	Lav/Medium	
Processer i jord og grundvand	Ja	

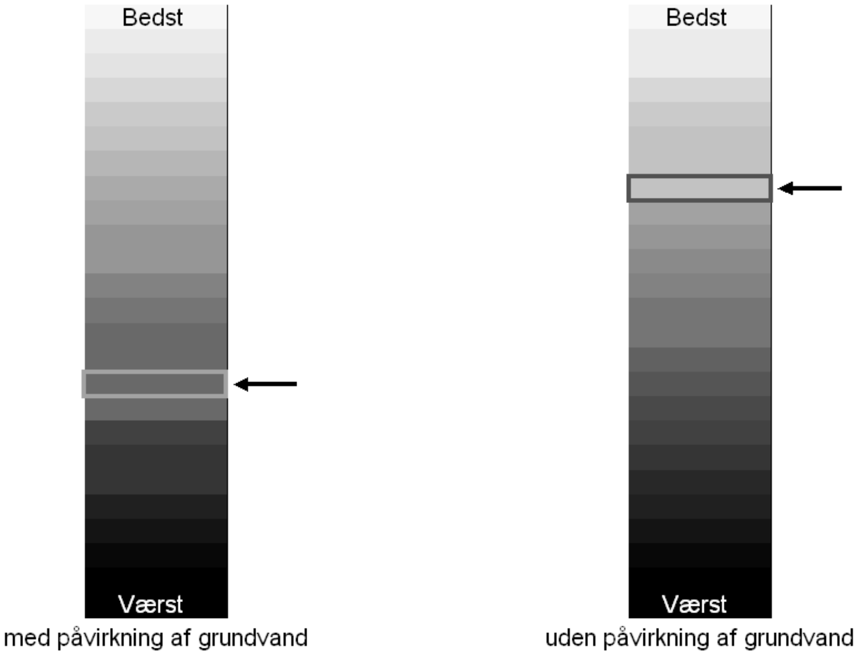


Figure 56 – Ranking for the removal of TSS

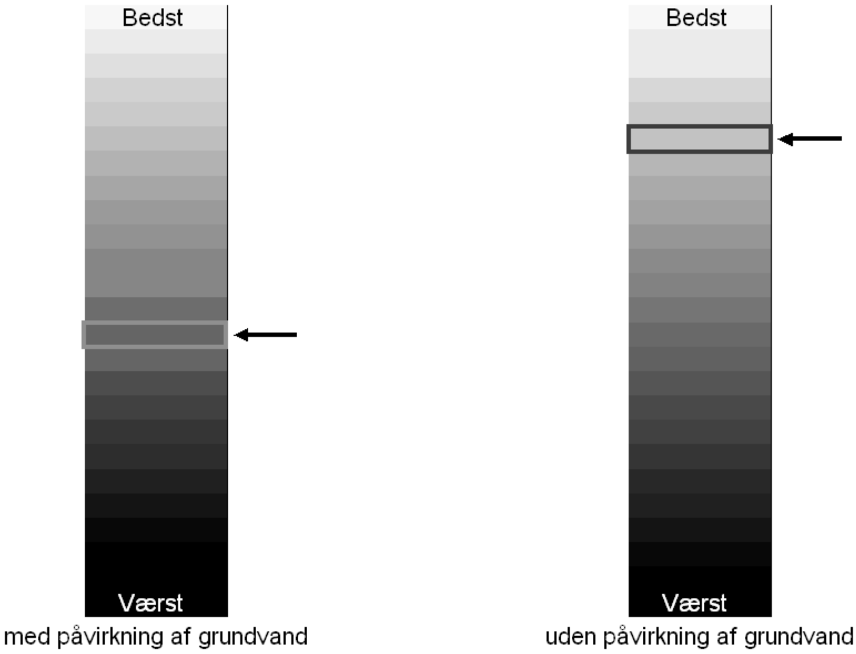


Figure 57 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

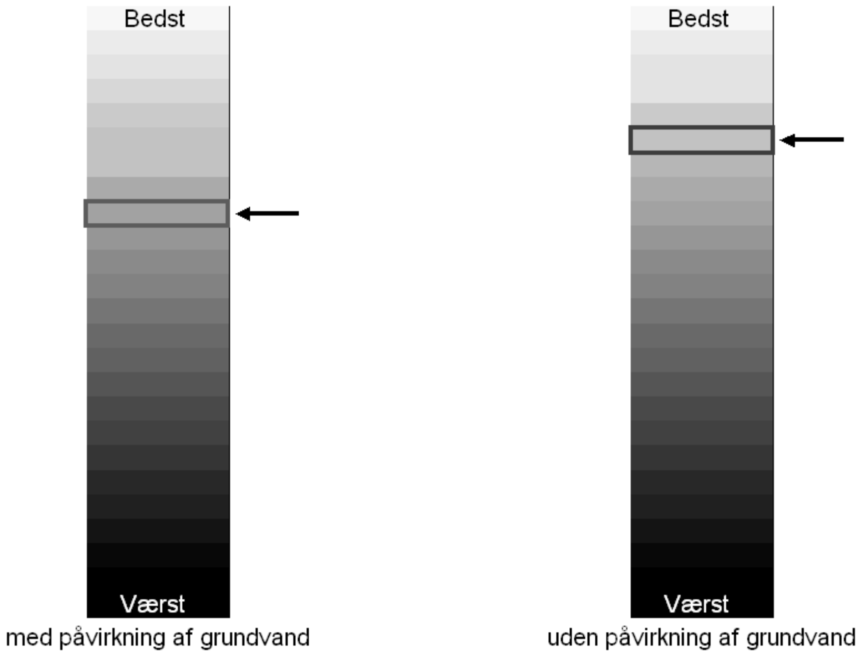


Figure 58 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

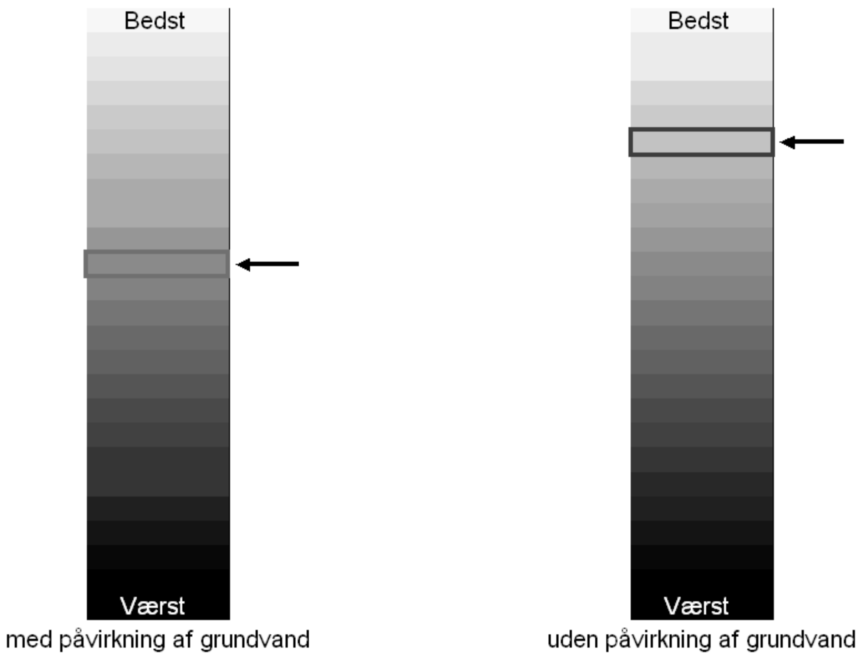


Figure 59 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.14 Gravet rende med sand/grus samt fordelerrør eller opsamlingsrør (Wadi eller mulden-rigole)

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Medium/Høj	Biocides, PAH
Fordampning	Medium	
Fotolyse	Lav/Medium	
Optag i planter	Medium/Høj	
Adsorption til substrat	Medium/Høj	
Filtrering	Medium	
Sedimentation	Lav/Medium	
Processer i jord og grundvand	Ja	

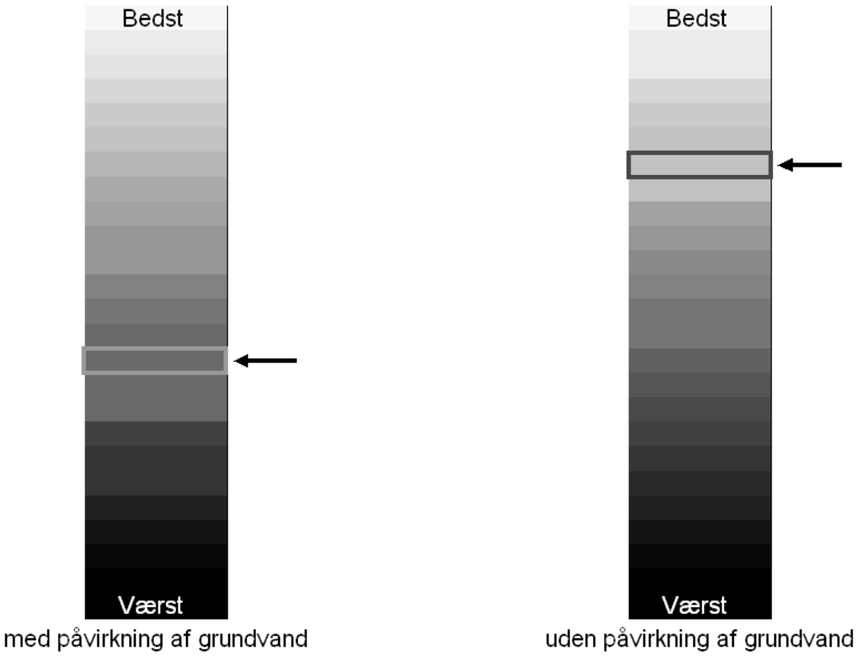


Figure 60 – Ranking for the removal of TSS

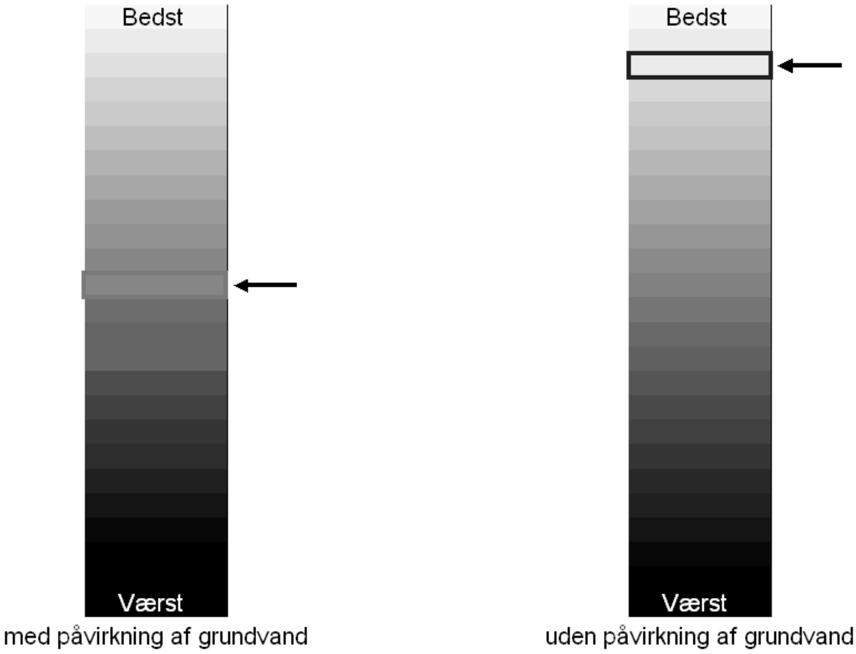


Figure 61 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

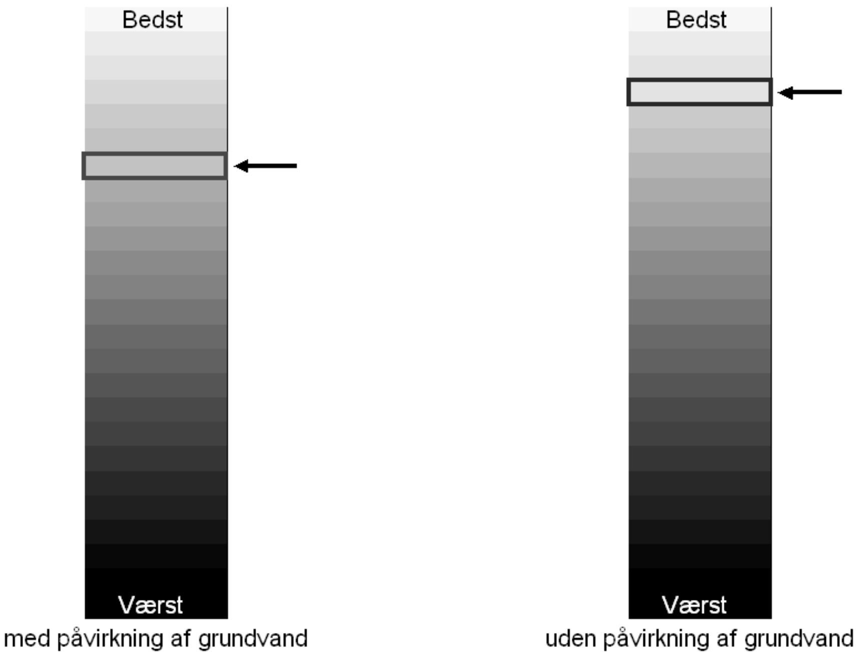


Figure 62 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

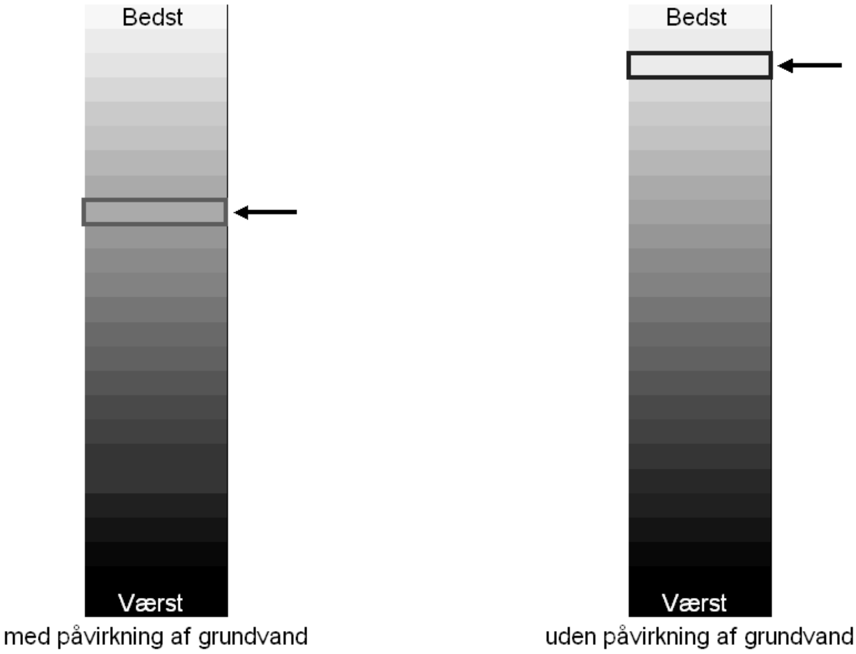


Figure 63 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.15 Tætte kanaler eller render udført i beton eller lign uden nedsivning

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Lav	PAH
Fordampning	Lav/Medium	
Fotolyse	Lav	
Optag i planter	Ikke Anvendelig	
Adsorption til substrat	Lav/Medium	
Filtrering	Ikke Anvendelig	
Sedimentation	Lav	
Processer i jord og grundvand	Nej	

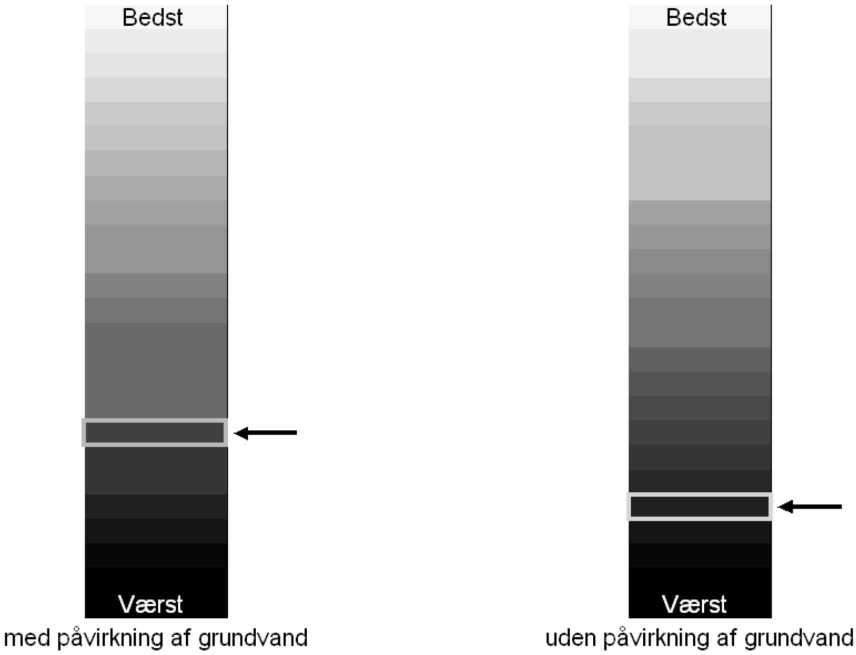


Figure 64 – Ranking for the removal of TSS

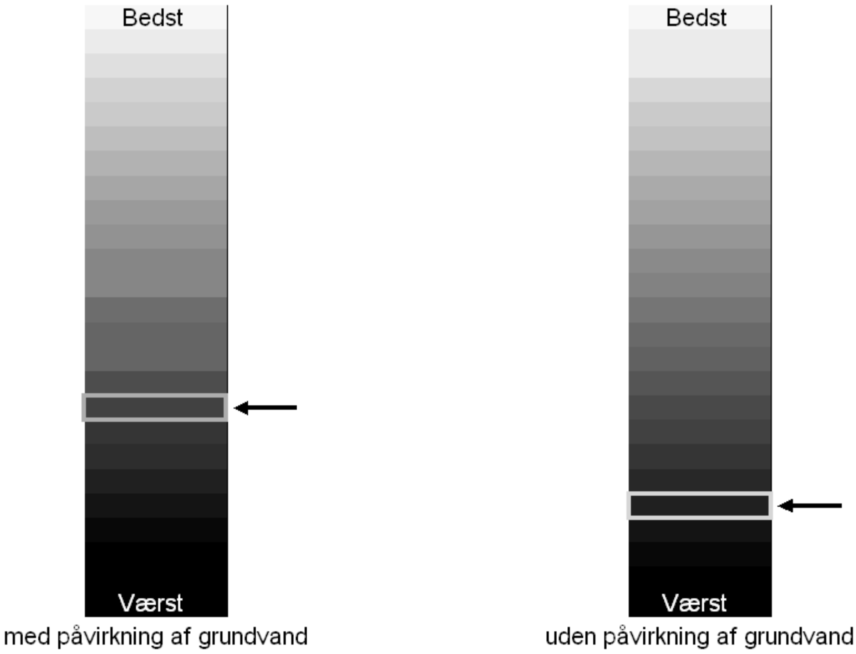


Figure 65 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

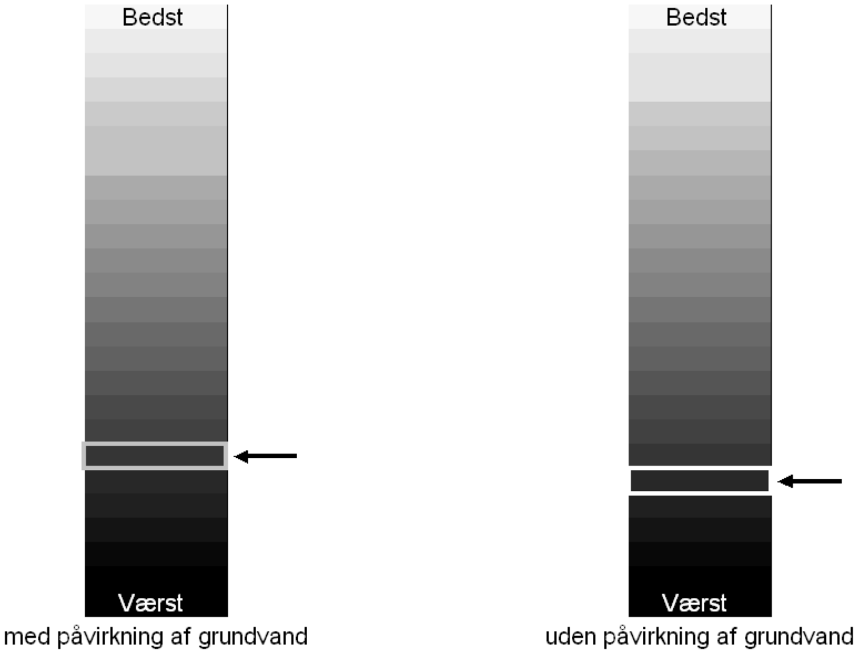


Figure 66 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

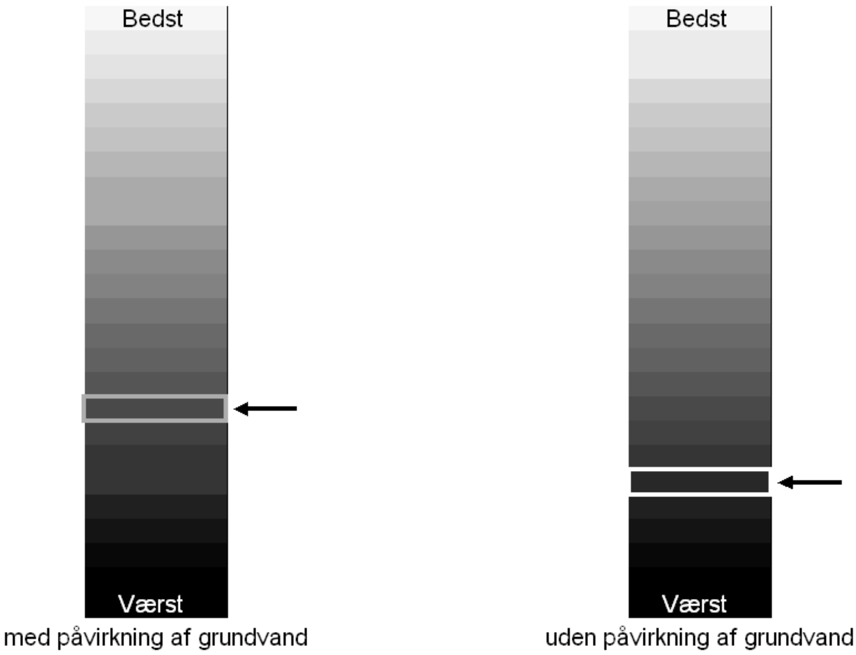


Figure 67 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.16 *Faskiner*

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Lav/Medium	Biocides, PAH
Fordampning	Lav	
Fotolyse	Ikke Anvendelig	
Optag i planter	Lav	
Adsorption til substrat	Medium	
Filtrering	Lav/Medium	
Sedimentation	Lav/Medium	
Processer i jord og grundvand	Ja	

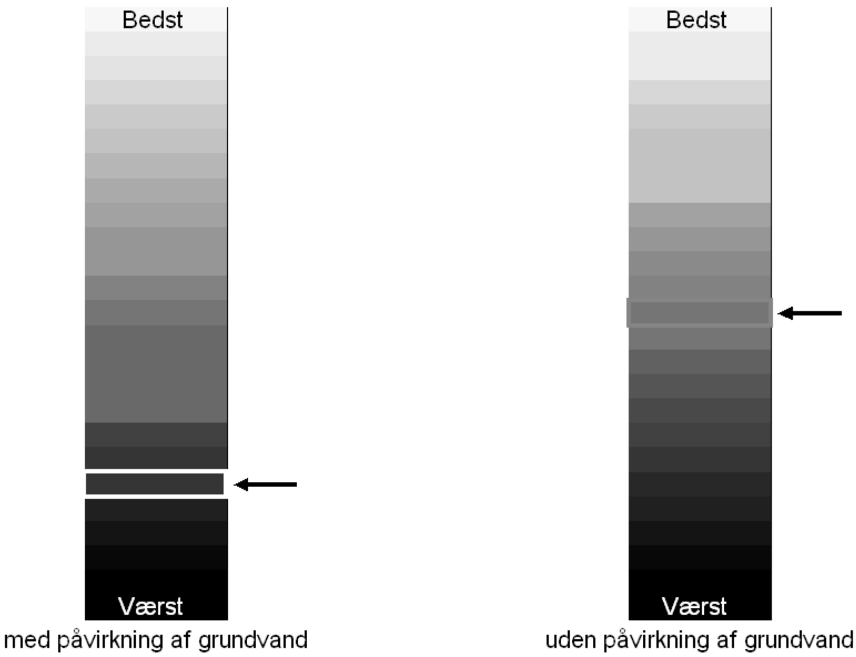


Figure 68 – Ranking for the removal of TSS

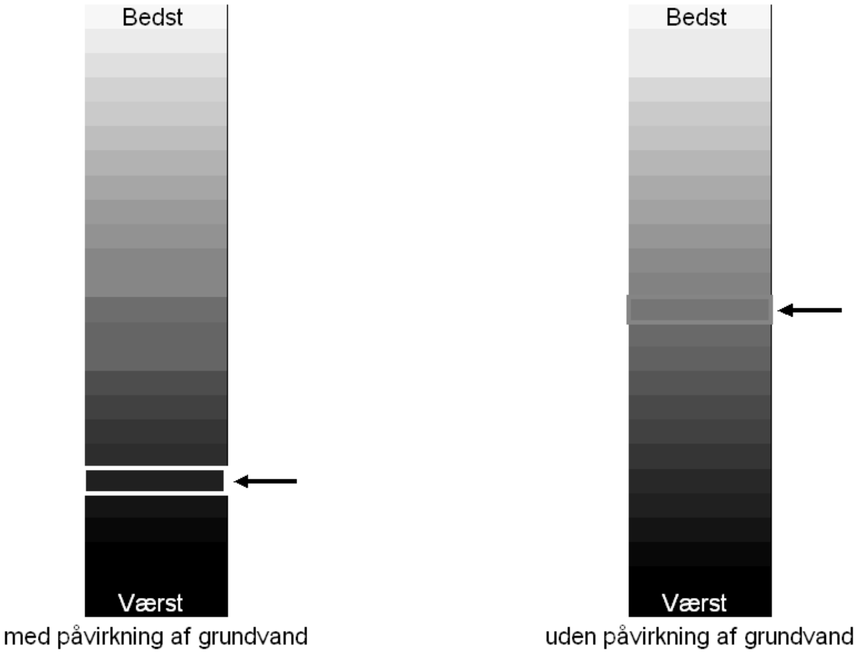


Figure 69 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

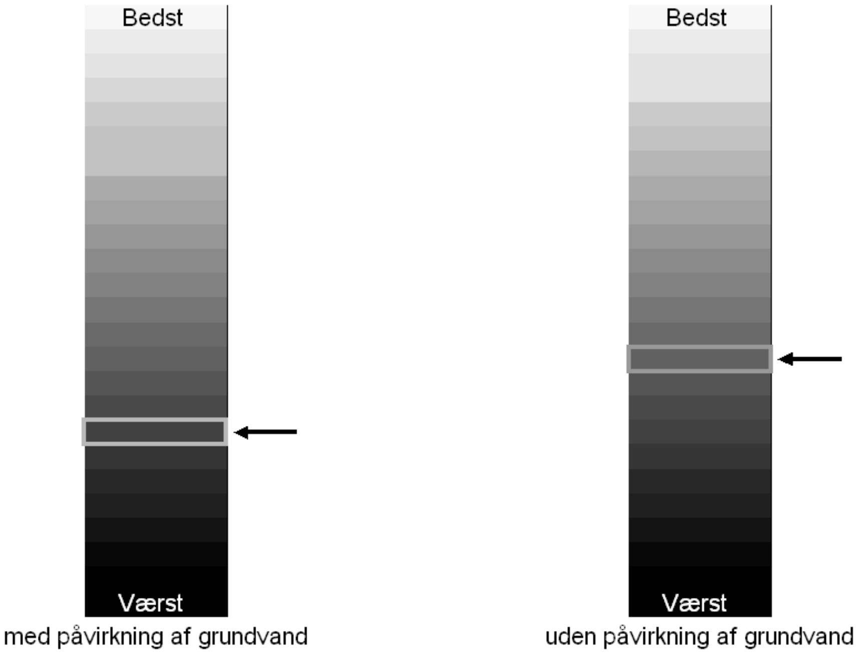


Figure 70 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

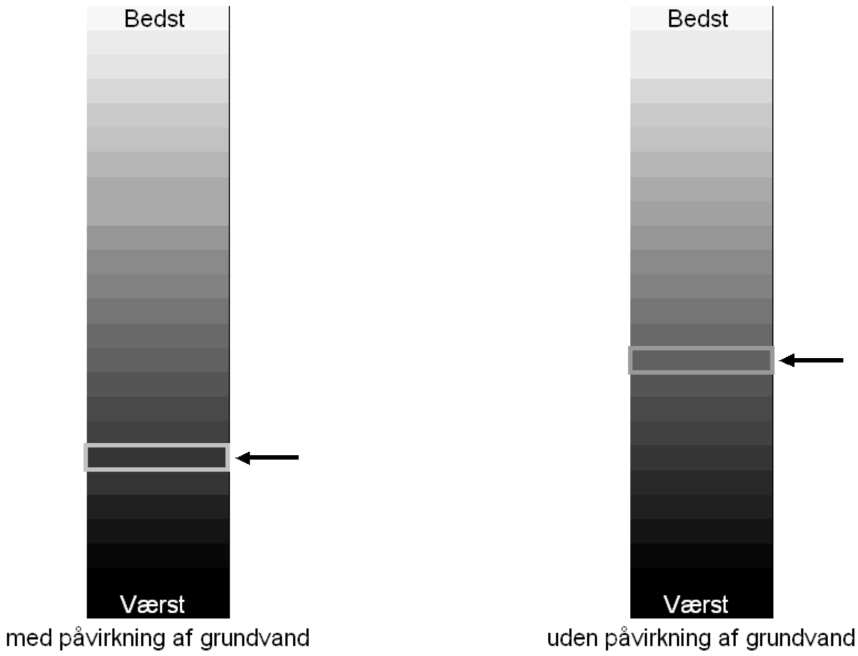


Figure 71 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.17 *Infiltrationsbrønde*

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Medium/Høj	Suspended solids, Biocides
Fordampning	Lav/Medium	
Fotolyse	Ikke Anvendelig	
Optag i planter	Lav	
Adsorption til substrat	Medium/Hoj	
Filtrering	Medium/Hoj	
Sedimentation	Lav/Medium	
Processer i jord og grundvand	Ja	

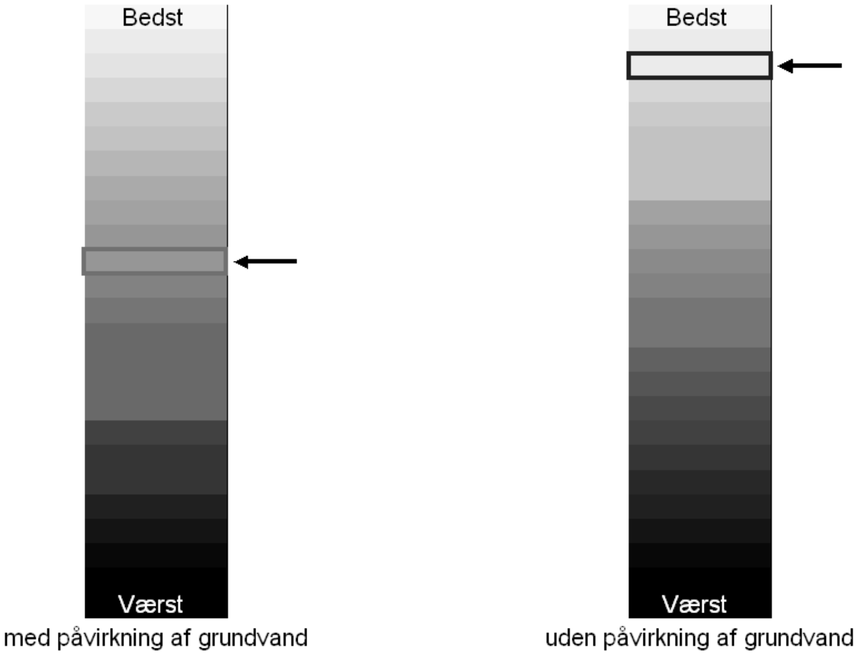


Figure 72 – Ranking for the removal of TSS

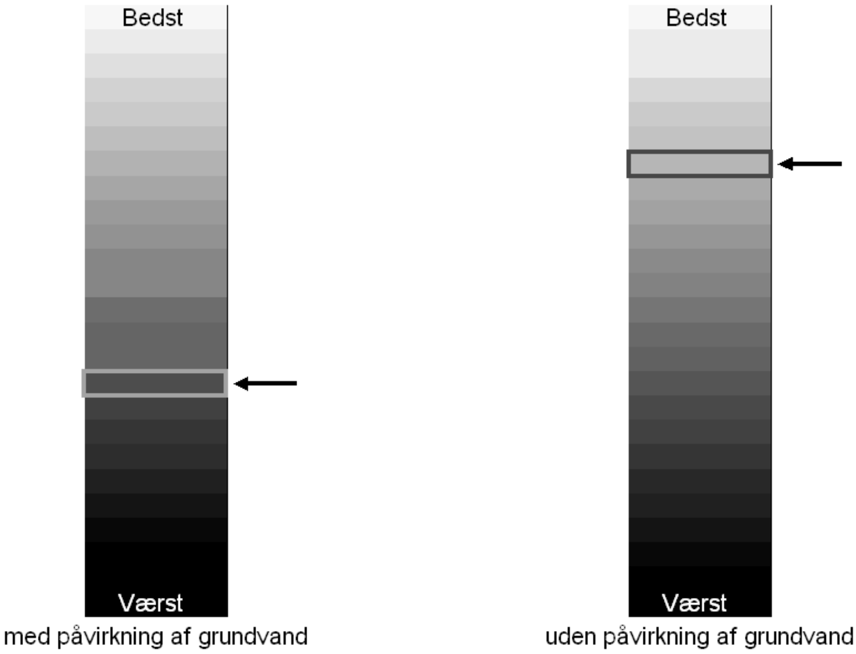


Figure 73 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

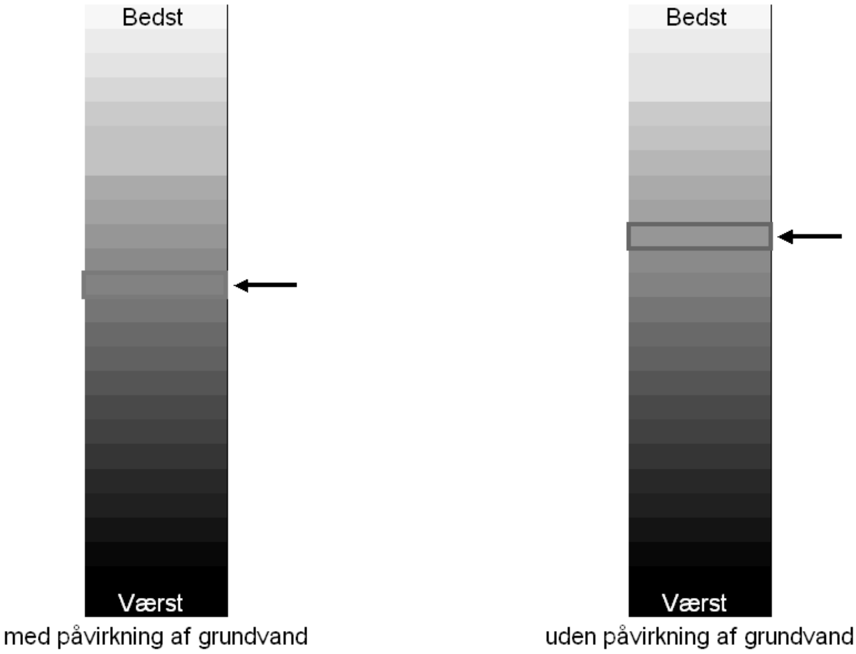


Figure 74 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

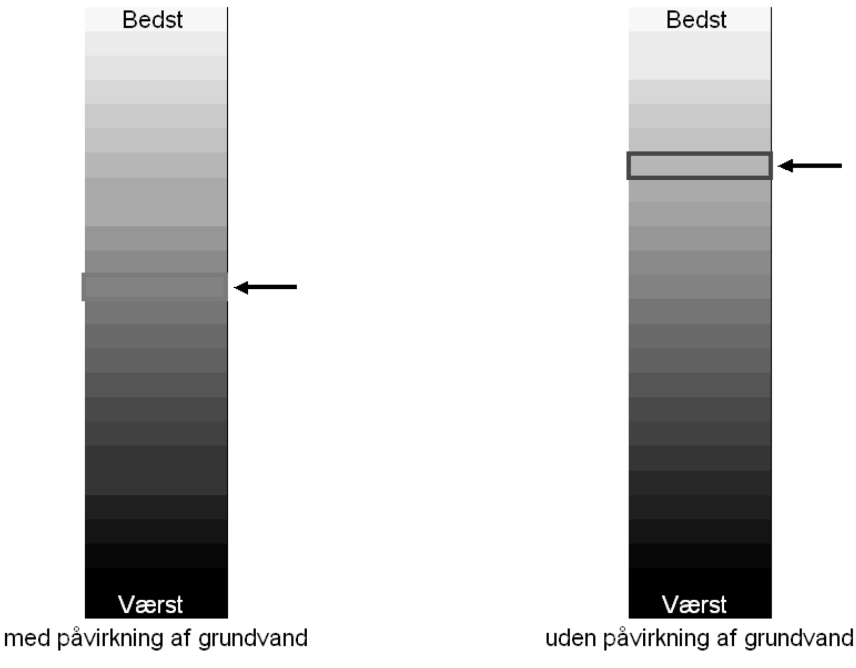


Figure 75 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.18 *Drosling af afløb*

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Ikke Anvendelig	Ingen
Fordampning	Ikke Anvendelig	
Fotolyse	Ikke Anvendelig	
Optag i planter	Ikke Anvendelig	
Adsorption til substrat	Ikke Anvendelig	
Filtrering	Ikke Anvendelig	
Sedimentation	Ikke Anvendelig	
Processer i jord og grundvand	Nej	

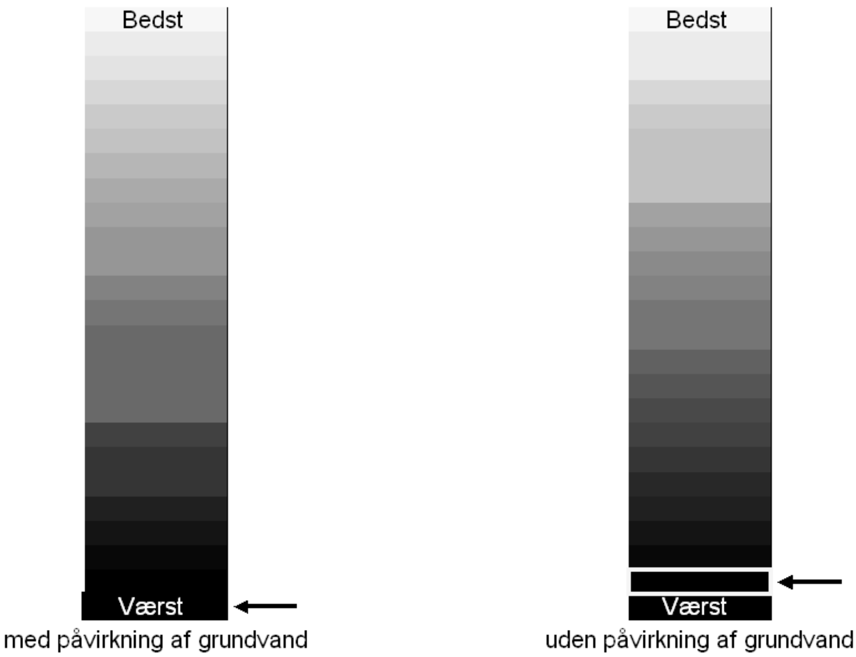


Figure 76 – Ranking for the removal of TSS

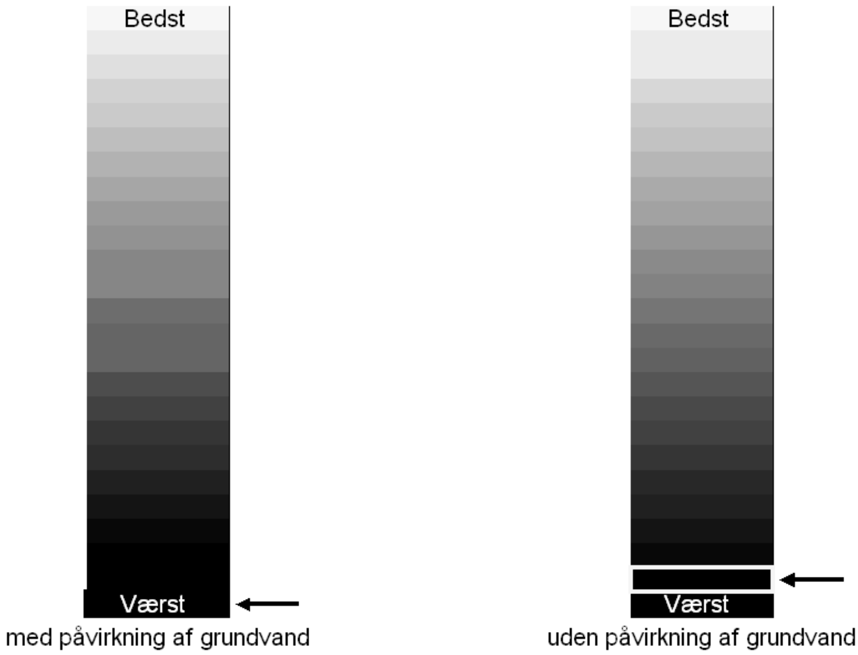


Figure 77 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

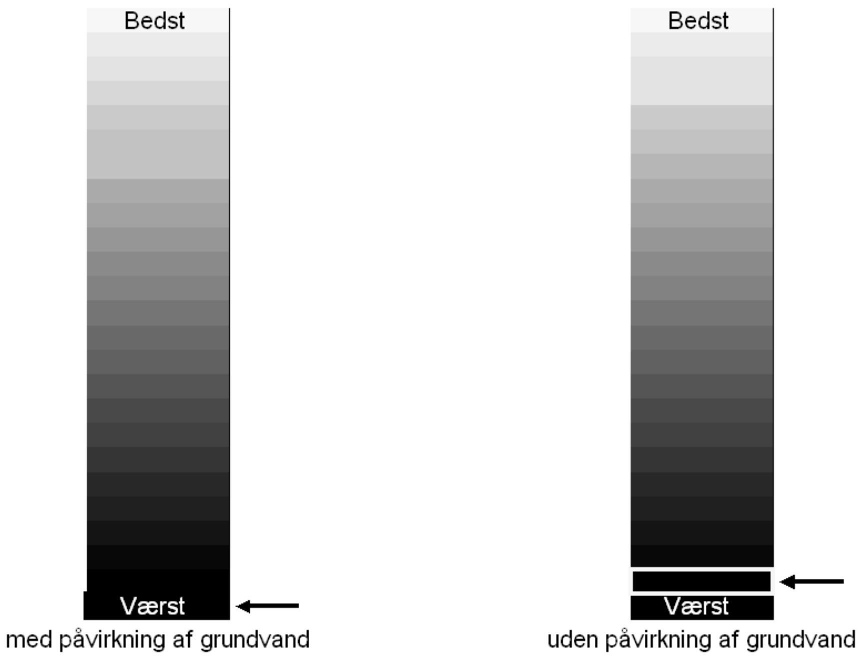


Figure 78 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

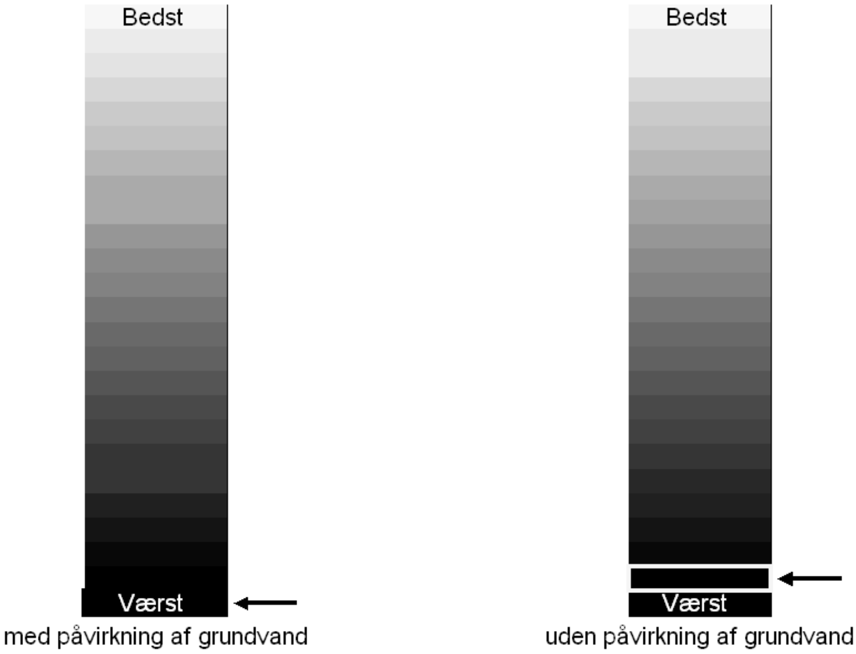


Figure 79 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.19 Kantstene og forsinkelse på befæstede arealer

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Ikke Anvendelig	Ingen
Fordampning	Ikke Anvendelig	
Fotolyse	Ikke Anvendelig	
Optag i planter	Ikke Anvendelig	
Adsorption til substrat	Ikke Anvendelig	
Filtrering	Ikke Anvendelig	
Sedimentation	Ikke Anvendelig	
Processer i jord og grundvand	Nej	

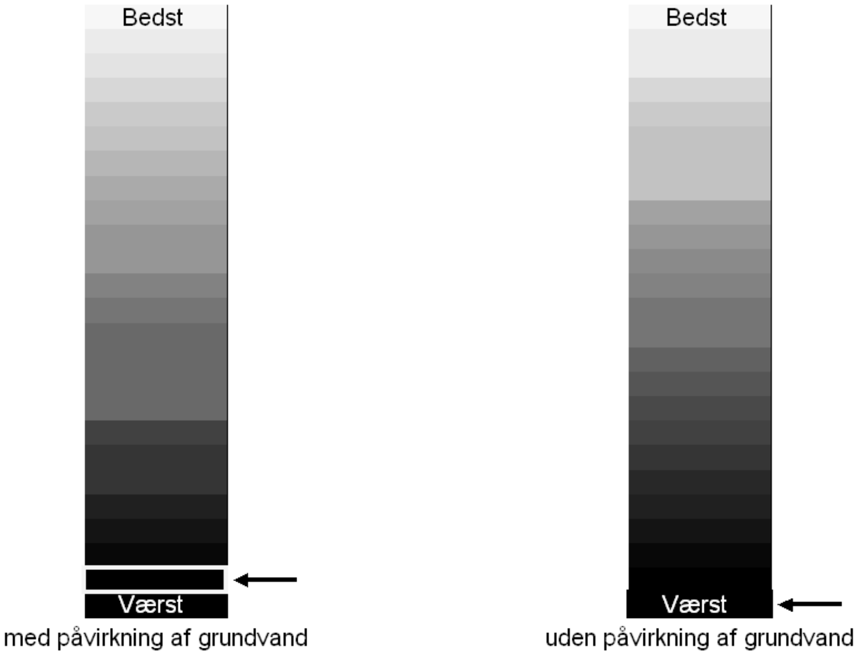


Figure 80 – Ranking for the removal of TSS

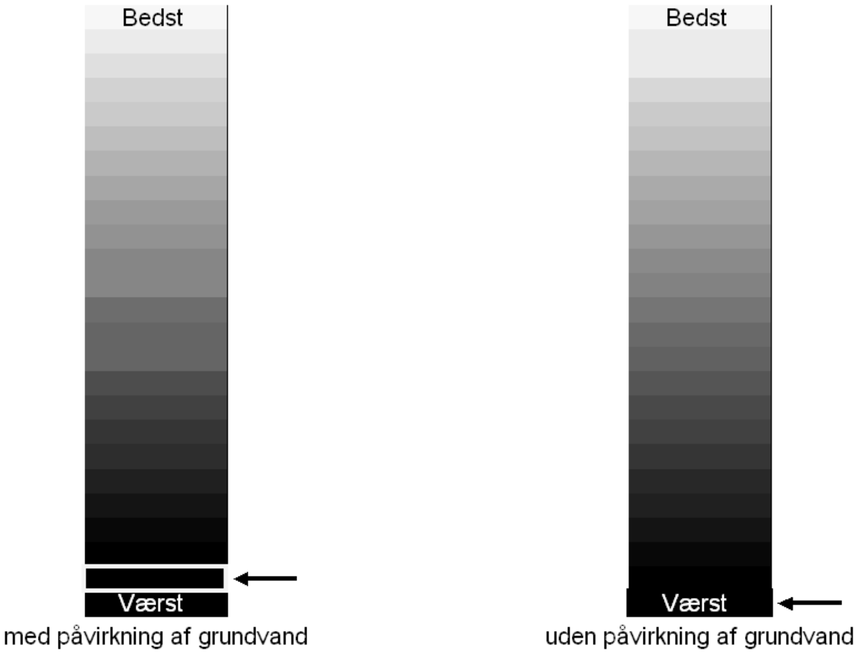


Figure 81 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

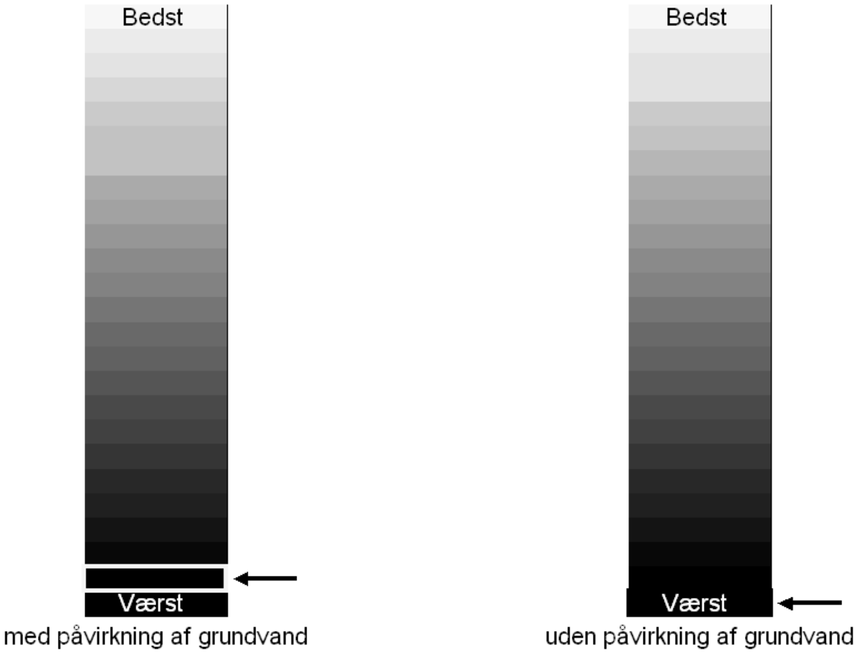


Figure 82 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

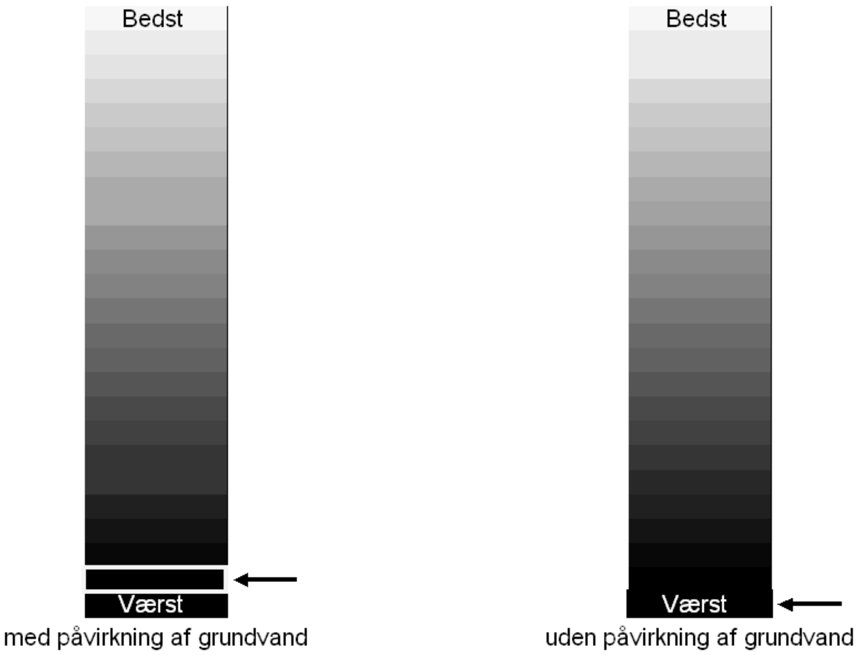


Figure 83 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.20 Sandfang

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Ikke Anvendelig	Suspended Solids
Fordampning	Ikke Anvendelig	
Fotolyse	Ikke Anvendelig	
Optag i planter	Ikke Anvendelig	
Adsorption til substrat	Lav	
Filtrering	Ikke Anvendelig	
Sedimentation	Medium/Hoj	
Processer i jord og grundvand	Nej	

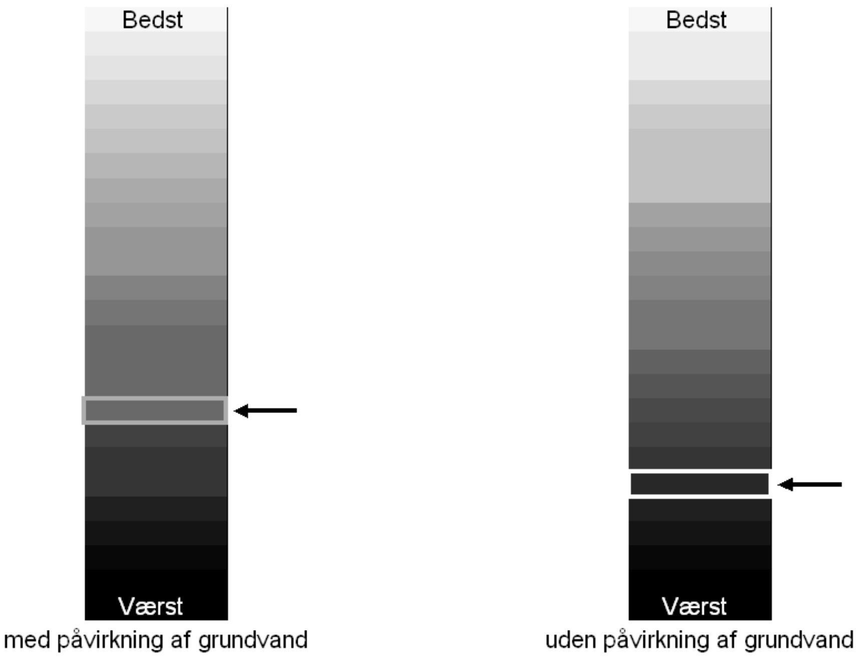


Figure 84 – Ranking for the removal of TSS

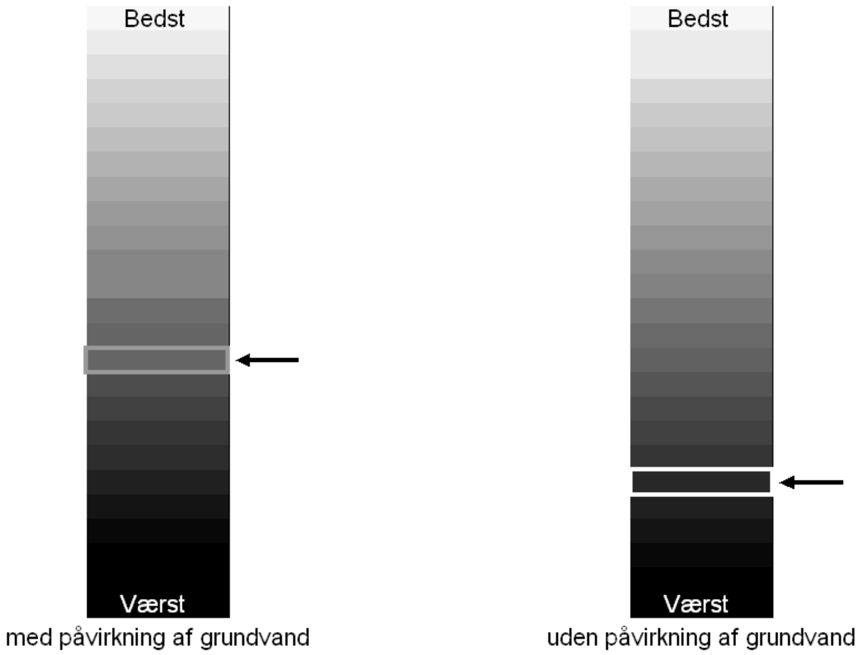


Figure 85 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

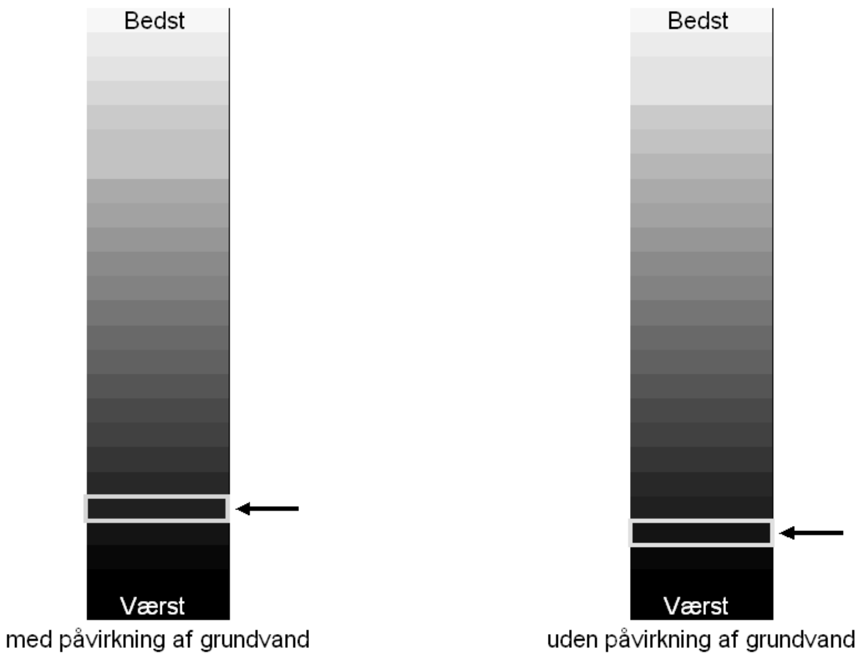


Figure 86 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

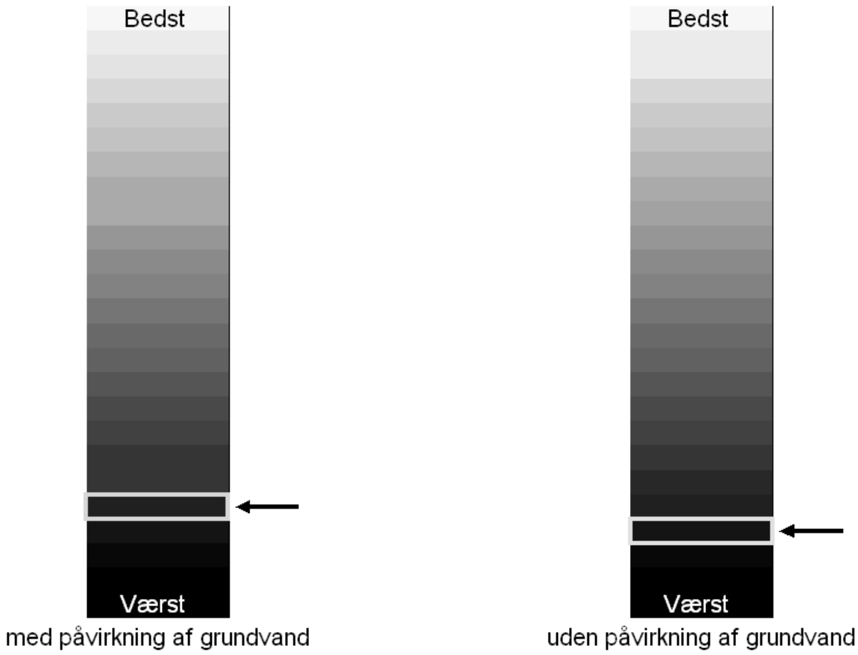


Figure 87 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.21 Olieuskiller

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Ikke Anvendelig	PAH
Fordampning	Ikke Anvendelig	
Fotolyse	Ikke Anvendelig	
Optag i planter	Ikke Anvendelig	
Adsorption til substrat	Lav	
Filtrering	Ikke Anvendelig	
Sedimentation	Ikke Anvendelig	
Processer i jord og grundvand	Nej	

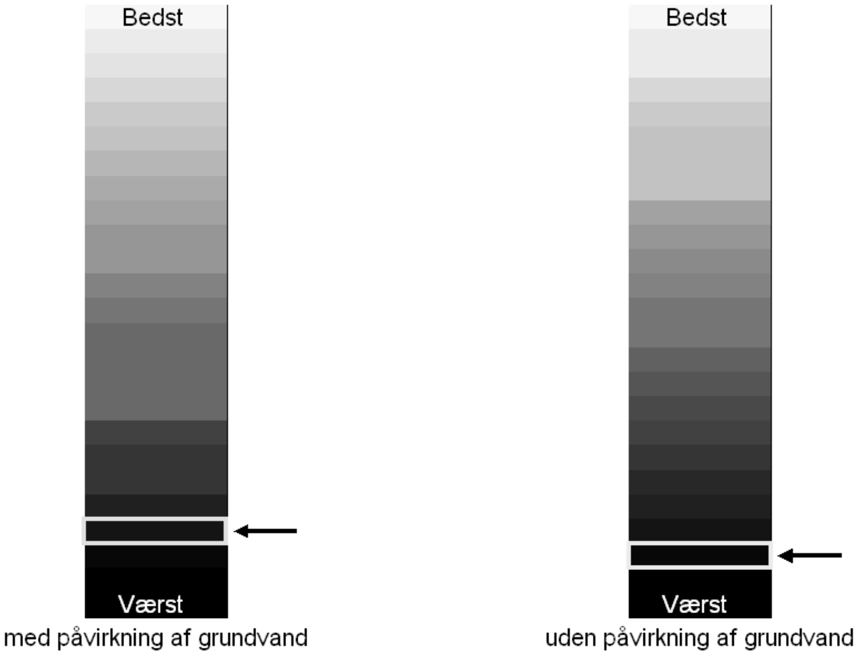


Figure 88 – Ranking for the removal of TSS

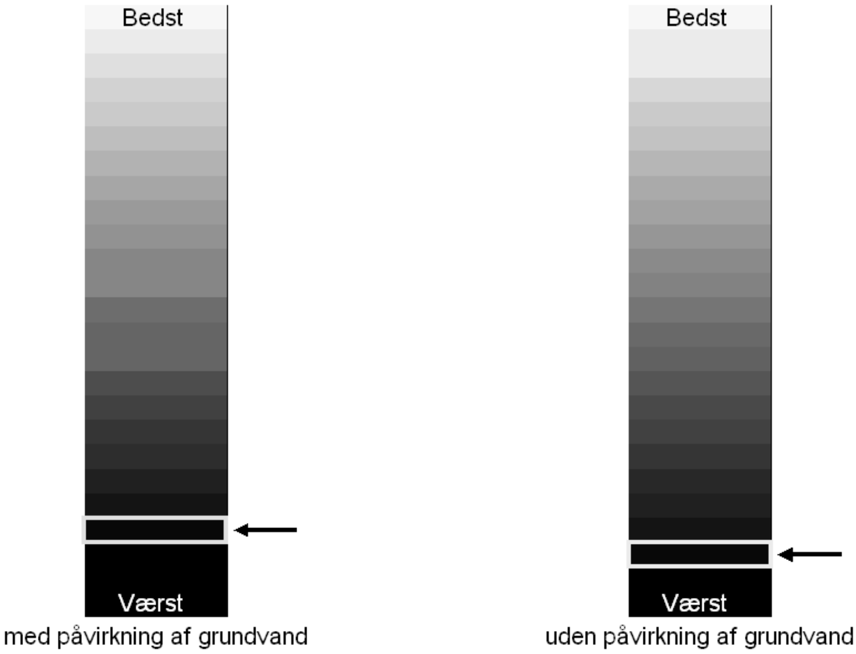


Figure 89 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

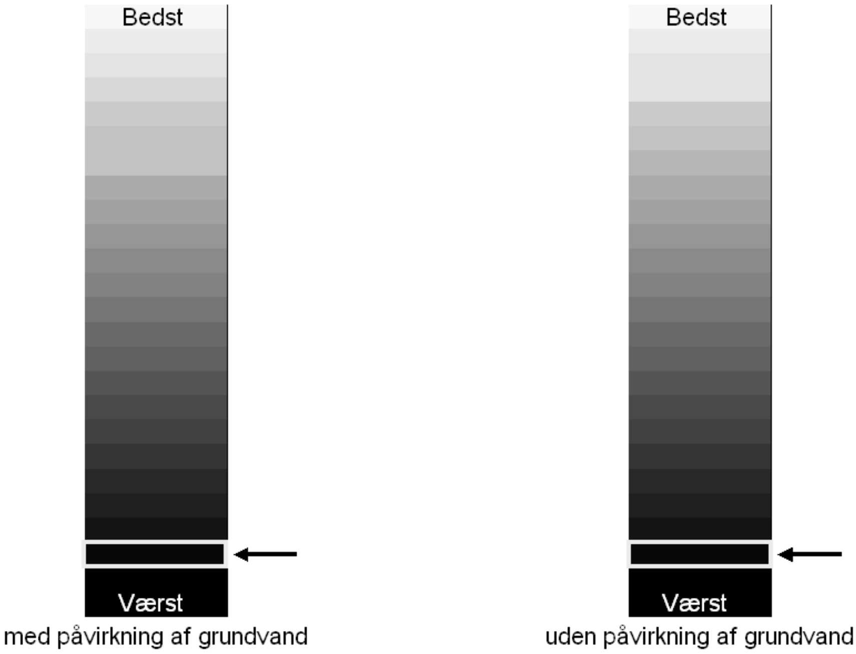


Figure 90 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

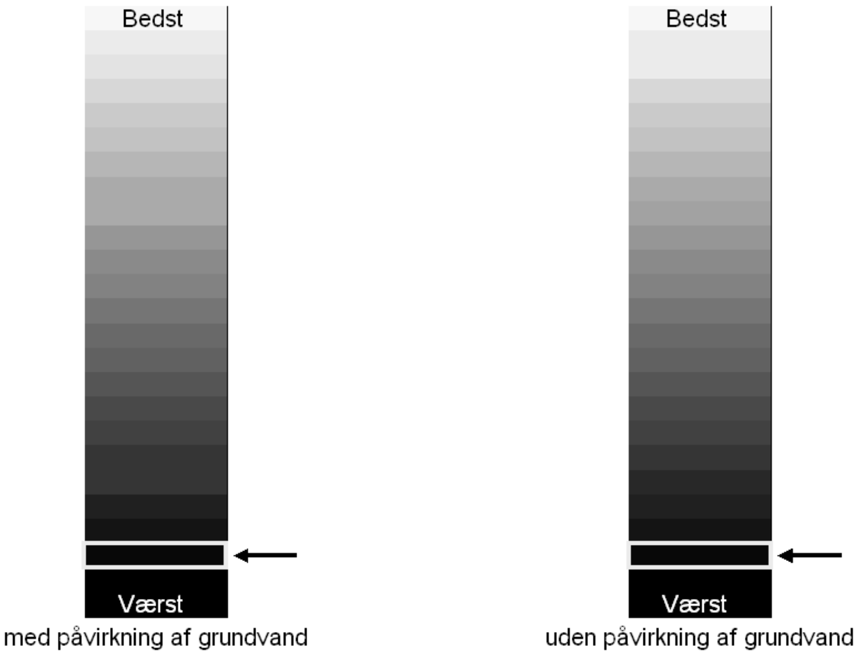


Figure 91 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.22 *Filtre og sier*

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Ikke Anvendelig	
Fordampning	Ikke Anvendelig	
Fotolyse	Ikke Anvendelig	
Optag i planter	Ikke Anvendelig	
Adsorption til substrat	Medium/Hoj	
Filtrering	Medium	
Sedimentation	Lav	
Processer i jord og grundvand	Nej	

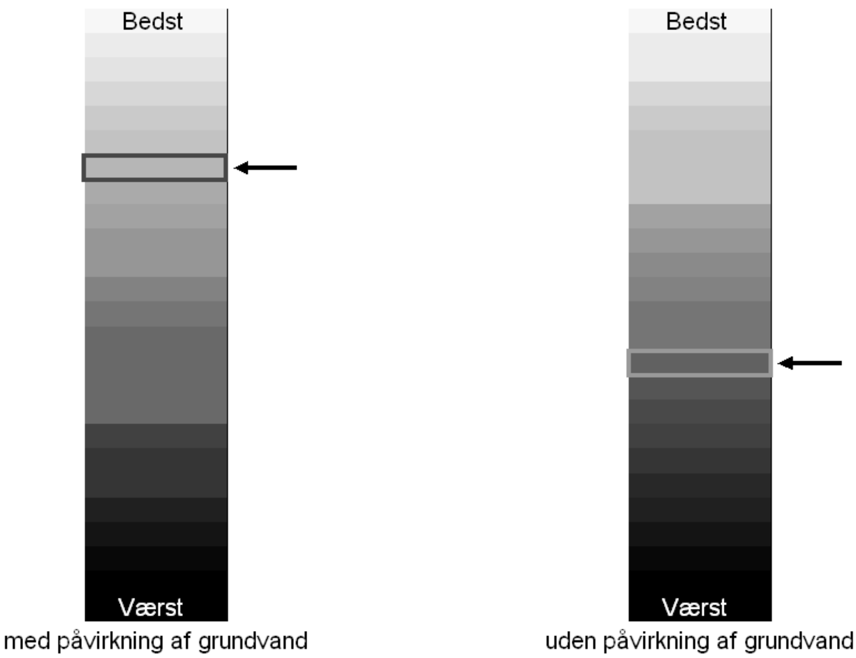


Figure 92 – Ranking for the removal of TSS

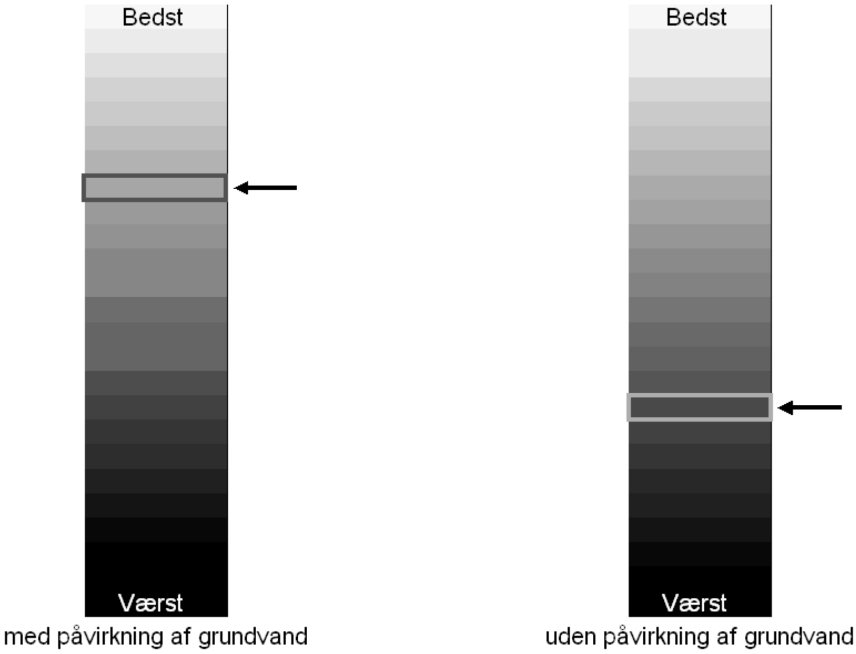


Figure 93 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

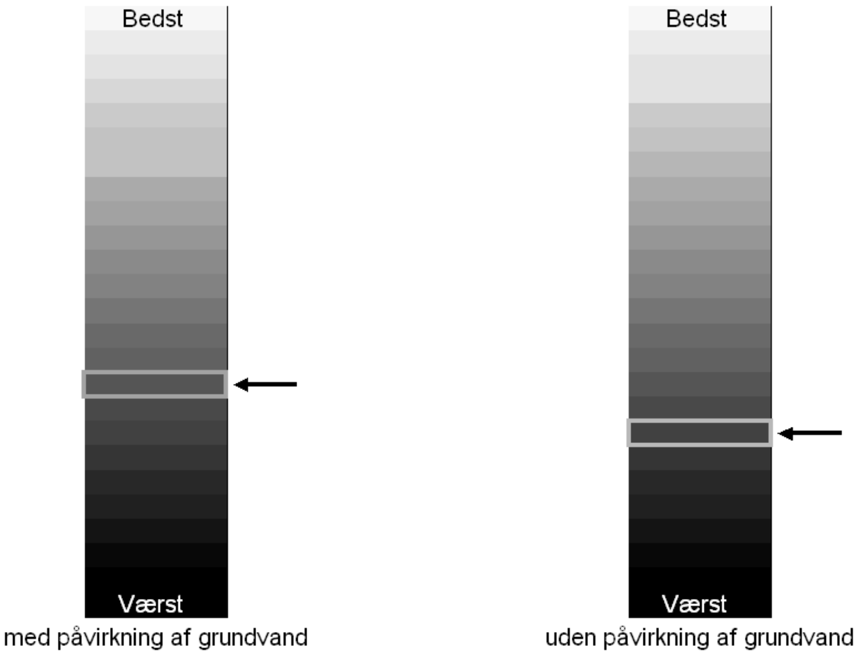


Figure 94 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

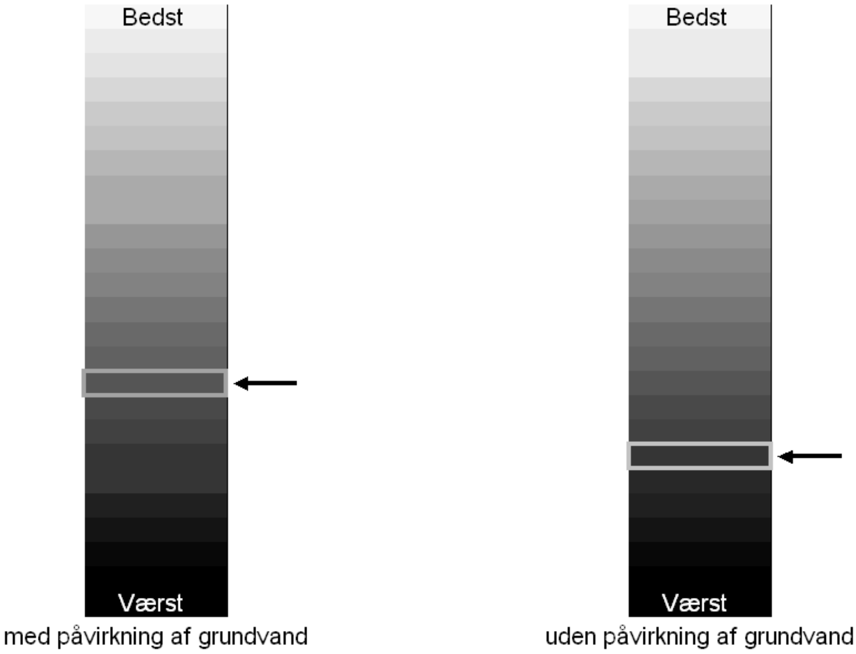


Figure 95 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.23 Adsorptionsanlæg

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Ikke Anvendelig	Suspended Solids, PAH
Fordampning	Ikke Anvendelig	
Fotolyse	Ikke Anvendelig	
Optag i planter	Ikke Anvendelig	
Sedimentation	Ikke Anvendelig	
Adsorption til substrat	Høj	
Filtrering	Høj	
Processer i jord og grundvand	Nej	

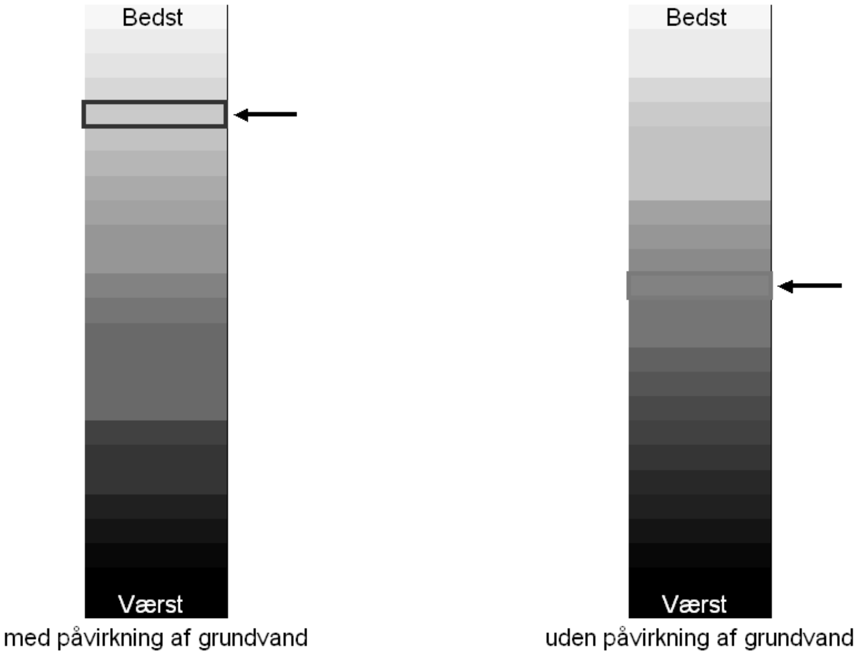


Figure 96 – Ranking for the removal of TSS

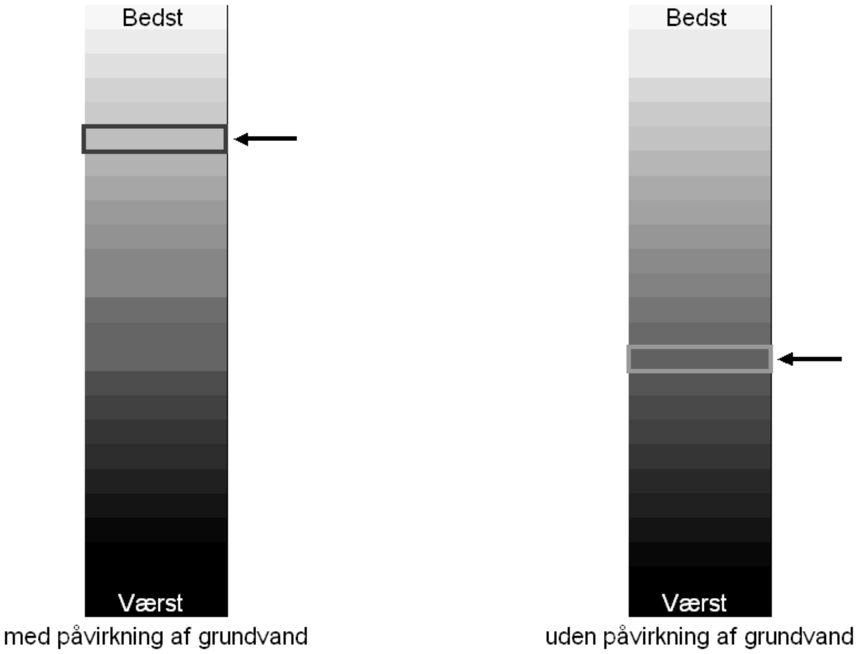


Figure 97 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

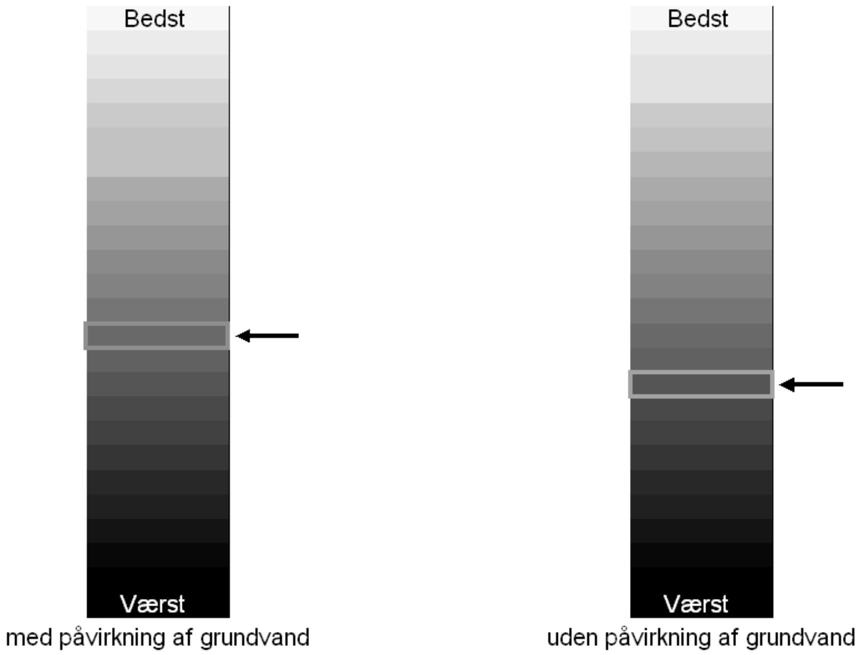


Figure 98 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

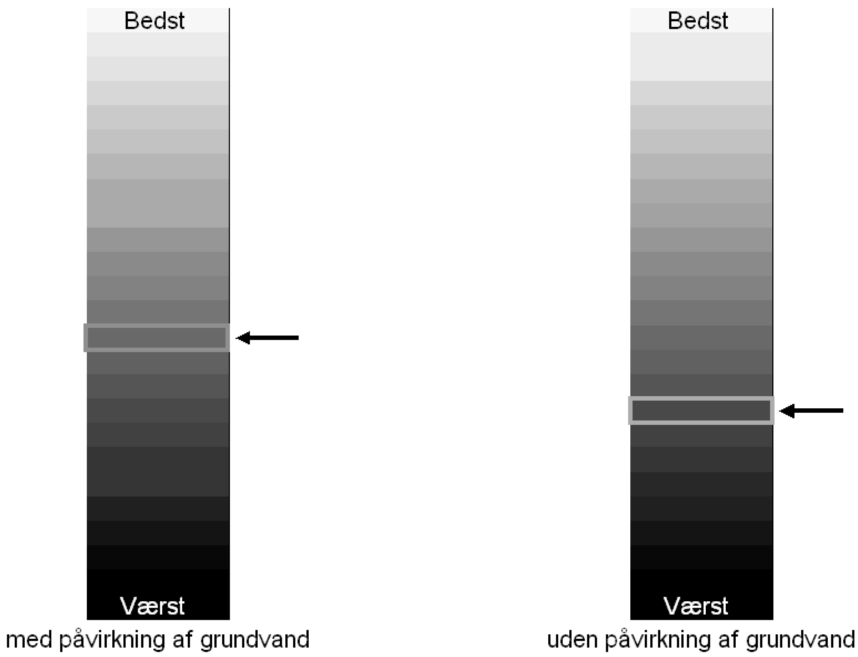


Figure 99 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.24 *Forbassiner med membran og uden beplantning*

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Lav/Medium	Suspended solid, PAH
Fordampning	Medium	
Fotolyse	Medium	
Optag i planter	Ikke Anvendelig	
Adsorption til substrat	Medium	
Filtrering	Ikke Anvendelig	
Sedimentation	Høj	
Processer i jord og grundvand	Nej	

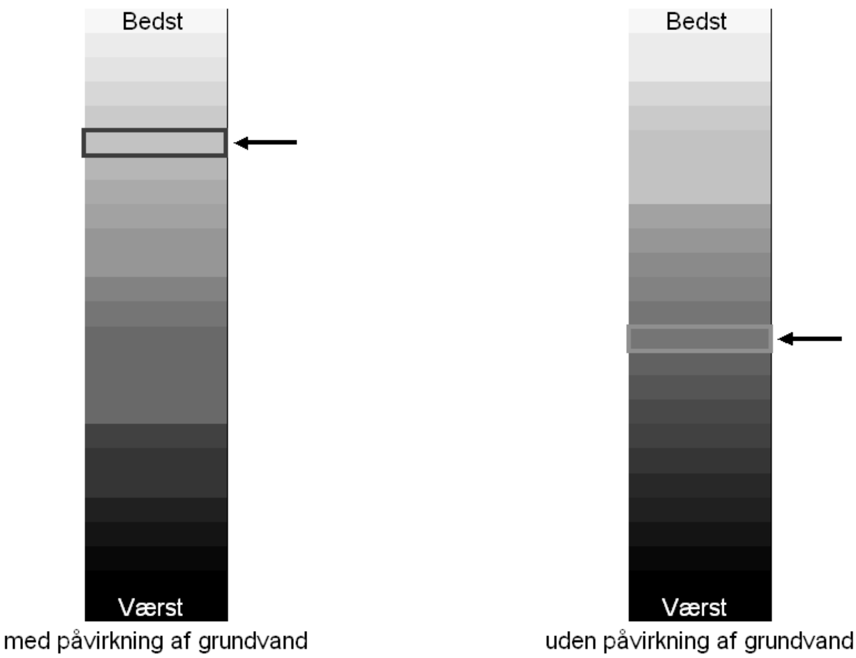


Figure 100 – Ranking for the removal of TSS

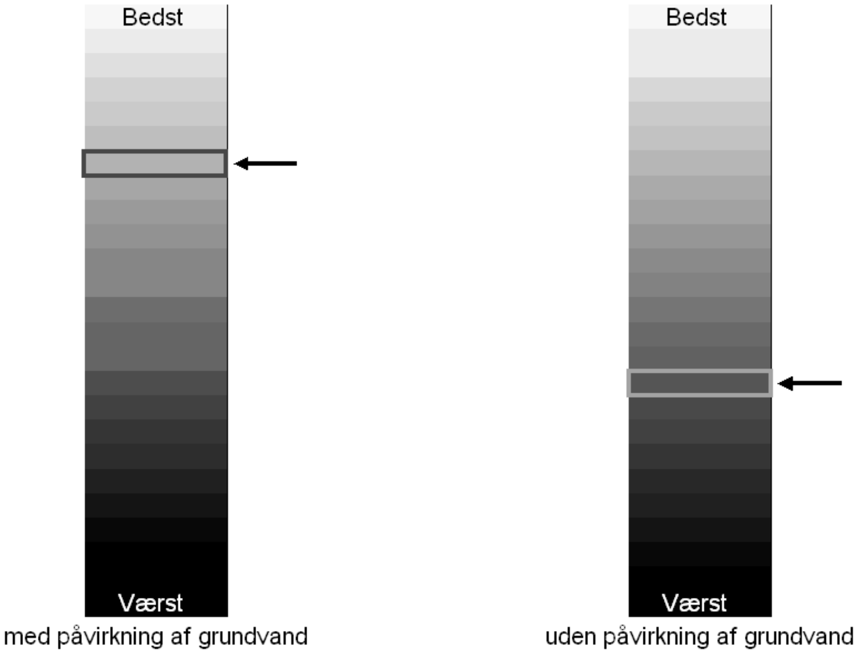


Figure 101 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

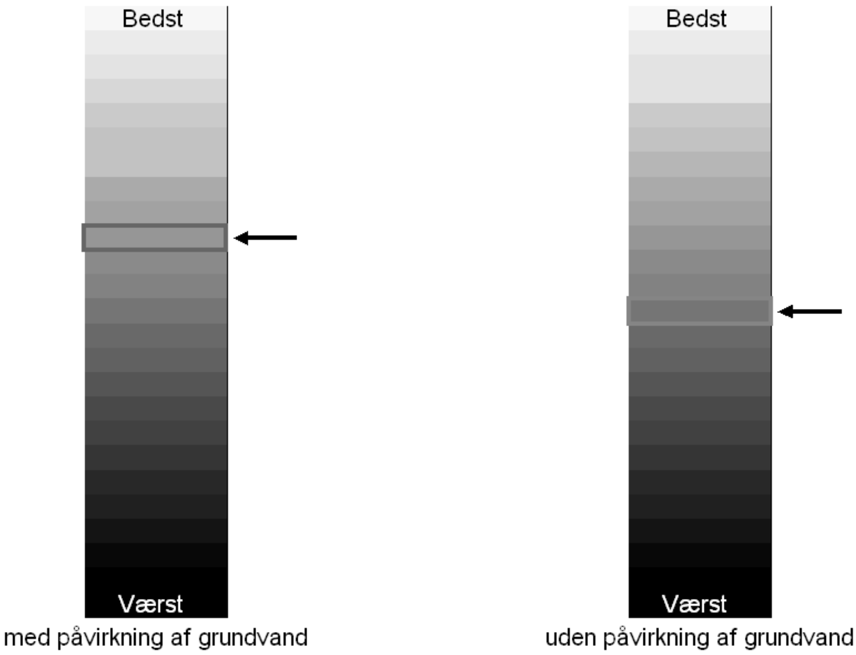


Figure 102 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

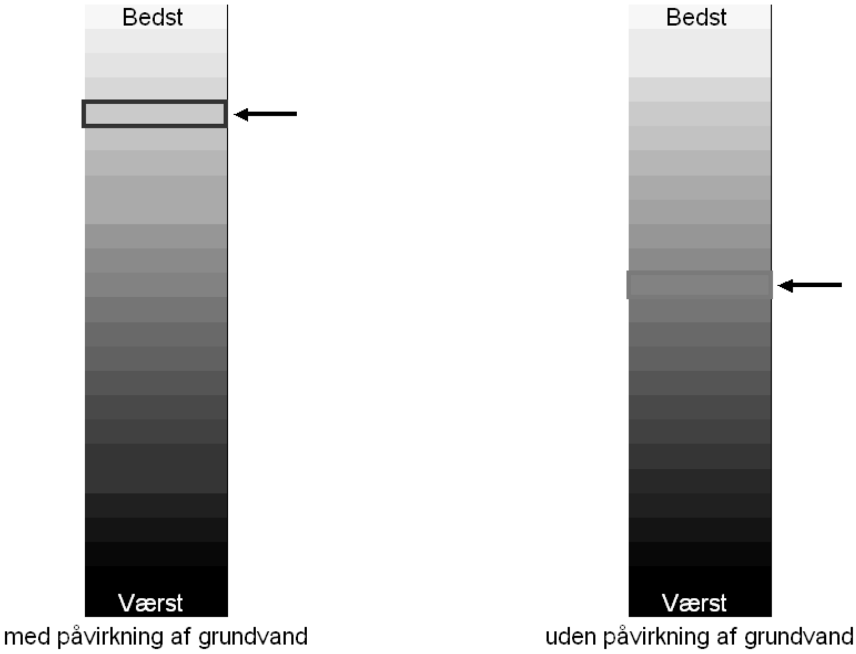


Figure 103 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

5.25 Forbassiner med membran med beplantning

Renseprocesser

Renseproces	Vigtighed af processen	Eksempel på fjernede stoffer
Mikrobiel nedbrydning	Medium	Suspended solid, PAH
Fordampning	Medium	
Fotolyse	Medium	
Optag i planter	Medium	
Adsorption til substrat	Medium/Høj	
Filtrering	Lav	
Sedimentation	Høj	
Processer i jord og grundvand	Nej	

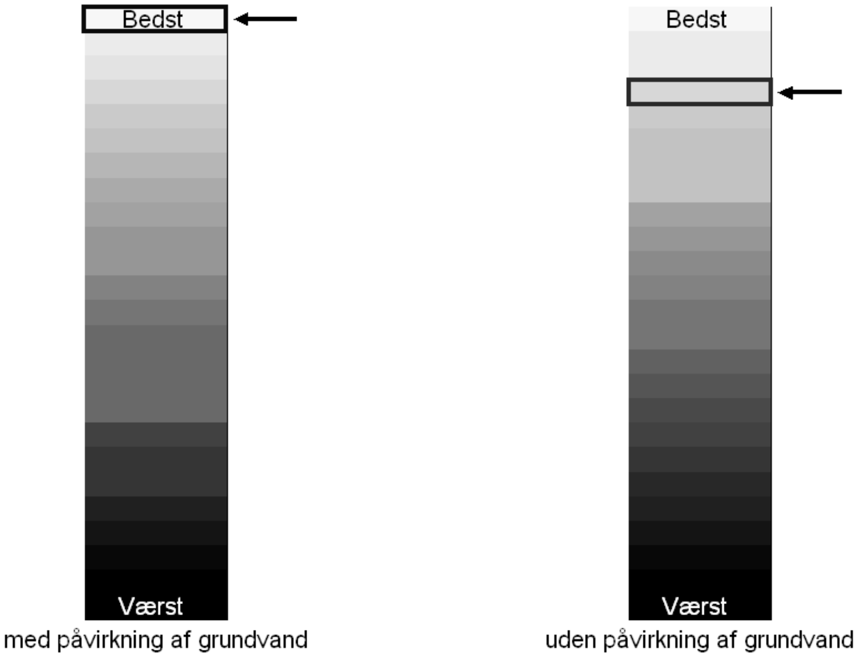


Figure 104 – Ranking for the removal of TSS

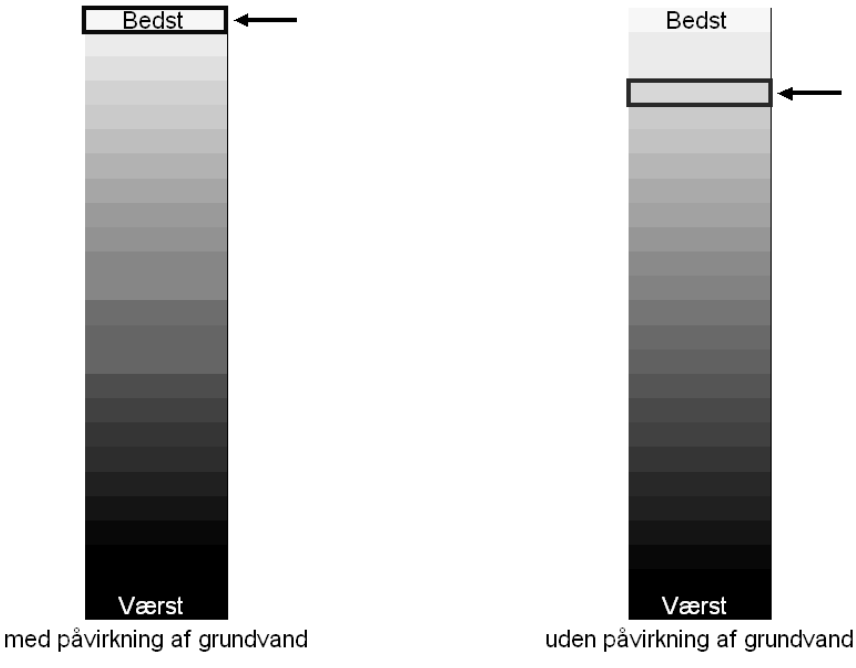


Figure 105 – Ranking for the removal of metals (Cd, Cr, Cu, Ni, Pb).

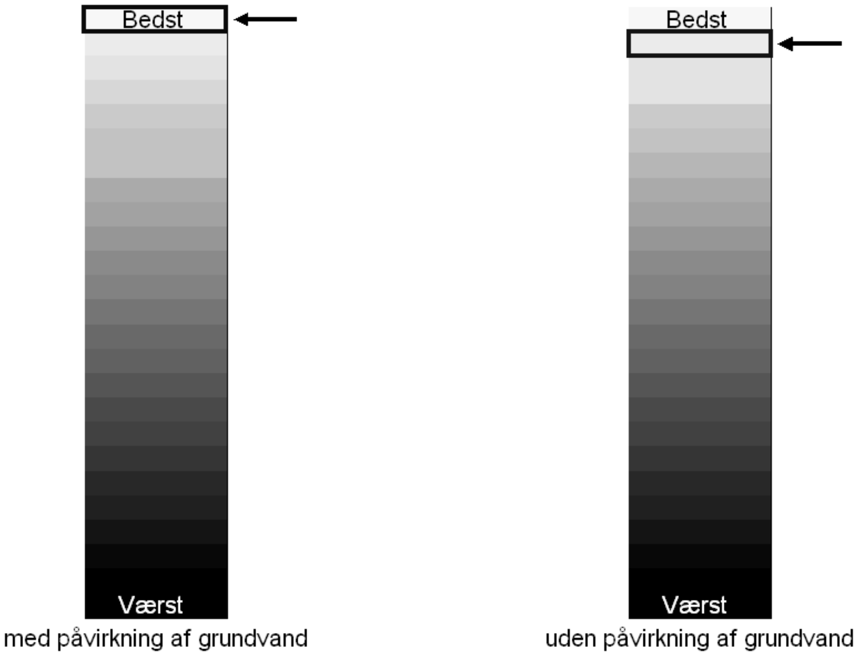


Figure 106 – Ranking for the removal of PAH indicators (fluoranthene, pyrene, DEHP).

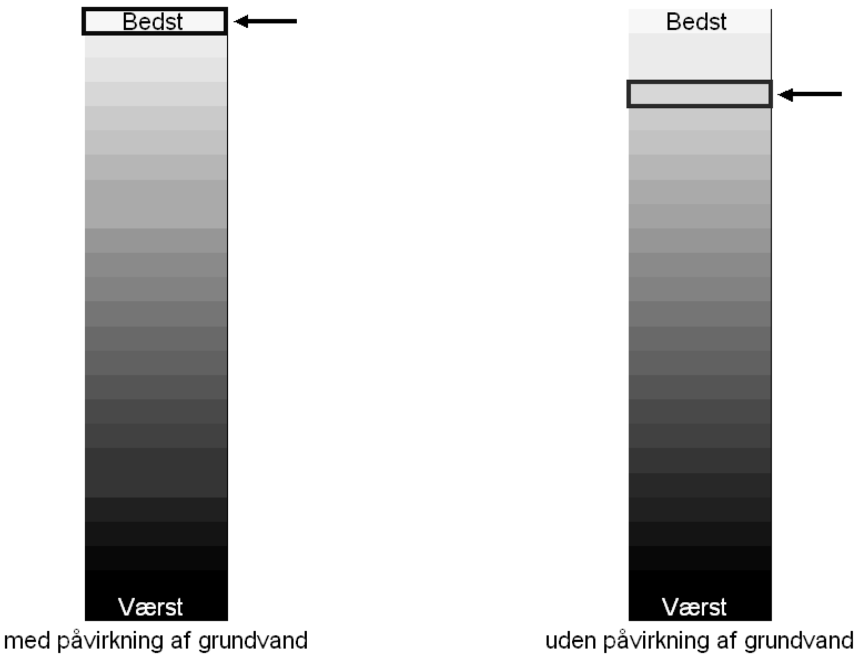


Figure 107 – Ranking for the removal of biocide indicators (diuron, glyphosate, isoproturon, terbutylazine, MTBE).

6 Summary and conclusions

The results of the ranking procedure listed in the previous chapter highlights that units with higher ranking are characterized by a wide range of removal processes. For example, permanent water volume, filtration or presence of biomass enhances the importance of certain removal processes and thus the final scoring. Also, the combination of different treatment units (e.g. the combination sandfang + forbassin) improves the removal potential as it benefits from the presence of a greater number of processes. In general, storage of stormwater in open air system with vegetation ensures high potential for removal of the various stormwater pollutant indicators that have been analyzed. All the systems based on stormwater infiltration (e.g. swales, infiltration trenches, etc.) are ranked in a medium position.

No major differences are noticed when looking at the different compounds indicators. Depending on the compound group, units can move up/downwards of a couple of position in the ranking. Generally, units tends to have a similar rank for different groups of compounds (i.e. there are no unit with good performance for one group and completely different potential for a second group).

The importance of groundwater protection in the final assessment is crucial for the final selection of the appropriate unit. The conservative approach adopted in the assessment penalizes a range of units that ensure good potential for pollutant removal, but allow stormwater infiltration (e.g. infiltration trench). When groundwater is not considered (i.e. by using Eq. 1), these units are ranked in a higher position (about 5-10 positions higher). Thus it is important to identify the soil and groundwater characteristics before selecting the most appropriate treatment option. In situations where groundwater protection is an issue, but the proposed conservative approach can be judged as excessive, a compromise between the two ranking approaches should be elaborated. However, the results of this elaboration would be strictly related to the area where the analysis is performed and could not be generalized.

As stated earlier, the results of this assessment are purely qualitative and are based on a series of hypotheses. These assumptions reflect general knowledge about the considered treatment systems. Additional data, related to the specific area under study or about the investigated treatment option, can be used to improve the assessment.

The estimation of potential removal efficiency for various stormwater treatment systems implies the calculation of mass/flow balances for the considered systems. These would require a great amount of measurements, which are seldomly available. The implementation of mathematical models for representing various stormwater treatment options might represent a valuable solution for performing a quantitative assessment with a low data-requirement.

Based on the comparison of both a qualitative and quantitative (when available) assessment, the user would be able to identity the most appropriate solution for the area under study. Also, these results can be integrated in a multi-criteria decision framework, which will integrate water quality issues with other issues that characterized urban water management (e.g. flood management).

7 References

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