Prospective environmental and economic assessment for biotreatment of micropollutants in drinking water resources in Denmark
Ivan Muñoz, Erik de Vries, Janneke Wittebol and Jens Aamand

ABSTRACT
A prospective environmental life cycle assessment (LCA) and financial cost assessment is performed to the application of bioaugmentation to sand filters in Danish waterworks, to remove 2,6-dichlorobenzamide (BAM) from drinking water resources. Based on pilot-scale and laboratory-scale data, we compare bioaugmentation to current alternative strategies, namely granular activated carbon (GAC) adsorption, and well re-location. Both assessments identified well re-location as the least preferred option, however, this result is very sensitive to the distance from the waterworks to the new well. When bioaugmentation is compared to GAC, the former has a lower impact in 13 impact categories, but if immobilized bacteria are used, the impacts are higher than for GAC in all impact categories. On the other hand, from a cost perspective bioaugmentation appears to be preferable to GAC only if immobilized bacteria are used.

INTRODUCTION
Filtration through biologically active sand filters is among the most widespread purification processes for drinking water production. However, contamination of the source water with organic micropollutants like pesticides, solvents, and pharmaceuticals often forces waterworks to either close down abstraction wells or to purify the water additionally before it is distributed. In Denmark, contamination of the groundwater with pesticides constitutes one of the biggest issues in the drinking water sector. It is estimated that between 1993 and 2009 around 130 wells all over the country have been closed due to pesticide pollution (Thorling et al. 2013). In this context, 2,6-dichlorobenzamide (BAM), a very stable degradation product of the herbicide dichlobenil, stands out as the micropollutant that has closed by far the highest number of abstraction wells. It has been detected in about 20% of the monitored wells, and in about 10% of the wells it is detected above the 0.1 μg/L threshold value (Thorling et al. 2011).

Activated carbon may be used to remove many types of organic micropollutants, but this technique is often expensive and may be ineffective towards certain compounds. In Denmark, the use of activated carbon is restricted, requiring a special permission from the authorities (Søgaard & Madsen 2013). A possible alternative to activated carbon is biological treatment. This strategy, called bioaugmentation (El Fantroussi & Agathos 2005), consists of introducing in the sand filters organisms capable of degrading specific compounds. This has been suggested as an economically feasible and environmentally friendly alternative (Albers et al. 2013). However, the environmental and cost performance of any technology or service cannot be taken for granted, and it deserves an objective assessment. In this context, life cycle assessment (LCA) is well positioned to provide such an in-depth evaluation in a prospective way, that is, by addressing the expected environmental consequences of technology or management choices. LCA has been extensively used to
assess drinking water production technologies and water provision planning (Muñoz & Rodriguez 2008; Vince et al. 2008; Stokes & Horvath 2010; Muñoz et al. 2010). Besides environmental sustainability, economic feasibility is also required for a new technology to find its way into the market, and for this reason an evaluation of financial costs constitutes an equally necessary exercise. To date, such an evaluation for bioaugmentation in waterworks has not been performed.

In this article we present a prospective environmental LCA and financial cost assessment of applying bioaugmentation to remove BAM in Danish waterworks, comparing it to existing strategies, namely granular activated carbon (GAC) adsorption, and well re-location.

METHODS

Goal and scenarios under assessment

The goal of the study was to compare the environmental and economic performance of bioaugmentation for BAM removal to existing alternatives using Denmark as an example. A typical Danish waterworks uses groundwater as water source, and applies a treatment consisting of aeration followed by sand filtration.

The scenarios to be assessed included two possibilities of applying bioaugmentation, and two current alternatives, as follows:

- Direct bioaugmentation, where Aminobacter MSH1 bacteria are directly inoculated in the sand filter as described by Albers et al. (submitted).
- Bioaugmentation with immobilized Aminobacter MSH1 bacteria, where the latter are immobilized in the sand filter within an alginate-sand matrix.
- GAC adsorption.
- Decommissioning the polluted well and opening a new one where BAM concentration is under the legal threshold value.

Main assumptions

Bioaugmentation is currently a technology under development and thus it is not applied in waterworks. As a consequence, many aspects of its deployment and application at full-scale are uncertain, and for this reason many assumptions had to be made to perform this prospective assessment. The most outstanding assumptions were the following:

- The existing sand filters in the waterworks are used, without any modifications to its operation, other than the inoculation with degrading bacteria. This choice was based on the fact that substantial modifications to the filters would incur in excessive costs.
- Above 50% of the BAM content in groundwater (around 0.2 μg/L in raw water) is removed by bioaugmentation. This is in accordance with pilot-scale tests (Albers et al. Submitted), and leads to drinking water meeting the legal BAM threshold.
- The frequency of inoculation is very uncertain at this point. A bimonthly frequency was assumed when direct bioaugmentation is used. This assumption was based on expert judgement (Albers 2013). When bacteria are immobilized this frequency is reduced. Based on laboratory-scale tests (Albers et al. submitted), an annual frequency was assumed.
- Industrial-scale production data for Aminobacter MSH1 bacteria are not available. As a surrogate, environmental and cost data for yeast production were used. Yeast was chosen due to the fact that it constitutes a cheap microorganism to produce. A successful deployment of bioaugmentation would require Aminobacter MSH1 to be produced using similarly cheap methods.
- When bioaugmentation is used, the well lifespan is increased as compared to a situation where BAM pollution is not treated, since the latter would lead to closure of the well. Treatment with GAC also leads to this beneficial effect, however in both cases the extent in years for this increase is uncertain. We assumed an increase of 50%, from an average of 50 years (Godskesen et al. 2013) to 75 years.
- Even though Aminobacter MSH1 is not a pathogen, a UV disinfection step is assumed to be applied to ensure microbiological safety of drinking water. In the case of GAC filtration UV filtration is needed, therefore a technology such as bioaugmentation, that introduces bacteria in the process, is very likely to need it as well.
- In GAC filtration, GAC is derived from hard coal, and regenerated in Belgium (Isager 2013).
In the well re-location scenario, the new well is located at 25 km of the waterworks instead of the average 5 km (Godskesen et al. 2013). This implies more piping material, as well as additional energy to transport water to the waterworks.

Due to the uncertainty involved in these choices, several sensitivity analyses were performed in order to check the robustness of the results.

**LCA scope and data collection**

The LCA study was carried out with the ISO 14040 and 14044 standards as main methodological guidelines (ISO 2006a, 2006b), and consequential modelling was used in the inventory analysis, as defined in Ekvall & Weidema (2004) and Weidema et al. (2009). The software used was SimaPro version 8.0.4 (Pré Consultants 2015).

**Functional unit**

The functional unit, i.e. the basis for comparing the four scenarios was the provision of 1 m³ of drinking water with a BAM concentration under 0.1 μg/L, where BAM concentration has been reduced by 50% from around 0.2 μg/L.

**System boundaries**

The product system included only those activities that were affected by the need to keep BAM levels under the legal limit. As a consequence, the following activities were excluded: waterworks construction and dismantling, common waterworks operations (groundwater abstraction, aeration, conventional sand filtration) and distribution of drinking water to consumers. Table 1 summarizes the specific activities included in each of the four scenarios.

**Data collection**

A wide variety of data sources were used in order to perform the life cycle inventory (LCI) analysis. Below we describe the main sources, whereas detailed inventory tables can be found in the supplementary material (available in the online version of this paper).

In the direct bioaugmentation scenario, the amount of microorganism inoculated were obtained from pilot-scale experiments as described in Albers et al. submitted. Industrial-scale production of Aminobacter MSH1 bacteria were approximated from data by Dunn et al. (2012) for yeast production using sugar beet molasses as main nutrient source. Energy used by the UV disinfection system was obtained from Lemming et al. (2012).

When bioaugmentation is used with immobilized bacteria, sodium alginate and quartz sand are used to prepare the carrier. The specific amounts of these materials were obtained from laboratory-scale tests (Lapanje 2014), whereas data for sodium alginate production were obtained from Langlois et al. (2012). Quartz sand production was modelled with generic data from the ecoinvent database v.2.2 (Althaus et al. 2004).

The GAC efficacy for adsorbing BAM was based on pilot-scale tests carried out in Denmark by Clausen et al. (2003). The inventory for GAC production was obtained

<table>
<thead>
<tr>
<th>Activities included in the four assessed scenarios</th>
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</thead>
<tbody>
<tr>
<td><strong>Bioaugmentation-direct</strong></td>
</tr>
<tr>
<td>Production and delivery to the waterworks of the BAM-degrading bacteria.</td>
</tr>
<tr>
<td>Energy used by a UV system.</td>
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<tr>
<td>Removal of BAM up to a concentration below 0.1 μg/L.</td>
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<tr>
<td>Emissions from BAM degradation in the sand filter.</td>
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<tr>
<td>Extending the lifetime of the existing well.</td>
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<tr>
<td><strong>Bioaugmentation-immobilized</strong></td>
</tr>
<tr>
<td>Those in the bioaugmentation scenario.</td>
</tr>
<tr>
<td>Production and delivery of carrier materials.</td>
</tr>
<tr>
<td>Disposal of carrier materials.</td>
</tr>
<tr>
<td><strong>GAC</strong></td>
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<tr>
<td>Production and delivery of GAC to the waterworks.</td>
</tr>
<tr>
<td>Energy used by a UV system in the waterworks.</td>
</tr>
<tr>
<td>Transport and regeneration of spent GAC.</td>
</tr>
<tr>
<td>Removal of BAM up to a concentration below 0.1 μg/L.</td>
</tr>
<tr>
<td>Extending the lifetime of the existing well.</td>
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<tr>
<td><strong>Well re-location</strong></td>
</tr>
<tr>
<td>Dismantling the existing well: disposal of construction materials and equipment.</td>
</tr>
<tr>
<td>Opening a new well: producing and delivering to the well site new construction materials and equipment, as well as the construction activities themselves.</td>
</tr>
<tr>
<td>Increased energy use for water transportation to waterworks.</td>
</tr>
</tbody>
</table>
from Sparrevik et al. (2011), whereas energy use by the GAC filter including the UV system in a Danish waterworks was obtained from Lemming et al. (2012). Data for GAC regeneration were obtained from Muñoz et al. (2007). A distance of 900 km was considered for transport to the regeneration plant.

Well infrastructure was obtained from Godskesen et al. (2013) who described in detail a typical Danish waterworks. From this same reference we also obtained inventory data for the well relocation scenario, namely the additional piping material as well as additional electricity for transporting water to the waterworks considering a distance of 25 km instead of 5 km.

Electricity production profiles in the foreground system were defined based on consequential LCI modelling, where only marginal suppliers of electricity were considered. Electricity profiles were defined for Denmark, Brazil, China, Belgium, Malaysia, and Europe (see ‘Marginal supply of electricity’ in the supplementary material, available in the online version of this paper).

All other activities included in the life cycle (fuels, auxiliary materials, transport services) were modelled by means of inventories from the ecoinvent database v.2.2 (Ecoinvent centre 2014). Transport distances for materials were defined based on averages as defined in the ecoinvent database v.2.2 (Frischknecht et al. 2004).

Impact assessment method

Life cycle impact assessment (LCIA) was carried out using the method developed by 2-0 LCA consultants ‘Stepwise 2006’ (Weidema 2009), however the USEtox model (Rosenbaum et al. 2008) was used for toxicity-related impact categories, in order to reflect the most recent developments in this area. The pollutant BAM does not currently have characterisation factors for human toxicity in USEtox. For this reason, they were calculated specifically for this study, as $1.84 \times 10^{-6}$ comparative toxic units (CTU) per kg BAM emitted to continental freshwaters (see ‘Characterization factor for BAM in human toxicity’ in the supplementary material, available in the online version of this paper). Also, the Stepwise method does not currently cover impacts on water resource use. In order to cover this gap, the impact category ‘water depletion’ from the ReCiPe method (Goedkoop et al. 2008) was used. This indicator excludes water used for cooling and water used in hydropower plants, as these are non-consumptive uses. This indicator measures water in volumetric units (m$^3$), without adjusting for water scarcity. Although this can be seen as a limitation, it must be highlighted that in the present study the groundwater abstracted in all scenarios originates in the same catchment area, whereby differences in water scarcity are considered irrelevant.

Cost assessment

Costs were calculated for 2014, excluding VAT, for an annual production of 800,000 m$^3$ drinking water. Both capital and operation costs were taken into account, with the former being annualized by means of a depreciation time of 22.5 years and an interest rate of 5%. Below we describe the main cost items included in the calculations, whereas the detailed figures can be seen in the supplementary material, ‘Cost model’ section (available in the online version of this paper).

The capital costs for direct bioaugmentation included an automatic inoculum cooling and dosing system, as well as the UV disinfection system. The operation costs included labour and monitoring, inoculum costs, as well as the UV system operation.

When immobilized bacteria are used, capital costs include the UV disinfection system, the carrier materials (sand, alginate, calcium chloride) and their installation in the sand filter. Operation costs include regeneration of the carrier materials on an annual basis, maintenance, monitoring, and the operation of the UV system.

In the GAC filtration scenario, costs included capital costs (construction and start-up) and annual costs for a 30 m$^3$ filter requiring regeneration every 1.5 years. Costs also included the investment and operation of the UV disinfection system.

The costs for construction of a new well at a distance of 25 km of the waterworks were estimated by the company Vitens (Jong 2014), and the decommissioning costs for the old well were estimated as 5% of the construction costs (Isager 2014). Increased power consumption for transport of water was estimated based on figures by Godskesen et al. (2013) and the average cost of electricity for industrial users in Denmark (Eurostat 2015).
RESULTS

LCA results

Figure 1 shows the LCIA results for the 16 impact categories included in the assessment. In this graph the scenarios are ranked in each impact category in relation to the highest-scoring scenario, which shows a value of 100%.

The impact assessment results show that in all impact categories, except nature occupation, the highest impact is achieved by applying the well re-location strategy. This is mainly explained by the fact that the new well is much further away from the waterworks and therefore electricity use for extracting and transporting the water increases above a factor 2. The additional capital equipment, such as pipes and other building materials play a secondary role in these results for well re-location.

When the treatment scenarios are compared, it can be seen that bioaugmentation with immobilized bacteria shows the highest impact in 14 impact categories. Finally, direct bioaugmentation appears to have a lower impact than GAC in 13 impact categories. Figure 2 shows for the global warming impact category how different activities influence the life cycle impact for the bioaugmentation scenarios. It can be observed that most of the impact is associated to the electricity needed to operate the UV system, and this is common to both scenarios (as well as to the GAC scenario). The reason for the higher impact of the immobilized bacteria scenario is related to the production, transport, and annual replacement of the carrier materials (alginate, sand, CaCl2). It can also be highlighted that the impact of inoculum production is very low in both scenarios.

Another aspect to highlight from Figure 1 is that all scenarios have the same impact in water depletion. This is due to the fact that the amount of freshwater extracted from nature is the same in all cases (1 m³), and the water used by the
background system (for production of energy and materials) is comparatively negligible.

**Costs**

Table 2 shows the results of the financial cost assessment, including capital costs, annual operation costs, and the net costs per m³ drinking water produced. According to these results, the well-relocation strategy involves the lowest cost, whereas direct bioaugmentation is the most expensive one, due to its relatively high operation costs. On the other hand, bioaugmentation with immobilized bacteria appears to be cheaper than GAC filtration, due to lower investment costs.

### Table 2 | Costs for the four scenarios assessed, for a waterworks producing 800,000 m³ drinking water per year

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Investment costs (€)</th>
<th>Annual operation costs (€)</th>
<th>Cost per m³ (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioaugmentation</td>
<td>80,000</td>
<td>150,000</td>
<td>0.20</td>
</tr>
<tr>
<td>Bioaugmentation, immobilized</td>
<td>170,000</td>
<td>80,000</td>
<td>0.11</td>
</tr>
<tr>
<td>GAC</td>
<td>840,000</td>
<td>60,000</td>
<td>0.15</td>
</tr>
<tr>
<td>Well re-location</td>
<td>4,334,000</td>
<td>8,200</td>
<td>0.42</td>
</tr>
</tbody>
</table>

**Sensitivity analyses**

Due to the inherent uncertainty of the model, several sensitivity analyses were performed in order to check the robustness of our results. Table 3 shows a qualitative description of these analyses and their outcome. The detailed quantitative results are available in the supplementary material, ‘Sensitivity analyses applied to the LCA’ and ‘Sensitivity analyses applied to the cost assessment’ sections (available in the online version of this paper).

The sensitivity analysis shows that the environmental performance of well re-location is very dependent on the assumed distance to the waterworks. If we consider the same distance as in the current waterworks (5 km) the impact as well as the cost of this scenario decreases.

### Table 3 | Summary of sensitivity analyses performed on the LCA and cost assessment

<table>
<thead>
<tr>
<th>Sensitivity analyses</th>
<th>Main outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>On the LCA: Carrier material used to immobilize bacteria: quartz sand replaced by expanded clay</td>
<td>The impact of the immobilized bacteria scenario increases, e.g. GHG emissions for this scenario increase more than 100%.</td>
</tr>
<tr>
<td>Inoculation frequency increases for both bioaugmentation scenarios</td>
<td>Direct bioaugmentation shows little sensitivity to this change in most impact categories. The immobilized bacteria scenario increases its impact very quickly if inoculation frequency increases.</td>
</tr>
<tr>
<td>Small-scale inoculum production: MSH1 bacteria produced according to laboratory-scale procedures</td>
<td>The impact of both bioaugmentation scenarios increases, e.g. in direct bioaugmentation GHG emissions increase by 500%.</td>
</tr>
<tr>
<td>Well relocation: new well at same distance than current wells (5 km)</td>
<td>Impact of well re-location decreases, e.g. in GHG emissions it involves 60% less impact than direct bioaugmentation. Well relocation becomes the best-performing scenario.</td>
</tr>
</tbody>
</table>

| On the cost assessment: Annual water production capacity | The immobilized bacteria scenario breaks even with GAC at 2 × 10⁶ m³/year. Well re-location remains the most costly option. |
| Inoculum costs | The immobilized bacteria scenario shows little sensitivity to inoculum cost, whereas direct bioaugmentation is very sensitive. The latter breaks even with GAC at an inoculum cost of around 2 €/litre. |
| Carrier regeneration frequency in the immobilized bacteria scenario | Costs rapidly increase with increased frequency. The immobilized bacteria scenario breaks even with GAC and direct bioaugmentation at a frequency of 8 and 5 months, respectively. |
| Well re-location: new well at same distance than current wells (5 km) | Relocation cost decreases from 0.42 €/m³ to 0.11 €/m³ and becomes the most economic option together with bioaugmentation with immobilized bacteria. |

GHG: greenhouse gas.
becoming the best-performing one in environmental terms, and the cheapest together with bioaugmentation with immobilized bacteria.

Direct bioaugmentation is not affected in environmental terms when inoculation frequency is increased, however when bioaugmentation is applied with immobilized bacteria, impacts sharply increase with increased inoculation frequency. As an example, greenhouse-gas (GHG) emissions increase by 30% if frequency increases from one to two events per year.

Bioaugmentation also appears to be very sensitive to how the inoculum is produced. When small-scale laboratory conditions are considered, the impact of bioaugmentation (both direct and immobilized) increases. In direct bioaugmentation this increase is by a factor of 5. Direct bioaugmentation is also substantially affected by inoculum costs. This shows that for this technology to be competitive, both in economic and environmental terms, inoculum production needs to be carried out at large industrial scale.

Another factor affecting bioaugmentation, when used with immobilized bacteria, is the type of material used in the carrier. When more energy-intensive materials are considered, like expanded clay, the impact sharply increases, in this case by more than a factor of 2 in terms of GHG emissions.

Discussion

To our knowledge, this is the first attempt at assessing bioaugmentation in waterworks, either from an environmental or an economic perspective. The figures obtained are only orientative, but even with the present degree of uncertainty they give us new insights on this emerging technology.

First of all, both assessments point to well re-location as the least preferable strategy for drinking water provision, however our sensitivity analyses show that if the new well is close enough to the waterworks, then this option becomes the best one.

Albers et al. (2013) claimed that GAC is a costly option. When compared to bioaugmentation, the latter appears to be an economically competitive option only when applied with immobilized bacteria. Direct bioaugmentation is the most expensive option after well re-location, although the overall cost is very sensitive to the price of the inoculum, which is at this stage very uncertain. Currently, bioaugmentation of sand filters in waterworks targets only BAM, for which degrading bacteria are available. In cases where waters are contaminated by multiple pollutants GAC application may be superior, as GAC also remove other contaminants in addition to BAM. Nevertheless, other pesticide-degrading bacteria exist that may in the future be utilized in combination with BAM-degrading bacteria to remediate waters polluted by more than one pesticide.

From an environmental point of view, both bioaugmentation scenarios seem to be in the same order of magnitude than GAC, with direct bioaugmentation showing slightly lower impact scores than GAC in many impact categories. A rather unexpected result is the fact that one of the main drivers for the environmental impact of bioaugmentation is the energy required by the UV system, regardless of whether bacteria are immobilized or not.

Given the uncertainty associated to our LCA, and the sensitivity it shows to some key parameters as shown in Table 3 we think it is too soon to extract precise conclusions on the relative sustainability of bioaugmentation, but in spite of this we can take home some lessons on how to improve this technology. As an example, our results indicate that an efficient production of Aminobacter MSH1 is a must for bioaugmentation to have similar or lower impact than GAC. Also, that using energy-intensive materials such as expanded clay to immobilize bacteria will probably increase the impacts too much, unless they can be reused.

In order to obtain a more accurate picture of this technology, an assessment would be required based on tests in an actual waterworks, where data reflect to a larger extent operation at full-scale. Many parameters that could not be defined accurately at small scale, such as modifications to the way the sand filter is operated, the quantities and type of carrier materials used, the frequency and volume of inoculum, or the pollutant removal efficiency, could be confidently defined.

CONCLUSIONS

An environmental and cost assessment has been performed to bioaugmentation of sand filters in Denmark, to remove the pollutant BAM from drinking water resources. We
have compared this emerging technology to two current alternatives, namely treatment with GAC, and re-location of the abstraction well. Both assessments clearly identified well re-location as the least preferred option; however, this is very sensitive to the distance of the new well to the waterworks. When bioaugmentation is compared to GAC, the former has a lower impact in 13 impact categories, but if immobilized bacteria are used, the impacts are higher than for GAC in all impact categories. On the other hand, from a cost perspective bioaugmentation appears to be preferable to GAC only if immobilized bacteria are used.

In spite of the high uncertainty related to assessing a technology at this early stage of development, this study has provided a first quantitative impression of the potential environmental impacts and costs of bioaugmentation, benchmarking the latter against current alternatives and pointing out key areas where either more knowledge is needed or attention should be put in order to minimize the environmental impacts and costs of this technology.

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