Measures to reduce micropollutant emissions to water

TEXTE
87/2014

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Summary

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Measures to reduce micropollutant emissions to water

Summary

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1 Background

In the European Water Framework Directive 2000/60/EC that established a framework for Community action in the field of water policy, Article 16 "Strategies against pollution of water" states that specific measures have to be implemented to combat the pollution to water from relevant pollutants or groups of pollutants. In Directive 2008/105/EC, environmental quality standards (EQS) were set for 33 priority substances or substance groups as target values to achieve a good chemical status of surface waters. Member States have to implement measures to reduce or avoid substances if these targets are exceeded. Some of the previous EQS were adjusted and twelve new substances were included as priority substances in Directive 2013/39/EC amending Directives 2000/60/EC and 2008/105/EC. In addition, a monitoring list was introduced for substances that are potentially hazardous for the aquatic environment and for which, so far, especially because of analytical difficulties, Europe-wide relevance cannot be proven, even though the amounts produced and consumed suggest considerable emissions to water are occurring. Based on this monitoring list, monitoring data are to be collected for these substances that can be compared across Europe. The European Commission's Joint Research Centre (JRC)[1] is responsible for the selection and analysis of substances. If pollution is confirmed across the whole of Europe, the relevant substances should be added to the list of priority substances, which is updated at regular intervals.

To reduce and avoid emissions of the relevant substances, in principle, it is conceivable to implement measures at source (substance avoidance / environmental protection integrated in production) as well as downstream measures along the emission pathway (e.g. end-of-pipe measures at the actual discharge points into water such as municipal sewage treatment plants or combined waste water and stormwater overflows). The effectiveness and associated costs of these measures play a major role when selecting suitable emission reduction options.

Many substances find their way into the municipal waste water system during their useful lives or via transportation processes so that this system represents an important, closed segment for a comparative analysis. Discharge via the municipal waste water system is the dominant emission pathway to water especially for household chemicals, substances used in commerce and industry (especially in small and medium-sized enterprises), pharmaceuticals and biocides.

Against this background, the primary objective of this study was to develop suitable measures or combinations of measures and their framework conditions to reduce the emission to water of micropollutants via the municipal waste water system that are characterized by high cost efficiency. The emission-relevant substance flows from this field were analysed for a total of twelve selected substances and substance groups. The emissions to water were modelled in addition to this for some of the substances. The results formed the basis for identifying and evaluating relevant emission reduction measures. The results were used to examine the interaction, effectiveness and cost efficiency of source-based and end-of-pipe measures and to derive promising combinations of measures. The experiences made in Switzerland with regard to introducing a fourth stage of purification and limiting diffuse emissions could also be assessed in the studies. In line with the general focus of the project on municipal waste water systems and organic micropollutants, possible measures in other areas causing pollution like, e.g. agriculture, were excluded here.

[1] The Joint Research Centre, JRC, is the European Commission's in-house science service assigned to the European Commissioner for Science, Innovation and Research. Its work supports decision processes at European level (https://ec.europa.eu/jrc/)

2 Methodology

Emission-based substance flow analyses were used to identify the relevant emission pathways for the selected micropollutants. Within this framework, the phases of production, useful life and post-utilisation were analysed with their respective input and output flows[2]. The necessary substance-specific information and data are mainly based on specialist literature, available databases and statistics as well as expert interviews. The analyses focused on the specific emission patterns of the substances, in particular; there were some gaps in the substance flow data available for the amounts produced and imported. To calculate the amount of pollutants emitted via the different pathways (point and diffuse sources), the modelling tool MoRE[3] (Modelling of Regionalized Emissions) and regionalized pathway analysis were additionally used for some of the substances. By illustrating measures and combinations of measures, the MoRE system also allows an assessment of activity options and reduction potentials. Concerning substance emissions via municipal sewage treatment plants, specific measures can be implemented in the model depending on the available treatment stages and plant size. The Neckar river basin was chosen as the region to be modelled.

The emission reduction measures analysed were derived from the identified emission pathways on the one hand; on the other hand, studies at the level of river basins and in marine protection were analysed as were other publications. To describe the costs and effect of a fourth stage of purification, supplementary literature data were analysed as were the experiences from ongoing studies in Baden-Württemberg, North Rhine-Westphalia and Switzerland. The cost calculations are based on a standardized method following the guidelines for calculating cost comparisons. Corresponding price corrections were made where different currencies and reference years were involved.

3 Identification of water-relevant micropollutants

A first overview was compiled based on the different national and international lists of water-relevant pollutants in order to obtain a base for selecting representative, water-relevant micropollutants for the more detailed study whose main emission pathway is the municipal waste water system. From this comprehensive compilation, relevant pollutants were derived for Germany based on different criteria (among other things, current production, use and level of pollution in Germany, data availability and relevance for the discharge via municipal sewage treatment plants). With the client's agreement, the following twelve substances were included in the studies: three biocides (terbutryn, triclosan, TBT), five pharmaceuticals (diclofenac, ibuprofen, metoprolol, sulfamethoxazole, iomeprol) and four other substances/substance groups (PAH (polycyclic aromatic hydrocarbons), nonylphenol, PFOS, HBCDD), each with very different applications and corresponding emission patterns.

[2] See European Commission (2012): Guidance Document No. 28 Technical Guidance on the Preparation of an Inventory of Emissions, Discharges and Losses of Priority and Priority Hazardous Substances, Technical Report – 2012 – 058 http://bookshop.europa.eu/en/technical-guidance-on-the-preparation-of-an-inventory-of-emissions-discharges-and-losses-of-priority-and-priority-hazardous-substances-pbKHAN12028/

and Hillenbrand, T.; Toussaint, D.; Böhm, E,; Fuchs, S.; Scherer, U.; Rudolphi, A.; Hoffmann, M. (2005): Einträge von Kupfer, Zink und Blei in Gewässer und Böden – Analyse der Emissionspfade und möglicher Emissionsminderungsmaßnahmen. Texte 19/05, Umweltbundesamt, Dessau.

[3] http://isww.iwg.kit.edu/MoRE.php;

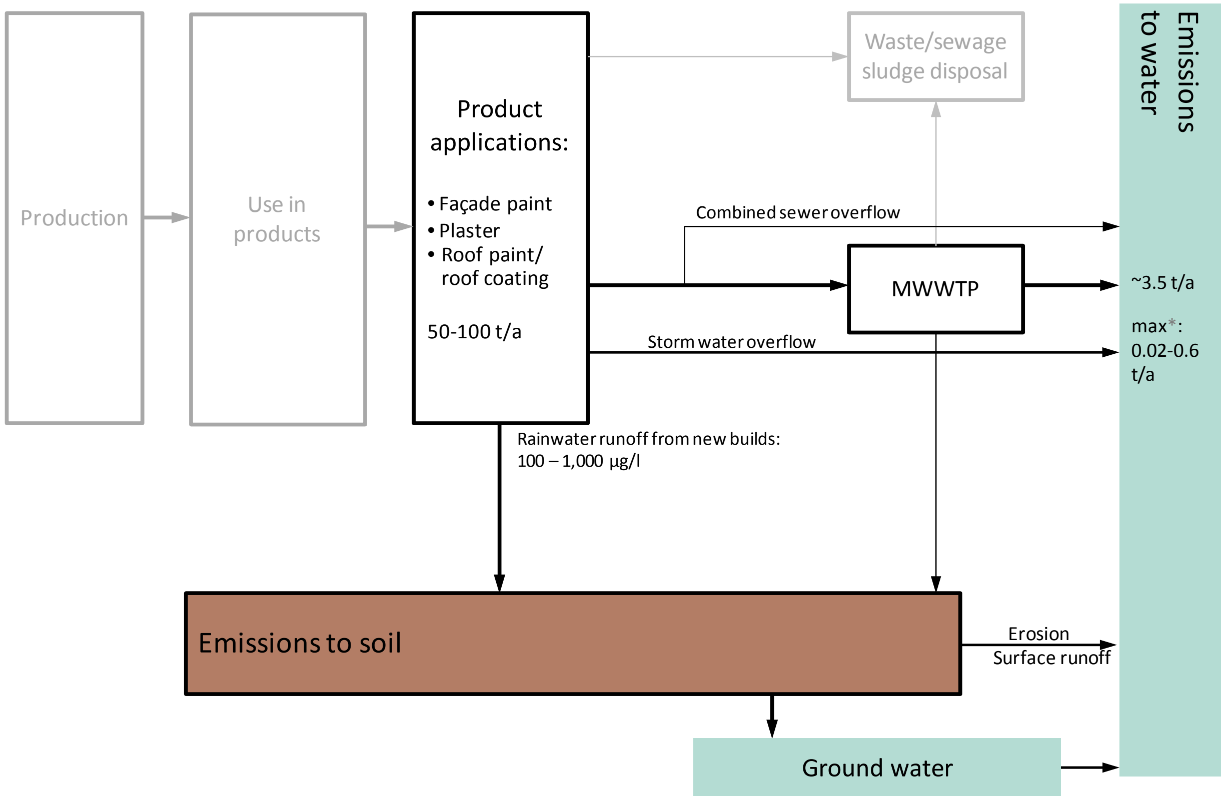
Fuchs, Stephan; Scherer, Ulrike; Wander, Ramona; Behrendt, Horst; Venohr, Markus; Opitz, Dieter et al. (2010): Berechnung von Stoffeinträgen in die Fließgewässer Deutschlands mit dem Modell MONERIS. Nährstoffe, Schwermetalle und Polyzyklische aromatische Kohlenwasserstoffe. 1. Aufl. 1 Band. Dessau-Roßlau (UBA-Texte, 45/10)

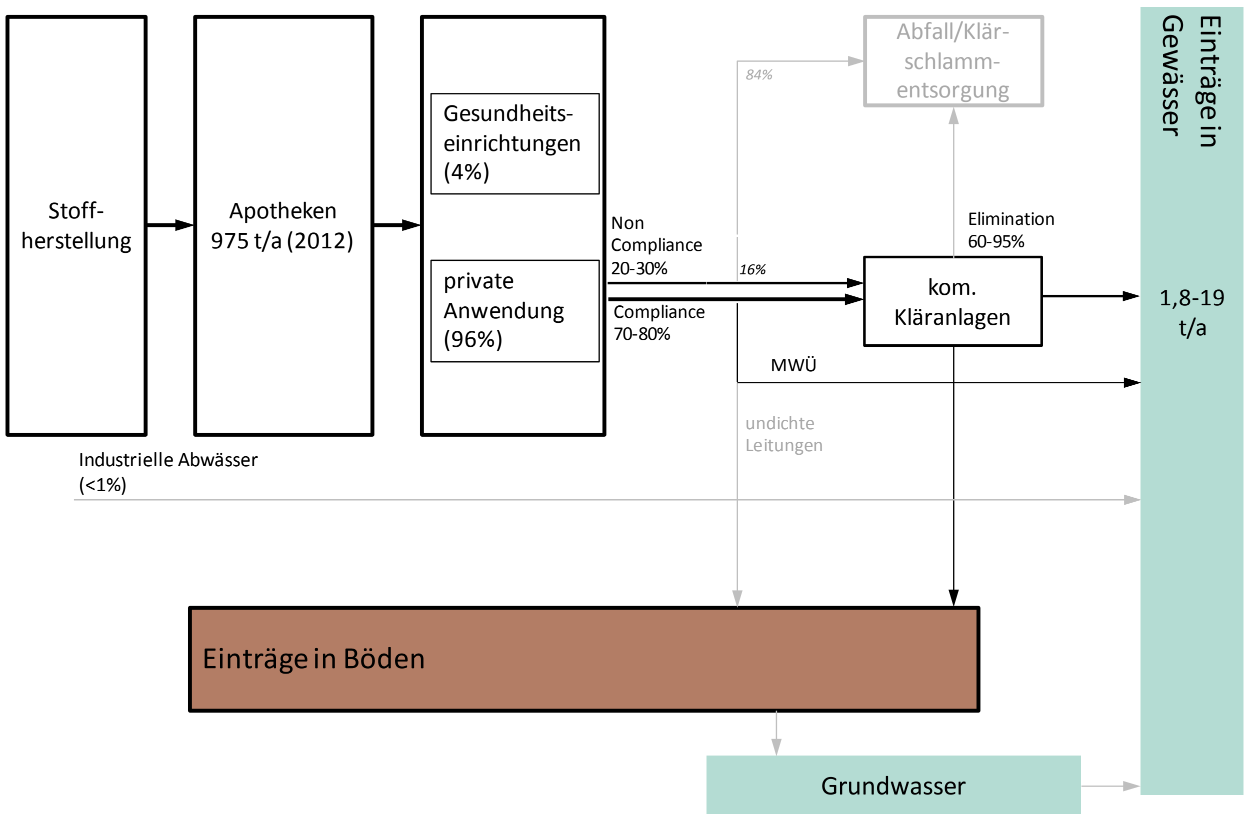
4 Developing illustrative substance flow analyses and emission patterns

For the selected pollutants, emission-based substance flow analyses show the substance flows that are particularly relevant for the resulting environmental pollution in the fields of substance production, the use of the respective substance in products, the application of the substance or product both in businesses and commerce as well as domestically and its subsequent disposal. The results are summarized in substance flow diagrams that focus on the emission pathways relevant to water. Figure 1 illustrates the results using the example of terbutryn and diclofenac.

Prior to modelling substance emissions, these substance flow analyses can be used to identify relevant applications and emission pathways and at the same time as the basis to derive suitable, cost-efficient measures to reduce the pollutant emissions to water.

Figures 1 a and b:Emission-based substance flow diagrams for a) Terbutryn and b) Diclofenac





5 Modelling substance emissions with MoRE

A regionalized pathway analysis using the modelling tool MoRE is used to quantify and assess the relevance of emission pathways.

The emission situation was determined in the Neckar river basin for the polycyclic aromatic hydrocarbons in the form of the sum parameter PAH_{16} of the EPA[4], nonylphenol, diclofenac, ibuprofen, iomeprol and sulfamethoxazole using a large database of general and substance-specific input data. Depending on the respective substance, different calculation approaches are used that vary in their complexity. The assessment results are modelled for individual years for the years 2008–2010 and subsequently summed up to obtain an average for this period. To make the results of the individual substances comparable with each other in relation to the water situation, a risk quotient (RQ) is applied to assess the risk. This quotient is calculated using the calculated environmental concentration (modelled load accumulated along the river divided by the regional flow at the outlet[5]) and a quality criterion, i.e. a target value at which no negative effects are expected. An $RQ < 1$ therefore means environmental concentrations beneath the target value and thus no environmental risk; an $RQ > 1$, in contrast, shows that a risk exists. An environmental quality standard was applied for nonylphenol, and PNEC values for the pharmaceuticals diclofenac, ibuprofen, and sulfamethoxazole. No suitable quality criterion could be found for PAH_{16} or the x-ray contrast agent iomeprol.

Modelling the current state yields a total discharge to water of 584 kg/a for PAH_{16}, 249 kg/a for nonylphenol, 756 kg/a for diclofenac, 1,132 kg/a for ibuprofen, 7,826 kg/a for iomeprol and 489 kg/a for sulfameth-

[4] 16 EPA-PAH (PAH_{16}) are considered, i.e. the 16 individual substances selected from several hundred individual PAH compounds by the United States Environmental Protection Agency (US EPA) because of their particular relevance.

[5] This is an approximation for the annual average concentration required for monitoring the annual average environmental quality standard.

oxazole. Comparing the modelled loads with the actually measured water loads for the PAH_{16} shows that the modelled loads are in a plausible range. There is a difficult data situation for nonylphenol because the measured concentrations in water are usually below the limit of determination so that it is not possible to calculate the load. The approach to quantifying the emissions of pharmaceuticals based on population has proven useful and reliable in other studies. Despite the fact that there is no comparison with measured water loads, it can be assumed that the modelled emissions are plausible. In principle, the observed pharmaceuticals are simple to model so that it can be expected that the modelled water concentrations are in the range of the actual environmental concentrations.

When estimating the impacts on water quality, it is not possible to draw a conclusion for PAH_{16} und iomeprol due to the lack of quality criteria. For nonylphenol, only risk quotients lower than one are calculated; consequently, no negative effects are expected. While the calculated concentrations for ibuprofen are far below the quality criterion, there are mixed results for diclofenac and sulfamethoxazole because a risk quotient larger than one is calculated at many catchment outlets.

The analgesic diclofenac, which is not easily biodegradable, has proven particularly relevant. The substance emissions are calculated based on a population-specific load determined using the amount consumed. This substance is particularly suitable as an indicator for the waste water pathway because emissions via municipal sewage treatment plans make up almost 98 % of total emissions (2 % sewerage systems). The modelled average total discharge to surface waters in the Neckar river basin equals 756 kg/a for the period 2008–2010. In order to be able to state whether the emitted loads jeopardise compliance with environmental quality targets, the emissions accumulated along the river are turned into concentrations at important catchment outlets using the mean discharge (MQ) as a hydrologic indicator. An estimate of the water loads by the LUBW Karlsruhe[6] based on measured values shows a comparable result so that both the emissions and the water concentrations calculated on this basis can be assumed to be plausible. To calculate the risk using the risk quotients, the modelled water concentration is standardised using the PNEC value of diclofenac (0.1 µg/l) as a quality criterion.

The results for the current situation show that at 45 of the 76 catchment outlets analysed, emissions are up to 8 times higher than the environmental quality criterion. As illustrated in Figure 4, the target value is not being met primarily along the main river and in the vicinity of built-up areas like Stuttgart, Backnang, Reutlingen, Pforzheim and Heidelberg. The results for the upper reaches of the Neckar tributaries are frequently RQ < 1. Consequently, the current status shows a clear need for action with regard to diclofenac water pollution.

6 Deriving and assessing measures to reduce and avoid substance emissions to water

The results of modelling substance emissions and plotting emission patterns were used to derive measures to reduce the substance emissions to water for the selected pollutants and these were assessed in terms of their effectiveness and costs.

Even if, in principle, reducing emissions at source seems to be a particularly sensible and effective first step – because this addresses polluters and prevents pollutants entering the environment so that there are no concerns about indirect pollution even in the long term – it still has to be questioned for each substance on a

[6] Spurenstoffinventar der Fließgewässer in Baden-Württemberg - Ergebnisse der Beprobung von Fließgewässern und Kläranlagen 2012/2013. Publisher: Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg Stuttgart; LUBW Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg; Karlsruhe. http://www.lubw.baden-wuerttemberg.de/servlet/is/243039/

case-by-case basis whether the emissions can be reduced to a sufficient extent by such activities. The available intervention options might not be efficient enough, or it might be almost impossible to limit emissions of the substance to the environment because of former applications linked to long-term emissions (e.g. the use of various biocides in construction products). It has to be taken into account that the EU has the regulatory authority for substance regulations right up to bans on production and use, so that national solutions are possible only to a very limited extent. High pollutant loads may also already exist in other environmental media (such as sediments for example) that are responsible for continued emissions to waterways. When comparing emission reduction measures, it is also important to consider additional side-effects such as the reduction of other nutrient or pollutant emissions with advanced waste water purification in municipal sewage treatment plants. In order to be able to draw conclusions about which actions are needed in the future, it is also relevant to differentiate between already introduced measures or those about to be implemented and new, additional measures.

Selecting the measures to be analysed in more detail was based on the following summarised considerations:

- The measures should be sufficiently effective with regard to the achievable emission reduction potential.
- Already introduced measures and any associated changes to the emission situation have to be taken into account as far as possible.
- Measures to implement the polluter-must-pay principle comply with the fundamental principles of environmental policy and are of particular significance.
- The requirement of high cost efficiency (or cost-effectiveness) has to be considered at the same time.
- Both source-based and end-of-pipe measures have to be considered.
- In line with the overall project’s main focus on emissions from municipal waste water systems, the field of agriculture was excluded from the analysis.

Table 1 shows the different approaches to measures for the analysed micropollutants or groups of pollutants. Information activities are usually source-oriented and predominantly address those causing the environmental pollution. They are therefore classified as a sub-group of this group.

The measures were then assessed for the further project work, in particular to identify cost-efficient combinations of measures, in terms of the following criteria:

- status or state of implementation,
- effect,
- costs,
- technical operating capability,
- secondary environmental effects.

The results are summarised in substance-specific profile sheets (measures-based substance profiles) (compare Table 2 and Table 3 as examples). The current need for action is derived based on individual criteria.

Concrete examples of source-based measures for the selected substances are e.g. substitution or encapsulation when using terbutryn in the construction sector, and import restrictions for textiles treated with nonylphenol ethoxylates (NPEO).

Table 1: Analysed approaches to source-based, decentralised or end-of-pipe emission reduction measures

Level of activity	Approaches
Measures at source	▸ Changes in applications ▸ Product modifications ▸ Substance substitution / replacements ▸ controlled disposal as preventive measure to pre-empt emissions to water
- *Information activities*	▸ Information campaigns for the general public ▸ Further training / information of the relevant specialists implementing the measures
Decentralised measures	▸ Indirect emitters (commerce, health care facilities) ▸ decentralised treatment of rainwater (at the level of buildings or districts)
End-of-pipe measures	▸ municipal sewage treatment plant (4th stage of purification) ▸ network of sewers: - treatment of rainwater - treatment of combined waste water and stormwater run-off

Table 2: Measures-based profile for terbutryn

Measures:	At source: a) substance substitution b) encapsulation c) construction measures	Information	Decentralised: Targeted decentralised rainwater treatment	End of pipe: a) improved centralised rainwater treatment b) improved municipal waste water treatment
Status	partially √	partially √	! (R&D required to some extent)	! (R&D required to some extent)
Effect	+	+	+	+
Costs (or cost-effectiveness)	moderate	moderate	moderate	High for specific individual substances
Technical operating capability:	√	√	√ (R&D required)	R&D required √
Secondary environmental effects	a) Assessment of the substitutes needed		+ (other pollutants)	+ (other pollutants) + (other pollutants) - (energy demand)
→Need to act:	R&D required, support for information activities		R&D required, need for legal amendments	R&D required; need for legal amendments

√ = *Measures being implemented*; ! = *measures available; + = positive effect of measure*;
- = *negative effect of measure*; R&D required = research and development needed

Table 3: Measures-based profile for pharmaceuticals

Measures:	At source: a) Reduction of amounts b) More environmentally-friendly pharmaceuticals	Information a) about more environmentally-friendly medicines / alternatives b) safe disposal	Decentralised: Waste water treatment in hospitals / clinical centres	End-of-pipe: Improved municipal waste water treatment
Status	! √	! some √	! (R&D required)	!
Effect	long term	(so far) little experienced data	depends on drug - to +	depending on drug: - to +
Costs (or cost-effectiveness)	moderate	moderate	low / medium with urine-diverting toilets: 24-42; mobile collection tanks 11-22; decentralised WWT: 190-310 €/patient	High for specific substances (e. g. diclofenac: 0.09-0.19 million €/kg)
Technical operating capability:	√	√	R&D required	√
Secondary environmental effects	a) possible effects of substitutes		- (energy demand)	+ (other pollutants) - (energy demand)
→Need to act:	Development of a system of environmental classification; Information activities for different target groups		R&D required; need for legal amendments	Need for legal amendments

√ = *Measures being implemented*; ! = *measures available; + = positive effect of measure*;
- = *negative effect of measure*; R&D required = research and development needed

7 Efficiency of advanced waste water treatment in municipal sewage treatment plants in Germany

Micropollutants can only be removed from waste water to an insufficient extent using today's technologies. To eliminate them completely, therefore, the waste water has to be purified with specialized process technologies that are also referred to as the "fourth stage of purification".

Of the many pilot projects conducted in German speaking regions and the advanced methods of purification realised to date in municipal sewage treatment plants, the use of ozone and of activated carbon have proven feasible for the targeted elimination of micropollutants. These two process technologies can remove a wide range of micropollutants from waste water to a comparatively large extent. In addition, they are easy to integrate into the existing purification process of a sewage treatment plant. Both process technologies require an additional downstream stage to post-treat the waste water subsequent to the “micropollutants stage”. When using powdered activated carbon, this additional stage removes the powdered activated carbon particles that are laden with micropollutants to the greatest possible extent and, when using ozonation, it removes the resulting degradation/transformation products.

Numerous studies have shown that the elimination rate of the individual substances largely depends on the dispensed amount of auxiliary material (activated carbon or ozone), the substance properties and the dissolved organic matter remaining in the waste water. Higher elimination rates can be achieved by increasing the amount of auxiliary material. The substance property is decisive for whether a substance is sufficiently eliminated by the amount of auxiliary material dispensed. In addition it has to be noted that the elimination efficiency of trace substances using activated carbon or ozone depends on the absolute concentration of the residual dissolved organic pollutants, which is in direct competition to the removal of micropollutants. This rule applies: higher organic background pollution of the waste water requires a specific higher amount of dispensed auxiliary material to remove trace substances. Overall, the numerous study results obtained so far show that a wide range of micropollutants can be eliminated to a large extent both by using ozone and by applying activated carbon. A majority of the pharmaceuticals, for example, can be eliminated to a high or very high degree. At the same time, however, it is also apparent that substances exist that cannot be eliminated or only to a comparatively low degree with the process technologies for removing micropollutants from waste water. These include, for example, the complexing agent EDTA or the x-ray contrast agent amidotrizoic acid and iomeprol.

Besides removing trace substances, it should also be noted that secondary purification effects are achieved by operating the process technologies considered suitable for removing micropollutants. Using activated carbon, for instance, reduces the subsequent chemical oxygen demand (COD) of the sewage plant effluent. If powdered activated carbon is used, the technically required addition of precipitants results in a recorded drop in the sewage plant effluent’s phosphorus concentration (P_{total} values). First experiences from operating the process technologies in practice show that sewage plant effluent values can be consistently achieved for both parameters in the range of or even below the threshold value (concentration or annual amount) listed in the German Waste Water Levy Act (AbwAG 2010) (the law governing the charges for discharging waste water into water bodies). Using ozone improves hygiene by significantly reducing germs in sewage plant effluent. Other additional positive purification effects result from having an additional stage to post-treat the waste water after trace substances have been eliminated. By using a filter as a further stage to re-treat the waste water, improved retention of microparticles can be achieved which in turn results in greater carbon and phosphorus elimination and the retention of particle-bonded trace substances. Furthermore, it can be shown that using activated carbon or ozone is accompanied by decolouration and odour reduction of the waste water.

Deciding which method is best suited to extending an existing sewage treatment plant depends on the local framework conditions on-site. Decisive factors include the location-specific waste water composition, availability of land to build on and existing buildings as well as economic aspects (costs of the process under the respective framework conditions, possibilities to offset the costs). Last, but not least, ecological and social aspects have to be considered when selecting a process to remove micropollutants. Alongside the positive experiences, it should be borne in mind that the discussed technical measures for eliminating micropollutants also cause unwanted environmental effects. Producing both ozone and activated carbon is associated with high energy costs. To produce activated carbon, raw materials containing carbon are also required. Most of the raw materials used such as hard coal or lignite are sourced from non-renewable resources abroad. When activated carbon is manufactured abroad, it cannot be ruled out that environmental pollution is being outsourced to the countries of origin of the raw materials. It should therefore always be questioned whether the selected technical measures to eliminate micropollutants comply with sustainability principles. The method selected should be the one with the highest efficiency and the greatest conservation of resources.

8 Costs of advanced waste water treatment in municipal sewage treatment plants

The costs estimation for a widespread application of the 4th stage of purification is based on multiplying the annual volume of waste water treated in each sewage plant by a specific cost factor.

$$\boldsymbol{Annual\ total\ costs} = \sum (\boldsymbol{Annual\ volume\ of\ waste\ water}\ \times\ \boldsymbol{spec.costs})$$

Data from the Urban Waste Water Treatment Directive of the German Federal Environment Agency are used as the basis for evaluating sewage treatment plant characteristics. The specific cost factors for each size class are based on an analysis of cost figures in the technical literature. The figures taken from the literature on the cost components of different plants are first adjusted to a standardised evaluation grid in order to guarantee their comparability. The standardisation has the following premises:

- Use of net amounts
- Adjustment of price developments between different reviewed years
- Currency conversion using purchasing power parities
- Uniform calculated interest rates and
- Uniform price for homogenous goods such as the use of electricity.

The application of purchasing power parities when converting different currencies is based on the underlying objective of trying to determine the costs of a comparable plant in Germany. This makes it necessary to take into account the structural differences in price levels between different goods in two countries and to exclude these from the conversion. Using purchasing power parities results in a more plausible cost estimate than using the exchange rate (either the bare exchange rate ore a more or less specified adjustment of the exchange rate). This study employs the purchasing power parities directly designated by OECD, EURO-STAT and the International Labour Organisation (ILO)[7] or interpolates the purchasing power parity where necessary from existing figures.

To harmonise the cost components recorded in euros or converted into euros, prices are adjusted to the reference year of 2012. This price adjustment is done using the price index available for each year.[8] Instead of a uniform consumer price index, the price development of each of the different components used for the 4th stage of purification – such as buildings, machines, different operating materials, wages, energy - was recorded and calculated separately. The conversion is done according to:

$$Costs_{reference\ year} = Costs_{review\ year} \cdot \frac{price\ index_{reference\ year}}{price\ index_{review\ year}}$$

Comprehensive price index series are published at regular intervals by the German Federal Statistical Office and the ILO.

In total, 17 publications featuring detailed cost data were reviewed. Cost data for 30 waste water treatment plants are presented in these publications, of which 16 are German treatment plants (3 in Baden-Württemberg and 13 in North Rhine-Westphalia), 7 are Swiss and 7 are model plants. Only the costs for ozonation and for the adsorption process using powdered activated carbon (PAC) and granular activated carbon (GAC) are included in the cost assessment. The cost figures presented are based on the following processes and applications:

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7 C.f. OECD (lfd.): Purchasing Power Parities (PPP) Statistics, URL: http://stats.oecd.org/Index.aspx; ILO (lfd.): Labour Cost, URL: http://laborsta.ilo.org/data_topic_E.html. For more methodological principles, see: Eurostat; OECD - Organisation for Economic Co-operation and Development (2012): Eurostat-OECD methodological manual on purchasing power parities. 2012 edition (Eurostat Methodologies and Working papers), Paris.

8 C.f. OECD (lfd.): Purchasing Power Parities (PPP) Statistics, URL: http://stats.oecd.org/Index.aspx; ILO (lfd.): Wages. http://laborsta.ilo.org/. Retrieved on 01.07.2014.

- ozonation (28 cost data),
- granular activated carbon filter downstream to the final clarification (7 cost data),
- granular activated carbon filter downstream to a filter (10 cost data),
- simultaneous use of powdered activated carbon (8 cost data),
- direct dosage of powdered activated carbon upstream to a filter (6 cost data),
- use of powdered activated carbon in a separate stage (23 cost data).

Table 4 gives an overview of the publications used and the process technologies on which the cost figures are based.

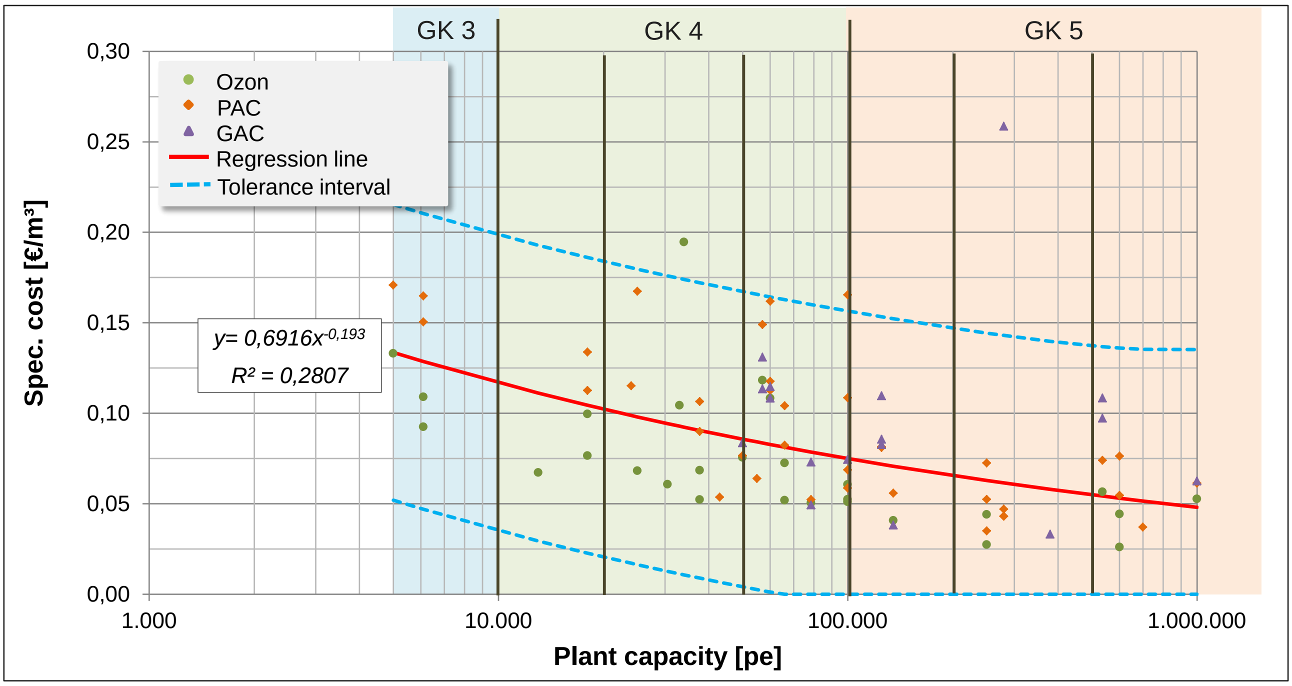
To determine the specific costs per cubic metre of treated waste water, the adjusted costs are divided by the annual volume of waste water specified in the respective literature source. Based on these cost figures, a regression analysis is applied to estimate the cost factors for different size classes of sewage treatment plant. These are used in the rest of the study as the basis for estimating the costs of a future expansion of sewage plants in Germany. Figure 2 presents the results.

Table 4: Literature sources of the cost data and the described process

Source	Sewage plant location	Status	Process / application
Ivashechkin (2006)	3 model sewage plants	Study	ozone PAC (simultaneous)
Fahlenkamp et al. (2008)	3 model sewage plants	Study	PAC (simultaneous) GAC (downstream to a filter)
Tacke et al. (2008)	1 model sewage plant	Study	ozone PAC (simultaneous) PAC (separate stage) PAC (dosage before the filter)
Hunziker Betatech AG (2008)	Untersee Aadorf Furt Au Luzern Werdhölzli	Study	ozone PAC (separate stage)
Abegglen et al. (2009)	Regensdorf	Pilot plant	ozone
Alt (2011)	Lage	Study	PAC (separate stage) PAC (dosage before the filter) GAC (downstream to a filter) GAC
Bornemann et al. (2012)	Dülmen Wuppertal-Buchenhofen	Study Pilot plant	PAC (dosage before the filter)
Blank; Alt (2012)	Harsewinkel	Study	ozone PAC (separate stage) GAC (downstream to a filter) GAC
Mauer; Alt (2012)	Bad Oeynhausen	Study	ozone PAC (separate stage) GAC (downstream to a filter) GAC

Kuhlmann; Alt (2012)	Detmold	Study	ozone PAC (separate stage) GAC (downstream to a filter)
Herbst; Hilbig (2012) Herbst; Maus (2013)	Neuss Ost	Study	PAC (dosage before the filter) GAC
Rölle; Weißert (2013)	Kressbronn Stockacher Aach Böblingen-Sindelfingen	In operation	PAC (separate stage)
Mertsch; Herbst; Alt (2013)	Duisburg-Vierlenden Obere Lutter Bad Sassendorf	Pilot plant	ozone GAC ozone
Kompetenzzentrum Mikroschadstoffe NRW	Espelkamp	Study	ozone
Dahlem Beratende Ingenieure GmbH & Co. (2013)	Paderborn-Sande	Study	ozone PAC (separate stage) GAC GAC (downstream to a filter)
Knollmann; Hübner (2013)	Rietberg	Study	ozone PAC (simultaneous) PAC (separate stage) PAC (dosage before the filter) GAC (downstream to a filter) GAC

Figure 2: Regression analysis of literature data



Because the cost estimate for future expansion is derived from existing cost figures, the associated resulting statistical uncertainty has to be taken into account. The regression function derived in the course of the work is capable of explaining approx. 28.1 % of the variances of individual plants (R^2 = 0.2807). Significant uncertainty has to be expected when predicting the future costs of constructing a new 4th stage of purification that takes plant size into consideration; this is reflected in the so called tolerance interval[9]. The range of tolerance intervals (and the statistical uncertainty expressed by this when predicting future figures) depends on the number *n* of analysed observations, the covariance between the dependent and independent variable of the regression function and/or the deviation of the size of the plant to be estimated from the average size of the analysed plants. According to the calculations of the tolerance interval, 95 % of the specific costs of constructing an additional 4th stage of purification in the future lie within the range of the calculated tolerance interval.

Taking these statistical uncertainties into account, the specific costs of the analysed size classes are estimated using the regression values of the respective size class mean. They range from 0.124 €/m³ for size class 3 to 0.051 €/m³ for sewage treatment plants larger than 1 million population equivalents (size class 5). These are net figures.

Including the specific costs for the additional post-treatment stage, which is based on the experiences of plant operators and different experts in the waste water management sector, the cost estimate shows that annual total costs of around 1.3 billion euros (net) can be expected when upgrading all the German sewage treatment plants in the size classes 3 to 5 (3,013 in total) to integrate targeted micropollutant removal (see Table 5). This sum contains both the calculated annual costs for the investment costs and the costs required to operate the additional process technologies. Other benefits due to funding support or possibilities to offset the waste water levy are not included in the calculation. About half of the total costs result from the necessity to post-treat the waste water. When looking at the costs for a 4th stage of purification, therefore, the costs for post-treatment always have to be taken into account as well.

When related to the single size classes, it can be shown that most of the costs are attributable to upgrading sewage treatment plants of size class 4 and 5. About 50 per cent of the estimated annual total costs are needed to extend sewage treatment plants of size class 4; a further almost 40 per cent are attributed to retrofitting plants of size class 5. To extend the size class 3 plants, around 10 per cent of the estimated annual total costs are required.

Table 5: Specific costs and calculated annual costs for nation-wide expansion of the 4th stage of purification in Germany from size class 3 upwards

Size class		Number of sewage plants	Annual volume of waste water (million m³/a)	Specific costs (€/m³)		Annual costs (million €/a)		
				Micropollutant stage	additional downstream stage	Micropollutant stage	additional downstream stage	Sum
3	-	896	542	0.124	0.10	67	54	121
4	A	784	876	0.108	0.08	95	70	165
	B	810	1,816	0.092		167	145	312
	C	294	1,339	0.079		106	107	213
5	A	117	918	0.069	0.05	64	46	110
	B	83	1,412	0.059		83	71	154
	C	18	739	0.051		37	37	74
	D	11	1,305			66	65	131
Total costs (net)						685	595	1,280

[9] While the confidence interval shows the probability area of the given costs information the tolerance interval gives the costs expectation about a new and additional plant

9 Treatment of micropollutants in Switzerland

Supplementing the assessments and calculations based on Germany, the experiences in Switzerland can be used regarding the introduction of advanced waste water purification in municipal sewage treatment plants. The emission of organic trace substances in water bodies via the emission pathway “purified municipal waste water” was identified as problematic in this country. Based on studies of the pollution situation and the evaluation of measures, on 21 March 2014, the Swiss parliament agreed to amend the Waters Protection Act. This change to the law states that selected municipal sewage treatment plants have to take steps to eliminate organic trace substances. The biggest sewage treatment plants of Switzerland are affected (serving > 80,000 population equivalents), sewage treatment plants in the catchment area of lakes (> 24,000 residents), and those plants at water bodies with a waste water share of more than 10 % (with > 8,000 residents). Because not all sewage plants are affected, but the entire population contributes to the pollution, use-based financing was embedded in the law. A waste water charge was introduced which is used to support the construction of systems to eliminate trace substances. The pollution resulting from emissions via diffuse sources and possible measures to reduce this are currently being examined.

10 Analysing and identifying effective and cost-efficient combinations of measures

Obvious improvements can be made using advanced measures in municipal sewage treatment plants for a wide variety of micropollutants, a large proportion of which are emitted from domestic applications (among others, pharmaceutical residues, textile chemicals, personal care products). Such measures seem especially suitable in large treatment plants and for relevant bodies of water (unfavourable ratio of waste water volume / water flow, drinking water relevance). To achieve the right level of effectiveness and cost-efficiency, however, additional substance-specific measures at source, information activities or even decentralised measures to capture and treat particularly polluted waste water streams (e. g. hospital effluents) should be considered, primarily in the catchment area of highly polluted water bodies (hotspots). These also contribute to implementing the polluter-pays principle.

The various objectives (sufficient emission reduction taking into account different local pollution loads, high efficiency, implementing the polluter-pays principle, promoting acceptance etc.) can only be achieved by combining the different approaches in an efficient way. Table 6 summarises the necessity for source-based measures and also their limits. These limits highlight the additional need for downstream, so called end-of-pipe measures. Advanced waste water purification in large municipal sewage treatment plants can greatly reduce the emitted load of a wide variety of micropollutants with high cost efficiency. This measure is especially relevant if water is strongly polluted (unfavourable ratio of waste water volume to water flow) or has to be protected (e.g. where drinking water is concerned). Another important aspect when compiling efficient combinations of measures is the potential that end-of-pipe measures often have to exert positive side-effects by additionally eliminating other substances (other micropollutants, micro-particles, phosphorus, germs). This applies to both a 4th stage of purification in municipal waste water treatment plants and to the advanced treatment of rainwater or combined waste water and stormwater run-off.

In order to be able to recommend combinations of measures to reduce and avoid micropollutant emissions to water, the 12 selected substances of the project are classed into four groups, each featuring similar framework conditions:

- Substances with outside applications/emissions (terbutryn, some PAH),
- Substances whose main emission pathway is via domestic waste water (triclosan, nonylphenol),
- Pharmaceuticals (application in the domestic sector and in health care facilities) and
- Industrial chemicals (PFOS, HBCDD).

Selecting advisable substance-specific combinations of measures is based on the preceding analyses of individual substance-specific measures. The different areas of action form the starting points for the relevant emission reduction measures and also the area of legislation concerned (water law, chemicals law, information activities). The measure options for pharmaceuticals are listed in

Table 7 as an example.

Table 6: Source-based measures: Necessity and limits

Necessity for source-based measures:
▸ Implementing the polluter-must-pay and the precautionary principles ▸ Widespread reduction of environmental pollution across environmental media ▸ Reducing emissions from pathways not or not sufficiently captured by end-of-pipe measures (e.g. emission pathway atmospheric deposition) ▸ (Additional) reduction of emissions from municipal sewage treatment plants (e.g. for poorly degradable pollutants)
Limits of source-based measures:
▸ Emissions from already existing applications (“storage” or “depots”) ▸ Applications or emission pathways which are not easily limited or cannot be done so completely (e. g. import products, niche products, airborne long-range transport) ▸ High performance applications which cannot be easily limited or not at all

Table 7: Substance-specific measures to reduce pharmaceuticals

Availability of measures	Potential / limitations	Effect
Substance substitution / use of more environmentally-friendly pharmaceuticals	• large-scale effect; but • very long-term; • costly; • R&D required	large, but substance-specific
Change in application (modified prescriptions, alternative, non-pharmacological therapies)	• low costs(?); • tried and tested; but • only applicable to some extent	small-moderate
Information activities (specialists + general public)	• low costs; • existing experiences; but • effect only limited and possibly only temporary	small-moderate
Decentralised waste water treatment of medical facilities	• captures hot-spots; but • unresolved cost allocation	large
4th stage of purification	• effect for complete catchment area; but • removal of pharmaceuticals only partially possible for specific substances	small-large

11 Modelling substance-specific combinations of measures using the example of the Neckar river basin

Having identified the need to act for several of the modelled substances, measures to reduce substance emissions were then modelled based on the available information. Depending on the substance or substance group and the relevance of the emission pathway, source-based and end-of-pipe measures were implemented in MoRE and their impact on reducing pollutant loads or reducing water concentration was compared with each other. The correlation of the impacts becomes clear using the following defined measures.

These measures are defined for the PAH_{16}:

a) Due to stricter requirements for domestic furnaces under the 1st Federal Imissions Protection Act (BImschV) (Federal Ministry of Justice and for Consumer Protection (2010)):
20 % reduction of atmospheric emissions.
The measure affects the emission pathways "Atmospheric deposition" and "surface run-off".
b) Improving the treatment effectiveness of the combined systems:
stormwater overflow tanks (SOT) and retention soil filters (RSF).
c) Combination of measures:
Reduction of atmospheric emissions by 20 % and
improving the treatment effectiveness of combined systems.

The following measures are defined for nonylphenol:

a) Equipping all sewage treatment plants > 50,000 p.e. with a 4th stage of purification;
b) Equipping all sewage treatment plants > 10,000 p.e. with a 4th stage of purification;
c) Through product labelling & information campaign:
20 % reduction of emissions via waste water pathway;
d) Combination of measures:
Equipping all sewage treatment plants > 10,000 p.e. with a 4th stage of purification und
20 % reduction of emissions via waste water pathway.

These measures are defined for pharmaceuticals:

a) Equipping all sewage treatment plants > 50,000 p.e. with a 4th stage of purification;
b) Equipping all sewage treatment plants > 10,000 p.e. with a 4th stage of purification;
c) Reduction of consumption of pharmaceuticals by 20 %;
d) Combination of measures:
Equipping all sewage treatment plants > 50,000 p.e. with a 4th stage of purification und
20% reduction in consumption of pharmaceuticals.

The result of the illustrated measures or combinations of measures for the PAH_{16} shows that up to 13 % of the total emissions to water can be reduced compared to the current situation due to the measure "20 % reduction of the atmospheric emissions". Upgrading stormwater overflow tanks (SOT) leads to an 8 % reduction relative to the total emissions. If a filter is connected downstream to the SOT such as, e.g. a retention soil filter (RSF), up to 19 % of the outflow pollutant load is reduced. The biggest reduction potential results from the combination of measures improving the treatment effectiveness (SOT & RSF) and simultaneous reduction of atmospheric emissions. As a result, up to 28 % of the total emission load into water is reduced compared to the current situation. Overall, an average emission reduction potential was able to be determined with the measures listed.

For nonylphenol, modelling reveals a very low reduction potential when equipping sewage treatment plants > 50,000 p.e. with a fourth stage of purification using powdered activated carbon. This only results in a load reduction of 7 % even after equipping all the treatment plants > 10,000 p.e. in the region. When equipping all the treatment plants > 10,000 p.e. with ozonation, much higher reduction potentials of up to 30 % result. For the source-based measure "Product labelling & information activities", a 20% reduction of the pollutant load is assumed compared with the current situation. 44 % reduction of the pollutant load is achieved when combining the two most effective measures: “Equipping all sewage treatment plants larger than 10,000 p.e. with ozonation” and “Product labelling & information activities”. Overall, an average to high emission reduction potential could be determined with the measures listed.

From the results of the modelled measures for diclofenac water quality it can be derived that, compared with the current situation, neither the measure “20 % less consumption” nor “equipping all treatment plants > 50,000 p.e. with a 4^{th} stage of purification” leads to widespread compliance with the quality criterion (PNEC value), even though a load reduction of more than 50 % is achieved by the latter measure. Even combining the measures “equipping all plants > 50,000 p.e.” and “20 % less consumption” and the associated load reduction of 60 % compared to the current state proves to be insufficient to remain below the diclofenac PNEC value over a large area. Concentrations below the PNEC value are only achieved to a large extent when equipping all the treatment plants > 10,000 p.e. with a fourth stage of purification. But although the diclofenac load is lowered by almost 77 %, catchment outlets that exceed the quality criterion can still be identified (see Figure 3 and Figure 4).

Compared to the current situation, 29 % of the emissions of ibuprofen are reduced with the measure “equipping all sewage treatment plants > 50,000 p.e. with a 4^{th} stage of purification”. This figure increases to 43 % by combining “equipping all plants > 50,000 p.e. with 4^{th} purification stage” with “20% reduction in consumption”. A very similar result with a 44 % load reduction results for the measure “equipping all sewage treatment plants > 10,000 p.e. with a 4^{th} purification stage”. At the same time, the water situation for ibuprofen is already found to be non-critical at present, so that the measures only show the potential to reduce pollutant loads.

The relevant measures for iomeprol reduce the pollutant load by 26 % (equipping all treatment plants > 50,000 p.e.), 41 % (equipping all treatment plants > 50,000 p.e. with 4^{th} stage of purification and 20% reduction of consumption) and 39 % (equipping all treatment plants > 10,000 p.e.). It was not possible to assess the water situation because there was no quality criterion available to do so.

From the results of the measures modelled for sulfamethoxazole-related water quality, it becomes clear that, compared with the current state, the measure “20 % less consumption” does not contribute to a clear improvement of the water situation. For the measures concerning the equipment of treatment plants, different pollutant load reductions result depending on the process used. Ozonation offers higher reduction potentials than powdered activated carbon. Compared to the current state, 54 % of emissions are reduced by “equipping all sewage treatment plants > 50,000 p.e. with 4th stage of purification with ozonation” which is a clear improvement in water quality. Combining the measures “equipping all sewage treatment plants > 50,000 p.e. with a 4th stage of purification with ozonation” and “20% reduction of consumption” achieves 63 % load reduction. A risk quotient between 1 and 2 is then identified only at single catchment outlets. “Equipping all plants > 10,000 p.e. with a 4th stage of purification with ozonation” proves to be sufficient to observe widespread positive effects and a risk quotient smaller than 1. This measure reduces the emissions by 82%.

Presenting the results of the modelled measures, especially of the fourth stage of purification, aims to illustrate how varied the substance-specific effects of the various measures can be in one river basin selected as an example. For several of the modelled substances, the applied targets can sometimes only be met by combinations of measures; for others, the modelled combinations of measures do not represent sufficiently efficient intervention options.

Modelling substance-specific measures makes it possible to evaluate the effects of the various options. The results show that a mix combining both source-oriented and end-of-pipe measures is necessary to achieve the goals of a good chemical status of water in line with the Water Framework Directive. Overall, the modelling results clearly highlight the need to implement emission-reducing combinations of measures.

Figure 3: Emission reduction potential of the measures modelled for diclofenac

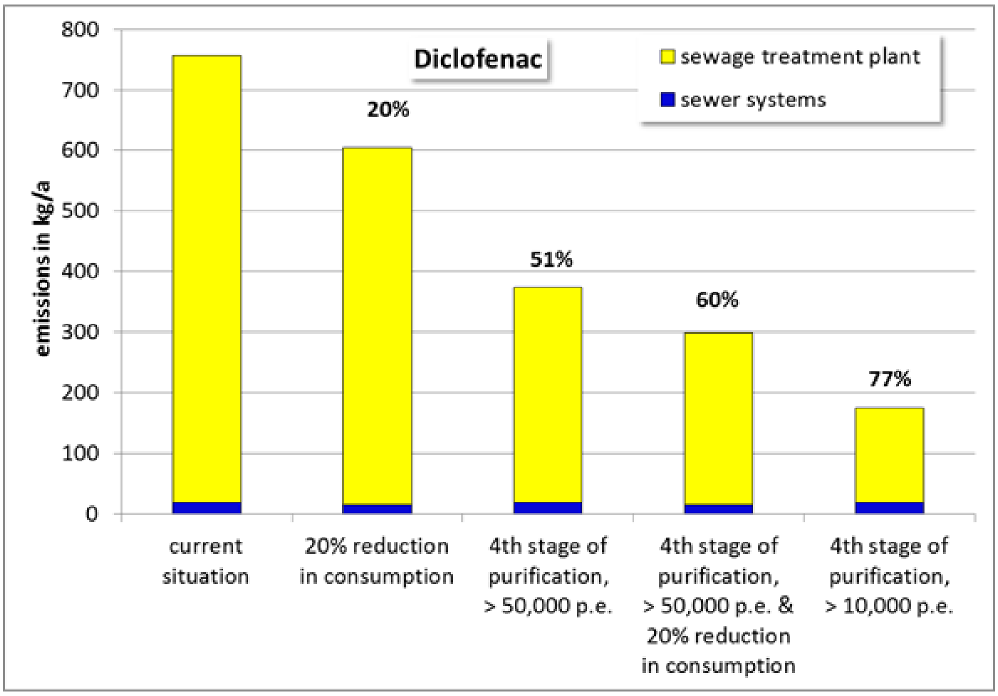
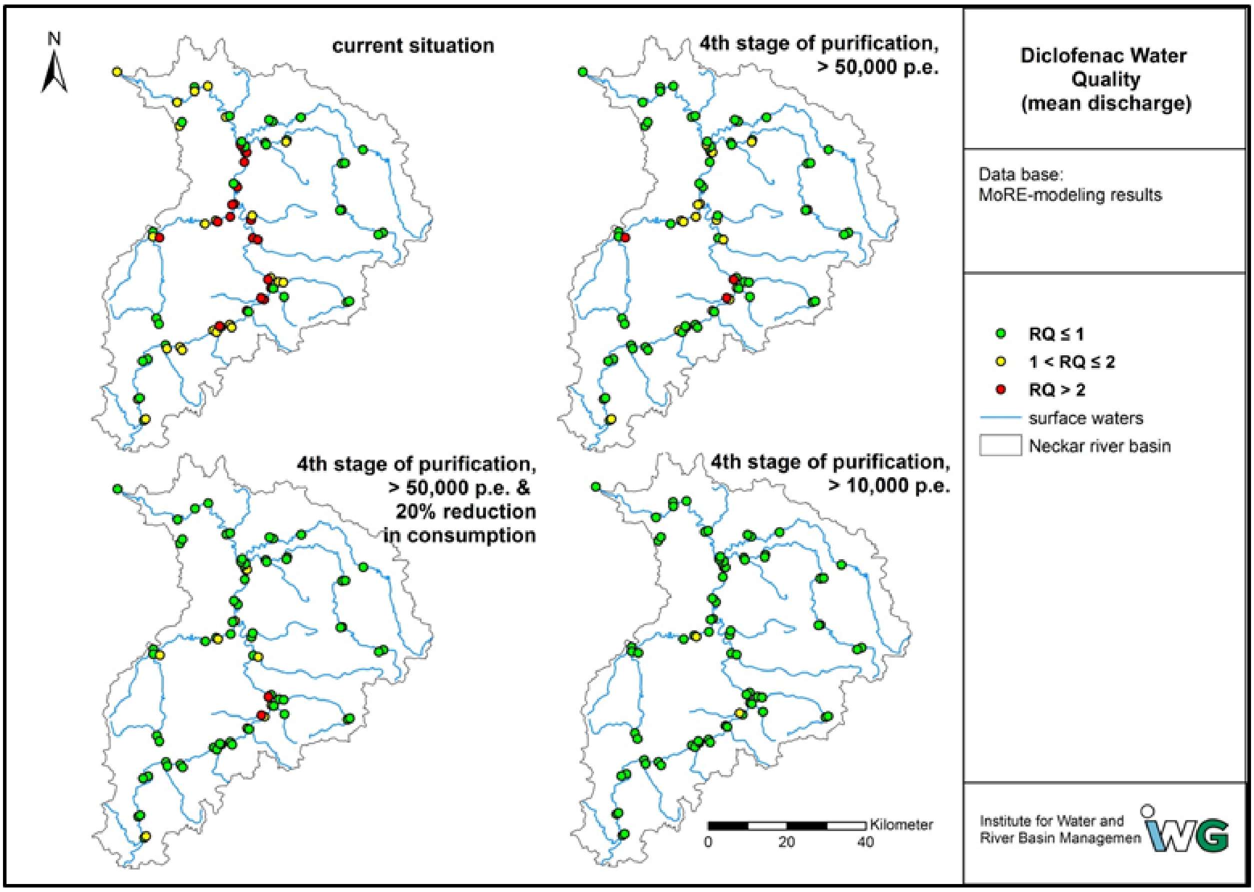


Figure 4: Result of the measures modelled for diclofenac water quality



12 Recommendations for measures and combinations of measures on the part of the federal government

The topic of micropollutants will play an important role in the future because of continued updates and supplements to the list of priority substances, among other reasons, in order to comply with the criteria of a good chemical and ecological status of waters under the Water Framework Directive. The existing demand for action in the field of micropollutants makes it necessary to design a long-term and unified strategy that covers all the areas of activity.

At the same time, the study's results show that both source-based and end-of-pipe emission reduction measures are available for all the analysed micropollutants and that only an efficient combination of the different approaches is able to meet the different objectives (sufficient emission reduction considering varying local pollution, high efficiency, implementation of the polluter-pays principle, promoting acceptance etc.).

The different regulatory authorities for the identified measures, the necessity for parallel measures in very different fields and the long-term planning horizons for river basin management are all decisive framework conditions for designing activities at national level. It therefore seems to make sense to group the different measures within a "**Micropollutant strategy"** of the German federal government. All the relevant stakeholders should be integrated in the strategy in a fair and representative way. The primary objective must be to comply with the existing water protection quality targets in the Water Framework Directive and Marine Strategy Framework Directive.

The "Micropollutant strategy" should be founded on the 3 pillars of "source-oriented measures" (including information activities), "decentralised measures" and "end-of-pipe measures". Source-oriented measures include import restrictions on textiles treated with pollutants, limitations of PAH emissions or information activities regarding the application and use of pharmaceuticals and biocides. Decentralised measures can reduce emissions of micropollutants at indirect dischargers (e.g. medical facilities, metal working and processing) while end-of-pipe measures mainly address emissions from municipal sewage treatment plants and from discharging rainwater or combined waste water and stormwater run-off. Research programmes spanning these pillars can develop additional emission reduction measures in the various fields or improve and optimise existing ones. In addition, it is recommended to continuously monitor the implementation of the strategy in order to document the achieved improvements, identify any need for adjustments and integrate potentially changing objectives (additional priority substances, new quality standards). Where substance laws are concerned, any requirements that can only be implemented at European level should be clearly communicated as early as possible at this level.

The challenges of such a micropollutant strategy resulting from the measures to be implemented that are associated with the stakeholder structure also suggest that such a strategy should be accompanied by an agenda process under the leadership of by the federal government.

13 Outlook

Further work is required to define the individual measures in more detail and derive concrete actions to be taken. Especially where source-based measures are concerned, background information relevant to their implementation has to be analysed including possible drivers and obstacles. In addition, it would be sensible to make improvements to modelling the flow and emission of substances in order to expand the region of analysis, the list of substances and the list of illustrated emission reduction measures with the objective of being able to use this set of instruments for an accompanying monitoring of measures.