POLAR ORGANIC MICROPOLLUTANTS IN THE WATER CYCLE

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Abstract. Emerging contaminants such as pharmaceuticals and biocides are released from sewage treatment plants and also from agricultural fields. They are increasingly monitored in surface and groundwater but are not yet included as priority compounds in European guidelines. Analysis of these mostly polar compounds and their sometimes relevant metabolites is more and more carried out by LC-MS-MS. The main elimination processes in sewage treatment plants are sorption and biodegradation. Both processes are difficult to predict in case of polar compounds and therefore fate studies are essential.

Keywords: micropollutants; pharmaceuticals; biocides; metabolites; emerging contaminants; priority compounds; tracer; chemical analysis; LC-MS; monitoring; surface water; groundwater

1. Definition and Origin of Micropollutants

Micropollutants are compounds which are detected in the concentration range of ng/L up to µg/L in the environment. In general, synthetic chemicals are meant, but natural substances, which are of anthropogenic origin such as estradiol, are often included.

An overview on different sources of products containing micropollutants and their release to the environment is given in Table 1. In general, point sources such as effluent of sewage treatment plants (STPs) and diffuse sources such as run-off of agriculturally used fields can be differentiated.

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Emissions into the environment are difficult to estimate. On one hand, emission data is often not available. Sales data on industrial chemicals, e.g. ingredients of personal care products, are very difficult to obtain. For pharmaceuticals, sales data were becoming available in several countries, thanks to the effort of researchers investigating their behavior in the environment in the last decade. Still, for many countries only rough estimations are available. According to IMS Health the equivalent of USD 96 billion was spent on drugs in retail pharmacies in the top five European markets during the year 2006.

TABLE 1. Overview of origin, type and pathways of organic micropollutants in the environment (main pathways are marked bold)

Source	Substance groups (examples)	Pathways in the environment
Urban settlements	Personal care products, human pharmaceuticals, detergents, chemicals used in construction business (dyes, lacquer, binder, wood preservatives), flame retardants, pesticides, biocides	Wastewater diffuse landfill site
Agriculture	Pesticides (insecticides, herbicides, fungicides), veterinary pharmaceuticals	Wastewater diffuse
Industry	industrial chemicals (polymers, dyes, varnishes, oxidants, reductants, detergents, corrosion inhibitors, biocides)	Wastewater landfill site
Traffic	ingredients of motor oils, lubricants, combustion products	diffuse landfill site

On the other hand, sales data are sometimes given but emission pathways are not known. For examples, pesticides are expected to be released mainly in agriculture. However, a study in Switzerland revealed that similar amounts of pesticides (approx. 1300 t/y) are used in agriculture as in urban settlements (Stamm et al., 2006). A study conducted for the catchment of lake Greifensee showed that 10–30% of the pesticides which are used only in agriculture reached the lake through sewage treatment plants (Gerecke et al., 2002). For pesticides with additional urban applications such as diuron, 60–80% of the load derived from STPs. The different emission pathways to the environment, as is the case for pesticides and biocides, need to be distinguished in order to determine realistic exposure scenario. As a result, effective reduction measures can be developed.

2. Selection of Priority Compounds

2.1. PRIORITIZATION USING ENVIRONMENTAL BEHAVIOUR DATA

In the European Inventory of Existing Commercial Chemical Substances (EINECS) approx. 100'000 chemicals are registered, which were marketed before 1981. There from ca. 30'000 substances marketed in volumes above 1 t/y and ca. 10'000 above 10'000 t/y. Since 1981 approx 3'800 new compounds came on the market. Until now an extensive risk assessment was carried out for approx. 3'000 compounds. The ranking of the relevance of compounds with regard to their aquatic pollution is complex and because of missing data often not possible. Apart from the production volume, the environmental behaviour and the toxicity is important for priorisation.

The environmental behaviour is mainly determined by the following processes:

- Transport (run-off, sedimentation, leaching, atmospheric deposition)
- Distribution between different phases (volatilization, sorption, bioaccumulation)
- Biological degradation (aerobic, anoxic, anaerobic; primary degradation versus mineralisation, cometabolism)
- Abiotic degradation (photolysis, chemical reactions like oxidation, reduction, hydrolysis)

Especially for new compounds the environmental behaviour is a priori not known. For an estimation e.g. of the distribution between different phases and transport processes physical chemical properties such as water solubility, log Kow, Koc, Kd, Henry coefficient, bioconcentration factor (BCF), and pKa are used. These data can be found in databases (e.g. scifinder, Beilstein, www.syrres.com/esc/datalog.htm, www.chemfinder.com, www.epa.gov) or, if not available, can be predicted by use of quantitative structure activity relations (QSAR). Some correlation between the different physical chemical properties exist, e.g. with decreasing water solubility and decreasing vapour pressure the log Kow and BCF increase indicating accumulation in lipophilic media. However, it should be emphasized that the prediction is mainly possible for non-polar compounds, while the prediction of the behaviour of polar or charged compounds is often not correct. For example, the use of log Kow values lead to an underestimation of the sorption of fluoroquinolones to sludge (Golet et al., 2003) or sulfonamides to soil (Stoob et al., 2006). The fluoroquinolone Ciprofloxacin has a Kow value of 1.8, but nevertheless sorbs to sludge in the STP by 80%, indicating that sorption is the main elimination process (Fig. 1).

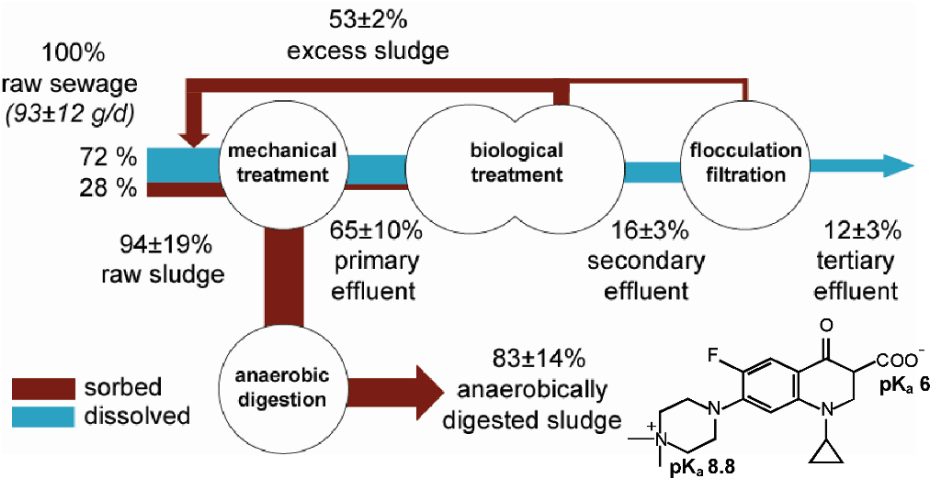
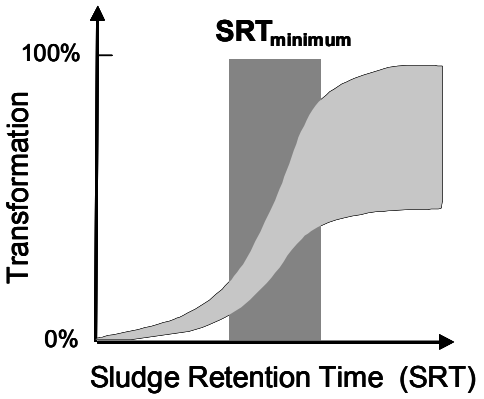


Figure 1. Significance of sorption as elimination process for the polar antibiotic Ciprofloxacin with a log Kow of 1.7 (modified from Golet et al., 2003), Copyright © 2007 American Chemical Society

The prediction of biological degradation (QSBR) with tools such as BIOWIN (EPISUITE), Catabol (Jaworska et al., 2002), or UM-PPS (Hou et al., 2003) is still at the beginning and until now almost exclusively possible for the aerobic degradation. So, biological degradation has to be tested by use of standardized OECD/ISO tests, preferably with real inoculum under realistic environmental conditions (TGD, 1996).

Biological degradation of different pharmaceuticals was studied within the EU project POSEIDON in a pilot plant membrane bioreactor with increasing sludge retention times (SRT) (Joss et al., 2005, Ternes and Joss 2006, Göbel et al., 2007). SRT was shown to be a major factor influencing the microbial transformation, as a minimal SRT is necessary to degrade the compounds (Fig. 2). Maximal achievable degradation occurs for many pharmaceuticals at SRT of 10–12 d, which is normally achieved in conventional STPs with a nitrifying step. Only for a few compounds like the antimicrobials Clarithromycin and Trimethoprim higher sludge retention time is needed for a substantial degradation to occur, indicating that the transformation of these compounds may be inversely correlated to the sludge loading, i.e. the ratio of substrate and sludge concentration, which decreases with increasing sludge retention time. Reduced sludge loading may cause an increase in the biodiversity of the active biomass, which seems to have an influence on the elimination of compounds undergoing co-metabolism, as assumed for antimicrobials. The observed degradation rates of various compounds differ significantly without showing any evident correlation to specific molecular structure: currently no quantitative

structure activity relationship (QSAR) can be identified. The observed removal rates vary form very fast (e.g. Estradiol, Paracetamol) to zero (e.g. Carbamazepine, Amidotrizoate). Therefore the degradation of each compound has to be determined experimentally until better prediction tools are available.



SRT	Transformation [%]
2 - 5 d	Bezafibrate (> 95%) Ibuprofen (> 90%) Sulfamethoxazole (50-75%)
5 -15 d	Diclofenac (15-40%) Ethinylestradiol (> 90%) Iopromide (30-90%) Roxithromycin (0-60%)
60 -80 d	Clarithromycin (90%) Trimethoprim (85%)
< 20d	Carbamazepine (0 %) Diazepam (0 %)

Figure 2. Dependency of transformation rate on sludge retention time for pharmaceuticals in STPs: maximal transformation of pharmaceuticals at minimal SRT is listed (Joss et al., 2005; Ternes et al., 2004; Göbel et al., 2007)

2.2. EXISTING PRIORITY COMPOUNDS IN EUROPE

In Europe und the USA several lists of priority compounds are assembled which partly are valid only for specific applications (Table 2). Parameters were weighted to a different extent depending on the focus of the list. For the aquatic environment the 33 priority substances of the water framework directive (WFD) are most relevant. For these compounds monitoring programs have been or will be developed in the next years. Besides some anorganic compounds (e.g. lead, nickel), several agro chemicals (Alachlor, Chloropyrifos, Isoproturon), industrial chemicals (Nonylphenol, Chloroform), combustion products (PAHs) and traffic emissions (Benzene) are included.

Emerging contaminants such as pharmaceuticals, personal care products and biocides, which are increasingly investigated in recent years (Bester 2006; Kolpin et al., 2002; Richardson and Ternes, 2005; Ternes and Joss, 2006), are not yet included in the lists of priority chemicals. These compounds often do not bioaccumulate to a high extent and are therefore not relevant for many lists since they are based on bioaccumulation and persistence criteria.

TABLE 2. Lists of priority compounds in Europe and USA with focus on water (modified from Schuelp et al., 2006)

Priority list	Based on	Focus	No. of compounds	Year
HELCOM Helsinki Convention	HELCOM Helsinki Commission	water pollution (marine environment)	47	1988/2000
North Sea Conference List of Priority Hazardous Substances	3rd declaration The Hague, Annex 1	water pollution (marine environment)	36	1990
IKSR	International Commission for the Protection of the Rhine	water pollution	92	2000
The 2000 OECD List of High Production Volume Chemicals	Decision-Recommendation of the Council on the Co-operative Investigation and Risk Reduction of Existing Chemicals	Existing Substances, High Production Volume Chemicals	about 5000	2000
Stockholm List/UN-POP	Stockholm Convention on Persistent Organic Pollutants (European Commission, UNEP)	Persistent organic pollutants POP	12	2001
Priority PBT Profiles	US EPA PBT Initiative	PBT pollutants	12	1998/2003
Proposed Priority Substances Water Framework Directive	Water Framework Directive and COMMPS-Procedure (European Commission)	water pollutants	33	2001
OSPAR List of Chemicals for Priority Action	OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic	water pollution (mainly marine environment)	42	2002
EPA National Primary Drinking Water Standards	Safe Drinking Water Act and CCL-Procedure	drinking water	87	2003

Recently, Muir and Howard (2006) used also bioaccumulation, persistence and long-range atmospheric transport criteria for their screening of possible new emerging contaminants in the environment and so there list contains also only compounds with large Kow values.

In order to protect the aquatic environment polar compounds, which contain polar and often bioactive functional groups, have also to be considered. Currently, there is an ongoing discussion about the amendment of several polar compounds such as x-ray contrast media, pharmaceuticals, detergents, pesticides, perfluorinated compounds and personal care products to the priority list (Draft proposal to Directive 2000/60/EC). Within one year the European commission has to make a proposal for their final classification. Especially critical are those compounds for which acute or chronic toxicological tests showed low effective concentrations. For instance, the anti-inflammatory drug Diclofenac exhibits a low no observable effect concentration (NOEC) in rainbow trout (Schwaiger et al., 2004; Triebskorn et al., 2004). Taking into account a safety factor of 10 a quality value of 0.1 µg/l results (Jahnel et al., 2006). This is in the range of concentrations found in surface waters influenced by STP effluents (Ternes 1998, Öllers et al., 2001). The same holds for Carbamazepine for which a quality value of 0.5 µg/l is proposed. Critical values in the range of concentrations of contaminated surface water derived by scientific risk assessment are discussed also for Bisphenol A, tin organic compounds, as well as several pesticides (Jahnel et al., 2006).

2.3. ENVIRONMENTAL SIGNIFICANCE OF TRANSFORMATION PRODUCTS

Transformation products which can be formed during chemical, biological or photolytic degradation are, apart from Nonylphenol, also not included in the above mentioned lists, due to the scarce knowledge of the transformation processes and the non-availability of reference compounds. However, the exposure of transformation products can be relevant as shown for pesticides in groundwater in the USA (Kolpin et al., 1997; 2004, Boxall et al., 2004) as well as in Switzerland (Hanke et al., 2007). In both studies several pesticide metabolites such as Metolachlor-ESA or -OXA were found in higher concentrations in groundwater than the parent compounds. While Metolachlor in groundwater of Swiss wells was found in the concentration range of 3–32 ng/L, the maximal concentration of the metabolites were at 480 ng/L for metolachlor-ESA and 210 ng/L for Metolachlor-OXA (Hanke et al., 2007). The parent compound was found in 13% of the wells in concentrations above the detection limit whereas Metolachlor-OXA were found in 12% and Metolachlor-ESA even in 33% of the wells.

For pharmaceuticals there is only little knowledge on the environmental exposure of human metabolites which are excreted from the human body instead of the parent compounds, often in considerable amounts. Some metabolites like Sulfamethoxazole and Ethinylestradiol conjugates are cleaved in STPs to the parent compound (Göbel et al., 2005, D'Ascenzo et al., 2003). Only a few recent studies include the fate of persistent human metabolites. Bendz et al. (2005) detected human ibuprofen metabolites not only in the STP but also in the receiving river and carbamazepine metabolites were found in STP effluent and even in drinking water (Miao et al., 2005; Hummel et al., 2006). Nearly no information is available until now about transformation products formed in the environment or STPs.

3. Analysis of Polar Micropollutants

In the last 15 years the analysis of polar organic compounds has dramatically improved. Main reason is the development and increased application of the HPLC-MS technology. Until the nineties of the last century mainly classical contaminants such as PAHs, PCBs, and pesticides which are detectable by GC-MS were studied. The coupling of mass spectrometry with HPLC opened up the sensitive quantification of polar compounds without time-consuming derivatization. State of the art is the analysis of polar compounds by HPLC separation followed by electrospray ionization and tandem mass spectrometric using selected reaction monitoring detection (McArdell et al., 2007). After appropriate enrichment e.g. by solid phase extraction (SPE) and use of the described technology detection limits in the lower ng/L-range can be achieved. One disadvantage of LC-MS in comparison to GC-MS is that the ionization of the compounds is not standardized and so no spectra libraries are commercially available. Therefore a screening of unknown compounds by interpretation of fragmentation pattern using large spectra libraries such as those available for GC-MS is nearly impossible. A new approach is the use of new hybrid tandem mass spectrometers. The combination of LC-Time of flight (TOF) (providing accurate mass measurements to generate elemental compositions of ions) with LC ion trap (providing structural information from fragmentation studies) is recently been applied for screening and identification of pesticides and their metabolites in environmental samples (Thurman et al., 2005; Hernandez et al., 2004; 2005). The limitation of TOF instruments in comparison to quadrupoles is their lower sensitivity, which hampers the detection and identification of analytes at low concentrations (Hernandez et al., 2005). The hybrid system of linear ion trap combined with the new orbitrap technology (LTQ-Orbitrap) enables higher sensitivity and higher mass accuracy up to 2 ppm and better (Hu et al., 2005; Makarov et al., 2006; Hollender et al., 2006).

As an example, in Figure 3 the approach for the sensitive identification of selected target compounds in an acquired LTQ-Orbitrap chromatograms is illustrated for the pesticide Metolachlor (15 ng/L) in an enriched surface water sample (Hollender et al., 2006). The target compounds can be extracted from the Orbitrap full scan chromatogram (Figure 3, I) using their exact mass. Reliable identification can be carried out by (1) comparing the measured and the theoretical mass of the molecular ion, (2) comparing the measured and predicted isotopic pattern (Figure 3, IIa and IIb) and (3) further confirmation by comparing the MS/MS spectra received in the iontrap with literature data or data predicted by appropriate software (Figure 3, IIIa and IIIb).

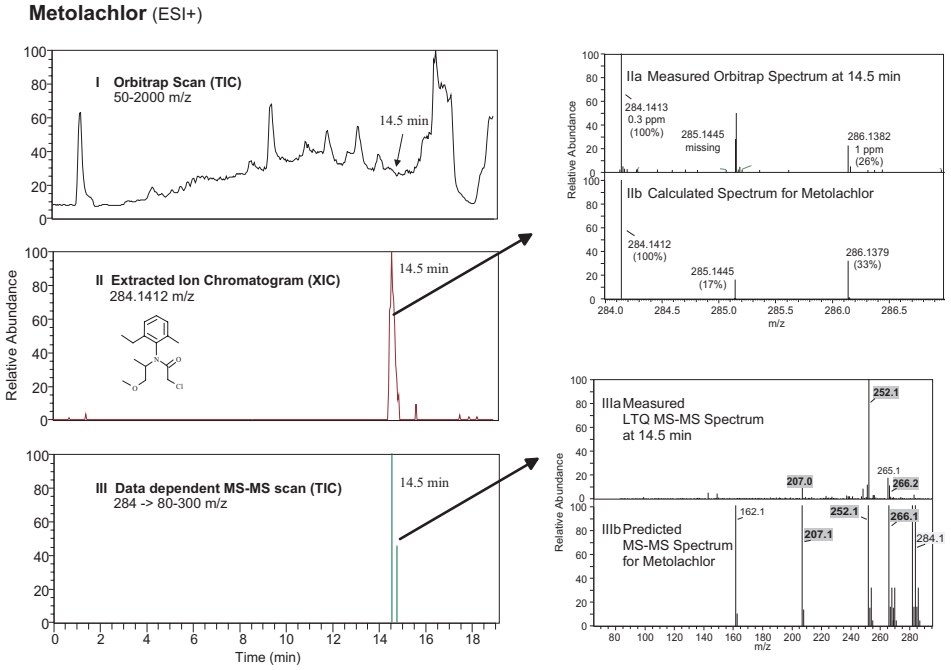


Figure 3. Identification of Metolachlor in a surface water sample using linear ion trap combined with orbitrap analyzer

4. Monitoring of Micropollutants in the Water Cycle

In the last 5–10 years large monitoring programs focusing on emerging contaminants in aquatic systems analyzed with LC/MS were carried out by research institutes, universities, but also federal environmental offices on the national and european level (Kolpin et al. 2002, Ternes 1998, BLAC 2003). Emphasis is on the discharge of micropollutants from wastewater in STPs into surface water. The results of the European project Poseidon and P-three are

important contributions in this field (Ternes and Joss, 2007, Reemtsma et al., 2006). In general, surface water which is influenced by wastewater, contains several polar compounds in concentrations above 0.1 ug/L. In Table 3 different micropollutants are listed which are very persistence or which often appear at elevated concentrations in surface water.

TABLE 3. Persistent organic micropollutants of urban and agricultural use which are often detected in surface water (Giger et al., 2006; Reemtsma et al., 2006; Schluep et al., 2006; Stamm et al., 2006; Ternes, 1998)

Substances from urban settlements	Pesticides, Biozides
Amidotrizoate (contrast medium)	Atrazine (herbicide not longer permitted in the EU, restricted use in Switzerland)
Benzotriazole (corrosion inhibitor)	Desethylatrazine (metabolite of Atrazine)
Bezafibrate (lipid regulators)	Desisopropylatrazine (metabolite of Atrazine)
Benzothiazolsulfonate (biocides)	2,6-Dichlorobenzamide (herbicide)
Carbamazepine (Antieptileptic)	Diuron (herbicide, biocides)
Clarithromycin (Antibiotic)	Diazinon (insectizide, low concentration but high effect)
Diclofenac (analgesic)	Glyphosate (herbicide, increasing application)
Ethylenediaminetetraacetic acid (EDTA, complexing agents)	Isoproturon (herbicide)
Iopamidol, Iopromid (contrast media)	Mecoprop (herbicide)
Methyl-tert-butylether (MTBE, gasoline supplement; restricted use, substituted partly by ETBE)	Metamitron (herbicide)
Naphtalinsulfonate (detergent)	Metolachlor (herbicide)
Metoprolol (beta-blocker)	Metolachlor-ESA (metabolite of Metolachlor)
Sulfamethoxazole (antibiotic)	2,4-Dichloro-phenoxy acetic acid (MCPA, herbicide)
Sulfophenylcarboxylate (metabolite of linear alkylsulfonates)	Simazine (herbicide)
Perfluorinated compounds (e.g. PFOS)	Terbutryn (herbicide, biocides)

Substances from urban settlements show different input dynamics compared to substances from agricultural use. The contamination of surface by wastewater from STPs is continuous whereas pesticides show a high time dynamic resulting from run-off events and seasonal applications (Leu et al., 2004).

Some of the compounds listed in Table 3 (e.g. Amidotrizoate, Carbamazepine, Sulfamethoxazole or Benzotriazol) can be also found in groundwater after aquifer passage (Blüm et al., 2005, Hanke et al., 2007, Ort et al., 2007, Sacher

et al., 2001) as shown in Figure 4 for Switzerland. The X-ray contrast media Iopamidol was found in the highest concentrations up to 88 ng/L, while the X-ray contast media Amidotrizoate was found more often but in lower concentrations (max. 50 ng/L). Sulfamethoxazole was the most abundant antibiotic found in concentrations up to 30 ng/L. These contaminants can be used as tracer for municipal wastewater because of their exclusive use in urban settlements. They are more persistent than Caffeine, which has recently successfully applied as indicator (Buerge et al., 2006) but is highly degradable in STP. The identification of tracers is more difficult for agriculture because some pesticides have additional urban application or are disposed through the sewage network as mentioned above.

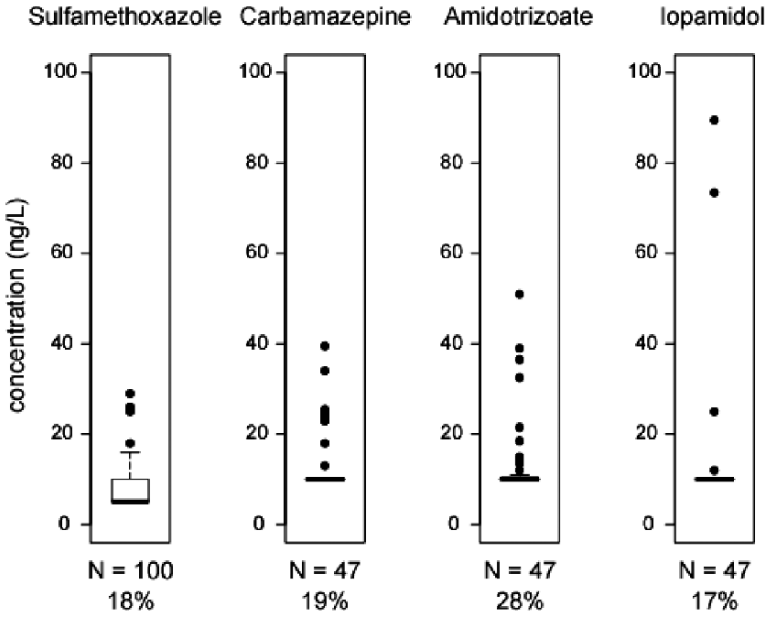


Figure 4. Concentrations of pharmaceuticals found in Swiss groundwater wells. N = number of investigated wells. x% = relative amount of findings above limit of quantification (LOQ). Values below LOQ were set equal to LOQ. (after Hanke et al., 2007), Copyright © 2007 SVGW Switzerland

Using these tracers the distance to a potential contamination source like polluted surface water or diffuse sources can be determined. This needs to be taken into account for the risk assessment of drinking water sources. To current knowledge the trace concentrations of pharmaceuticals in groundwater do not pose a risk for human health. However, following the precautionary principle, discussions are ongoing if drinking water quality limits should be introduced.

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