

available at www.sciencedirect.comwww.elsevier.com/locate/scitotenv

Occurrence and fate of emerging wastewater contaminants in Western Balkan Region

Senka Terzić^{a,*}, Ivan Senta^a, Marijan Ahel^a, Meritxell Gros^b, Mira Petrović^{b,c},
Damia Barcelo^b, Jutta Müller^d, Thomas Knepper^d, Isabel Martí^e, Francesc Ventura^e,
Petar Jovančić^f, Dalila Jabučar^g

^aCenter for Marine and Environmental Research, Ruđer Bošković Institute, Bijenička 54, 10002 Zagreb, Croatia

^bIIQAB-CSIC, Department of Environmental Chemistry, Jordi Girona 18-26, 08034 Barcelona, Spain

^cInstitució Catalana de Recerca i Estudis Avançats (ICREA), Barcelona, Spain

^dEuropa University for Applied Sciences Fresenius, D-65510 Idstein, Limburger Strasse 2, Germany

^eAGBAR, Sociedad General de Aguas de Barcelona, Avinguda Diagonal, 211, 08018-Barcelona, Spain

^fFaculty of Technology and Metallurgy, Karnegijeva 4, 11120 Belgrade, Serbia

^gHydro-Engineering Institute-Sarajevo (HEIS), Stjepana Tomića 1, 71000 Sarajevo, Bosnia and Herzegovina

ARTICLE INFO

Article history:

Received 7 September 2007

Received in revised form

4 March 2008

Accepted 4 March 2008

Keywords:

Emerging contaminants

Pharmaceuticals

Personal care products

Surfactants

Gas chromatography/mass spectrometry

Liquid chromatography/tandem mass spectrometry

Western Balkan

ABSTRACT

This paper reports on a comprehensive reconnaissance of over seventy individual wastewater contaminants in the region of Western Balkan (WB; Bosnia and Herzegovina, Croatia and Serbia), including some prominent classes of emerging contaminants such as pharmaceuticals and personal care products, surfactants and their degradation products, plasticizers, pesticides, insect repellents, and flame retardants. All determinations were carried out using a multiresidue analytical approach, based on the application of gas chromatographic and liquid chromatographic techniques coupled to mass spectrometric detection. The results confirmed a widespread occurrence of the emerging contaminants in municipal wastewaters of the region. The most prominent contaminant classes, determined in municipal wastewaters, were those derived from aromatic surfactants, including linear alkylbenzene sulphonates (LAS) and alkylphenol polyethoxylates (APEO), with the concentrations in raw wastewater reaching into the mg/l range. All other contaminants were present in much lower concentrations, rarely exceeding few µg/l. The most abundant individual compounds belonged to several classes of pharmaceuticals (antimicrobials, analgesics and antiinflammatories, β -blockers and lipid regulators) and personal care products (fragrances). Due to the rather poor wastewater management practices in WB countries, with less than 5% of all wastewaters being biologically treated, most of the contaminants present in wastewaters reach ambient waters and may represent a significant environmental concern.

© 2008 Elsevier B.V. All rights reserved.

1. Introduction

Wastewaters represent one of the main routes of input of anthropogenic organic and inorganic contaminants into the

environment. Due to their distinct differences in composition and related specific treatment requirements, domestic and industrial wastewaters are often kept in separate wastewater collection and treatment systems, which allows a more

* Corresponding author. Tel.: +385 1 4561 042; fax: +385 1 4680 242.
E-mail address: terzic@irb.hr (S. Terzić).

efficient source control and specific pollutant mitigation strategies. In contrast, municipal wastewaters in the developing countries such as those of the Western Balkan (WB) region (Bosnia and Hercegovina, Croatia, and Serbia) are mainly of mixed type and include both, domestic and industrial wastewaters (Kaštelan-Macan et al., 2007). Moreover, a vast majority of wastewaters in the WB countries is released to the environment either without any treatment or after being treated only mechanically. As a consequence of such poor wastewater management practices in WB countries, organic load discharged into the receiving waters, is often very high and characterised by a rather complex chemical composition. Besides various types of law-regulated contaminant classes, wastewaters contain a large number of various specific organic constituents for which environmental quality criteria are yet to be determined. In the last decade, a growing number of reports on the occurrence of unregulated anthropogenic compounds, frequently referred to as novel or emerging organic contaminants, expressed concern about their possible undesirable effects in the environment (Daughton and Ternes, 1999; Daughton, 2004; Fent et al., 2006).

The identification and determination of many previously undetected organic anthropogenic compounds in waste-

waters, including a large number of pharmaceuticals and personal care products, has seen a dramatic progress in recent years along with a rapid development of new analytical techniques (e.g. Gros et al., 2006a; Gonzalez et al., 2007; Richardson, 2007). Several extensive national and multinational monitoring programs have been launched in the last few years in order to provide comprehensive reconnaissance of the occurrence of various pollutants, with a special emphasis on pharmaceuticals, hormones and other polar organic wastewater contaminants (Ternes, 1998; Kolpin et al., 2002; Reemtsma et al., 2006; Zuccato et al., 2006). All these studies confirmed the presence of complex mixtures of unregulated contaminants, having various origins, and raised concern about their potential interactive effects.

In contrast to rapidly accumulating information on emerging contaminants in the USA and Western Europe, the data on the occurrence and fate of individual organic contaminants in countries of the WB region are very scarce and limited in terms of number of compounds measured and geographic distribution of the sampling points (Terzić and Ahel, 2006). An exception is a study on surfactant-derived alkylphenolic compounds in Croatia, which indicated their widespread occurrence in municipal wastewaters (Kveštak et al., 1994),

Table 1 – List of sampling sites and types of samples analysed

No	Sampling site	Type of WW*	WWT**	Sample analyzed
<i>Bosnia and Herzegovina</i>				
1	Sarajevo — main sewer	Municipal	No	Raw water
2	Pharmaceutical industry Bosnalijek, Sarajevo	Industrial	No	Raw water
3	Tannery KTK, Visoko	Industrial	No	Raw water
4	Textile industry Viteks, Visoko	Industrial	No	Raw water
5	Main sewer of the iron smelter, Zenica	Industrial	No	Raw water
6	Cellulose production Natron, Maglaj	Industrial	No	Raw water
<i>Croatia</i>				
7	Velika Gorica	Municipal	Yes	1) Raw water; 2) primary effluent; 3) secondary effluent
8	Bjelovar	Municipal	Yes	1) Raw water; 2) secondary effluent
9	Čakovec	Municipal	Yes	1) Raw water; 2) secondary effluent
10	Varaždin	Municipal	Yes	1) Raw water; 2) secondary effluent
11	Vinkovci	Municipal	Yes	1) Raw water; 2) secondary effluent
12	Pula	Municipal	Yes	1) Raw water; 2) primary effluent
13	Rijeka	Municipal	Yes	1) Raw water; 2) after mechanical treatment
14	Split	Municipal	Yes	1) Raw water; 2) after mechanical treatment
15	Split — sewer center	Municipal	No	Raw water
16	Zagreb	Municipal	Yes	Raw water
17	Novi Zagreb	Municipal	No	Raw water
18	Karlovac	Municipal	No	Raw water
19	Sisak	Municipal	No	Raw water
20	Osijek	Municipal	Yes	Raw water
21	Belišće	Municipal	No	Raw water
22	Zadar	Municipal	No	Raw water
23	Slavonski Brod	Municipal	No	Raw water
<i>Serbia</i>				
24	Belgrade — sewer center	Municipal	No	Raw water
25	Dishes factory, METALAC, Gornji Milanovac	Industrial	Yes	Raw water
26	Pulp and paper factory, UMKA, umka	Industrial	Yes	1) Before WWT 2) after WWT
27	Factory of herbicides, FITOFARMACIJA, Zemun	Industrial	No	After washing of machines and reactors and after recycling
28	Pharmaceutical Industry GALENIKA, Zemun	Industrial	Yes	1) Before WWT 2) after WWT
29	Public Railway Transport Enterprise, Washing Center, Belgrade,	Technical	No	Washing effluent

*WW — waste water **WWT — waste water treatment.

Table 2 – List of contaminants analysed and analytical methods used

Target compounds	Acronym	Analytical technique	References
Acetaminophen	ACE	LC/MS/MS	Gros et al., 2006b
Acetyl cedrene	AC	GC/MS	Mitjans and Ventura, 2005
Amberonone	AMB	GC/MS	Mitjans and Ventura, 2005
Aprobarbital	AB	GC/MS	Peschka et al., 2006b
Atenolol	ATE	LC/MS/MS	Gros et al., 2006b
Atrazin	ATR	GC/MS	Peschka et al., 2006a
Atrazin–desethyl	DEA	GC/MS	Peschka et al., 2006a
Atrazin–desisopropyl	DIA	GC/MS	Peschka et al., 2006a
Azithromycin	AZI	LC/MS/MS	Senta et al., 2005
Bayrepel	BAY	GC/MS	Knepper, 2004
Bezafibrate	BEZ	LC/MS/MS	Gros et al., 2006b
Bisphenol A	BPA	LC/MS/MS	Petrović et al., 2003
Bultalbitol	BB	GC/MS	Peschka et al., 2006b
Carbamazepine	CARB	LC/MS/MS	Gros et al., 2006b
Clofibric acid	CLO	LC/MS/MS	Gros et al., 2006b
Ciprofloxacin	CIP	LC/MS/MS	Senta et al., 2005
Diclofenac	DCF	LC/MS/MS	Gros et al., 2006b
Dimethoat	DIM	GC/MS	Peschka et al., 2006a
Enrofloxacin	ENR	LC/MS/MS	Senta et al., 2005
Epoxiconazole	EPO	GC/MS	Peschka et al., 2006a
Erythromycin*	ERY	LC/MS/MS	Senta et al., 2005
Famotidine	FAM	LC/MS/MS	Gros et al., 2006b
Fluoxetine	FLU	LC/MS/MS	Gros et al., 2006b
Galaxolide	HHCB	GC/MS	Mitjans and Ventura, 2005
Gemfibrozil	GEM	LC/MS/MS	Gros et al., 2006b
Hexobarbital	HB	GC/MS	Peschka et al., 2006b
HHCB lactone	HHCBL	GC/MS	Mitjans and Ventura, 2005
Ibuprofen	IBU	LC/MS/MS	Gros et al., 2006b
Indomethacine	IND	LC/MS/MS	Gros et al., 2006b
Josamycin	JOS	LC/MS/MS	Senta et al., 2005
Ketoprofen	KET	LC/MS/MS	Gros et al., 2006b
Lansoprazole	LANS	LC/MS/MS	Gros et al., 2006b
Linear alkylbenzene sulfonates	LAS	LC/MS/MS	Di Corcia et al., 1999
Loratidine	LOR	LC/MS/MS	Gros et al., 2006b
Mefenamic acid	MFA	LC/MS/MS	Gros et al., 2006b
Metamitron	MTM	GC/MS	Peschka et al., 2006a
Metoprolol	MTP	LC/MS/MS	Gros et al., 2006b
Mevastatin	MEV	LC/MS/MS	Gros et al., 2006b
Musk xylene	MX	GC/MS	Mitjans and Ventura, 2005
N-diethyl- <i>m</i> -toluamide	DEET	GC/MS	Knepper, 2004
Naproxen	NAP	LC/MS/MS	Gros et al., 2006b
Nonylphenol	NP	LC/MS/MS	Petrović et al., 2003
Nonylphenol ethoxylates	NPEO	HPLC; LC/MS	Ahel et al., 2000
Nonylphenoxy acetic acid	NP1EC	LC/MS/MS	Petrović et al., 2003
Nonylphenoxyethoxy acetic acid	NP2EC	LC/MS/MS	Petrović et al., 2003
Norfloxacin	NOR	LC/MS/MS	Senta et al., 2005
Octylphenol	OP	LC/MS/MS	Petrović et al., 2003
Octylphenoxy acetic acid	OP1EC	LC/MS/MS	Petrović et al., 2003
Ofloxacin	OFL	LC/MS/MS	Gros et al., 2006b
Paroxetine	PAR	LC/MS/MS	Gros et al., 2006b
Pentobarbital	PB	GC/MS	Peschka et al., 2006b
Picolinafen	PIC	GC/MS	Peschka et al., 2006a
Prapranolol	PROP	LC/MS/MS	Gros et al., 2006b
Pravastatin	PRAV	LC/MS/MS	Gros et al., 2006b
Propiconazole	PCZ	GC/MS	Peschka et al., 2006a
Propyphenazone	PRO	LC/MS/MS	Gros et al., 2006b
Ranitidine	RAN	LC/MS/MS	Gros et al., 2006b
Roxithromycin	ROX	LC/MS/MS	Senta et al., 2005
Secobarbital	SB	GC/MS	Peschka et al., 2006b
Simazin	SIM	GC/MS	Peschka et al., 2006a
Sotalol	SOT	LC/MS/MS	Gros et al., 2006b
Sulfadiazine	SDZ	LC/MS/MS	Senta et al., 2005
Sulfamerazine	SMR	LC/MS/MS	Senta et al., 2005
Sulfamethazine	SMZ	LC/MS/MS	Senta et al., 2005
Sulfamethoxazole	SMX	LC/MS/MS	Senta et al., 2005

Table 2 (continued)

Target compounds	Acronym	Analytical technique	References
Sulfapyridine	SPY	LC/MS/MS	Senta et al., 2005
Sulfathiazole	STZ	LC/MS/MS	Senta et al., 2005
Tebuconazole	TEB	GC/MS	Peschka et al., 2006a
Terbutryn	TBN	GC/MS	Peschka et al., 2006a
Terbutylazin	TBA	GC/MS	Peschka et al., 2006a
Terbutylazin-desethyl	DET	GC/MS	Peschka et al., 2006a
Tonalide	AHTN	GC/MS	Mitjans and Ventura, 2005
Traseolide	TRA	GC/MS	Mitjans and Ventura, 2005
Trimethoprim	TMP	LC/MS/MS	Senta et al., 2005
Tris-2-chloroethyl phosphate	TCEP	GC/MS	Meyer and Bester, 2004
Tris-2-chloropropyl phosphate	TCPP	GC/MS	Meyer and Bester, 2004

*ERY was determined as anhydrous ERY (ERY-H₂O).

and several reports dealing with the occurrence of phenazone type of analgesic compounds and caffeine in Croatian municipal wastewaters (Ahel and Jeličić, 2001; Jeličić and Ahel, 2003; Ahel et al., 2004). Furthermore, some pharmaceutically derived compounds, including propyphenazone and isopropylidene intermediates from the vitamin C production, were shown to be the most prominent individual contaminants in the leachate of the main landfill of the city of Zagreb (Croatia) (Ahel et al., 1998). More recently, a comprehensive characterisation of the organic contaminants in the wastewater of the city of Zagreb, performed using an effects-directed analytical approach, showed a presence of numerous toxicants (Grung et al., 2007).

To the best of our knowledge, there are no reports in the open literature, documenting the occurrence of emerging contaminants in domestic and industrial wastewaters in Bosnia and Herzegovina and Serbia. Only scarce reports, focused mainly on the distribution of classical pollutants such as pesticides (Gašić et al., 2002) and petroleum hydrocarbons (Dalmacija et al., 2003) in soils and receiving surface waters can be found.

Along these lines, this paper aims to fill the existing gap by providing for the first time a comprehensive report on the occurrence of a wide spectrum of individual organic wastewater contaminants in municipal and industrial wastewaters from the WB region, including various groups of emerging contaminants. Highly specific LC/MS/MS and GC/MS analyses were applied to determine the occurrence and behaviour of more than seventy individual organic trace contaminants in Croatian, Bosnian and Serbian wastewaters. The analytes included representatives of seven different classes of contaminants, including pharmaceuticals, surfactants, plasticizers, pesticides, repellents, flame retardants and fragrances.

2. Experimental

2.1. Sampling sites

Sampling was performed in autumn 2004 and spring 2005 in the framework of the EU FP6 project on "Reduction of environmental risks posed by emerging contaminants through

advanced treatment of municipal and industrial wastes" (EMCO) and included two sampling campaigns in Croatia (16 locations), and one in Bosnia and Herzegovina (6 locations) and Serbia (7 locations). The majority of samples from Bosnia and Serbia were untreated municipal and industrial wastewaters, while in Croatia, effluents from the existing wastewater treatment plants (WWTPs) were also collected. The list of samples analysed is given in Table 1. It should be stressed that only few WWTPs (Čakovec and Bjelovar) contained facilities for 24-hour flow-proportional composite sampling, while on some other locations (Rijeka, Split, Varaždin) composite samples were prepared by mixing grab samples, taken over a diurnal cycle. For all other locations, only grab samples were available.

2.2. Sample pre-treatment and analysis

The collected samples were analysed for the presence of a wide spectrum of organic trace contaminants (Table 2). The main classes of target compounds included pharmaceuticals, surfactants, plasticizers, pesticides and fragrances and involved several analytical protocols for multi-residue analysis of different contaminant groups based on GC/MS and LC/MS techniques. Before further analysis, all wastewater samples were filtered through glass-fiber filters and thus represent only dissolved fraction.

The enrichment of all analytes from the collected wastewater samples was performed by solid-phase extraction (SPE) following earlier developed analytical protocols (for references see Table 2). Surfactant residues were enriched on C₁₈ cartridges, while other target analytes were extracted using Oasis HLB cartridges. The Oasis extracts were divided into four identical aliquots and distributed to the participating laboratories for analyses on different groups of target contaminants. The following analytical methods were used for trace level quantification.

2.2.1. Surfactants

The determination of surfactant residues included two major types of aromatic surfactants, anionic surfactants of linear alkylbenzene sulphonate (LAS) type and nonionic surfactants of alkylphenol polyethoxylate (APEO) type. A special emphasis was on the comparatively persistent biotransformation

Table 3 – List of contaminants analysed and their concentration ranges in raw municipal wastewaters (n = 24 for surfactants, pesticides, repellents, flame retardants and pharmaceuticals except barbiturates; n = 17 for barbiturates; n = 18 for fragrances)

Compound class	Analyte	LOD(μg/l)	No positive samples	Concentration range (μg/l)	Mean value (μg/l)*
Pharmaceuticals					
Antimicrobials	TMP	0.012	24	0.035–2.55	0.781
Sulfonamides	SDZ	0.001	24	<LOD — 0.132	0.026
	STZ	0.001	3	<LOD — 0.004	0.002
	SPY	0.004	22	<LOD — 0.931	0.339
	SMR	0.001	4	<LOD — 0.020	0.006
	SMZ	0.002	11	<LOD — 0.186	0.047
	SMX	0.001	24	0.019–11.6	1.18
	ERY	0.001	24	0.024–0.420	0.134
	AZI	0.002	24	0.006–1.14	0.456
	JOS	0.008	4	<LOD — 0.016	0.013
	ROX	0.001	3	<LOD — 0.050	0.031
Fluoroquinolones	NOR	0.003	23	0.016–2.94	0.976
	CIP	0.007	21	<LOD — 2.61	0.405
	ENR	0.002	8	<LOD — 0.018	0.012
	OFL	0.042	0	<LOD	–
Analgesics and antiinflammatories	KET	0.028	19	<LOD — 1.52	0.561
	NAP	0.009	22	<LOD — 1.55	0.335
	IBU	0.012	23	<LOD — 11.9	3.20
	IND	0.007	3	<LOD — 0.240	0.177
	DCF	0.010	24	0.050–4.20	0.859
	MFA	0.003	9	<LOD — 0.120	0.053
	PRO	0.007	12	<LOD — 0.461	0.083
Psychiatric drugs	CARB	0.018	24	0.120–1.55	0.419
	FLU	0.035	0	<LOD	–
	PAR	0.006	0	<LOD	–
Antiulcer agent	LANS	0.014	0	<LOD	–
Histamine H1 and H2 receptor agonists	LOR	0.004	0	<LOD	–
	FAM	0.012	3	<LOD — 0.12	0.059
	RAN	0.024	3	<LOD — 0.758	0.253
β-blockers	ATE	0.042	23	<LOD — 7.56	1.88
	SOT	0.029	13	<LOD — 1.08	0.221
	MTP	0.012	5	<LOD — 4.68	0.953
	PROP	0.012	5	<LOD — 0.255	0.132
Lipid regulator and cholesterol lowering drugs	CFA	0.002	7	<LOD — 0.110	0.057
	GEM	0.003	23	<LOD — 1.70	0.377
	BEZ	0.009	7	<LOD — 0.260	0.065
	PRAV	0.060	0	<LOD — 1.17	–
	MEV	0.018	0	<LOD	–
Barbiturates	AB	0.080	0	<LOD	–
	BB	0.080	0	<LOD	–
	HB	0.080	0	<LOD	–
	PB	0.080	0	<LOD	–
	SB	0.080	0	<LOD	–
Surfactants	LAS	0.200	24	0.242–9450	2903
	NPEO	0.100	24	5–392	89
Metabolites	NP	0.069	24	0.460–4.40	1.66
	OP	0.017	24	<LOD — 0.272	0.128
	NP1EC	0.001	22	<LOD — 3.20	0.741
	NP2EC	0.001	17	<LOD — 4.37	0.586
	OP1EC	0.002	4	<LOD — 0.107	0.050
Plasticizers	BPA	0.013	22	<LOD — 2.06	0.510
Pesticides	DIM	0.080	1	<LOD — 0.80	–
	SIM	0.080	2	<LOD — 0.50	0.3
	ATR	0.080	9	<LOD — 28.0	3.3
	TBA	0.080	1	<LOD — 0.10	–
	TBN	0.080	2	<LOD — 0.15	0.1
	MTM	0.150	0	<LOD	–
	PCZ	0.080	0	<LOD	–
	TEB	0.080	0	<LOD	–
	EPO	0.080	0	<LOD	–
	PIC	0.080	0	<LOD	–

Table 3 (continued)

Compound class	Analyte	LOD($\mu\text{g/l}$)	No positive samples	Concentration range ($\mu\text{g/l}$)	Mean value ($\mu\text{g/l}$)*
Metabolites	DEA	0.100	0	<LOD	–
	DIA	0.100	0	<LOD	–
	DET	0.100	0	<LOD	–
Insect repellents	DEET	0.080	16	<LOD — 6.9	0.84
	BAY	0.100	3	<LOD — 2.2	1.3
Flame retardants	TCEP	0.080	9	<LOD — 0.5	0.19
	TCPP	0.080	22	<LOD — 2.5	0.46
Fragrances					
Polycyclic musks	HHCB	0.006	18	0.03–2.67	0.63
	AHTN	0.007	17	0.052–0.86	0.25
	HHCB	0.010	17	<LOD — 1.21	0.57
	TRA	0.005	12	<LOD — 0.34	0.12
Nitro musks	MX	0.009	16	<LOD — 0.56	0.17
Other fragrances	AC	0.005	17	<LOD — 13.9	1.6
	AMB	0.008	17	<LOD — 16.5	2.8

*Mean value was calculated as an arithmetic mean of all values above a detection limit.
<LOD — below detection limit.

products of APEO (Ahel et al., 1994), including nonylphenol (NP) and nonylphenoxy carboxylic acids (NPnEC). The analyses of the parent nonylphenol polyethoxylates (NPEO) were performed using HPLC with fluorescence detection (Ahel et al., 2000), while LC/MS technique was used for qualitative confirmation purposes. For LAS and NPEO biotransformation products, LC/MS/MS analytical procedures, based on electrospray ionisation in negative mode, have been adopted (Di Corcia et al., 1999; Petrović et al., 2003).

2.2.2. Pharmaceuticals

A multiresidue LC/MS/MS method for simultaneous determination of 3 classes of antimicrobials, including 6 sulfonamides, trimethoprim, 3 fluroquinolones and 5 macrolides was developed (Senta et al., 2005) using a modification of the method proposed by Goebel et al. (2004).

Determination of all other pharmaceutical compounds was performed by multiresidue LC-MS-MS method developed by Gros et al. (2006b). This included a determination of trace level of 25 different pharmaceutical compounds, belonging to a wide range of different therapeutical classes.

2.2.3. Personal care products

A GC-MS multiresidue method for the analysis of fragrances, including polycyclic musks (galaxolide, tonalide, traseolide, and HHCB lactone), nitro musks (musk xylene), amberonne and acetyl cedrene, was applied as described in details by Mitjans and Ventura (2005). Insect repellents, including DEET and Bayrepel were also determined using GC/MS technique (Knepper, 2004).

2.2.4. Other contaminants

The plasticizer bisphenol A was determined along with other alkylphenolic compounds derived from APEO surfactants using the same electrospray LC/MS/MS method in negative ionization mode (Petrović et al., 2003).

The organophosphate flame retardants were determined using GC/MS technique as described by Meyer and Bester (2004).

Pesticides, including triazine herbicides and their metabolites, triazole fungicides and organophosphate acaricide dimethoate, were determined by a multiresidue GC/MS methods as described in Peschka et al. (2006a).

3. Results and discussion

3.1. Occurrence of emerging contaminants in wastewaters

As can be seen from Table 1, the present study encompassed two distinct types of wastewaters, i.e. municipal and industrial wastewaters. Since the two types of wastewaters differ significantly with respect to the complexity of contaminants present, levels of specific classes of emerging contaminants and management requirements, for sake of clarity, the results for each group are discussed separately. Nevertheless, it should be kept in mind that municipal wastewaters, which contain mainly domestic sewage, in WB countries often include a significant contribution of wastewaters having industrial and institutional origin (Kaštelan-Macan et al., 2007).

3.1.1. Municipal wastewaters

A summary of the results, obtained during the reconnaissance of the selected contaminant classes in municipal wastewaters in WB countries, showing concentration ranges and mean values for individual chemical compounds, is given in Table 3. Fig. 1 shows the frequency of detection of individual analytes. For sake of clarity, the data presented in Fig. 1 were divided into two groups, the first one corresponding to pharmaceuticals as the most numerous contaminant class investigated (Fig. 1A) and the second one covering all other non-pharmaceutical classes (Fig. 1B). The results presented in Table 3 and Fig. 1 refer exclusively to raw wastewater samples and represent only a dissolved fraction, since all samples were filtered before the SPE enrichment. Since most of the target compounds belong to the relatively polar chemicals, the

dissolved fraction is expected to correctly reflect the total contaminant loads in analysed wastewaters.

Overall, the results showed that the levels of wastewater contaminants, found in raw municipal wastewaters of WB countries were rather similar to the levels found in other European regions (Ternes, 1998; Clara et al., 2005; Reemtsma et al., 2006; Zuccato et al., 2006; Santos et al., 2007). Fifty six (56) out of 76 target compounds were confirmed in at least one sample. The concentrations as well detection frequencies of individual compounds were highly variable (see Fig. 1 and Table 3).

3.1.1.1. Surfactants. Surfactants were clearly the most abundant chemical class in all examined wastewaters, ranging from 330–9450 $\mu\text{g/l}$ for linear alkylbenzene sulphonates (LAS) and 5–395 $\mu\text{g/l}$ for nonylphenol polyethoxylates (NPEO). Analyses of LAS revealed that these anionic surfactants belong to the most abundant anthropogenic compounds in wastewaters. All examined municipal wastewaters are of the mixed type and show relatively uniform LAS levels.

Analyses of surfactant-derived alkylphenolic compounds confirmed earlier findings on their widespread occurrence in

Croatian wastewaters, however the concentration levels were relatively low and suggest a decreasing trend in comparison to some previous campaigns conducted in early 1990s (Kveštek et al., 1994). The concentration of nonylphenol (NP), as the most toxic and most potent endocrine disrupting compound derived from NPEO surfactants (Jobling et al., 1996), was present in concentrations up to 4.4 $\mu\text{g/l}$ with an average value of 1.7 $\mu\text{g/l}$. Besides NP, all municipal wastewaters contained detectable levels of other metabolites derived from NPEO surfactants, in particular nonylphenoxy carboxylic acids (NPEC). The composition of alkylphenolic compounds was highly variable and revealed a strong impact of various biotransformation and physico-chemical processes on the distribution of individual alkylphenolic compounds in various types of wastewater samples. The most abundant alkylphenolic species in non-treated wastewaters was NP, while NPEC were the dominant species in biologically treated effluents, which is in agreement with earlier reports on this subject (Ahel et al., 1994; Clara et al., 2005).

Octylphenolic analogues of NPEOs and their metabolites represented only a small percentage of the total alkylphenolic compounds in all analysed samples, typically less than 10%.

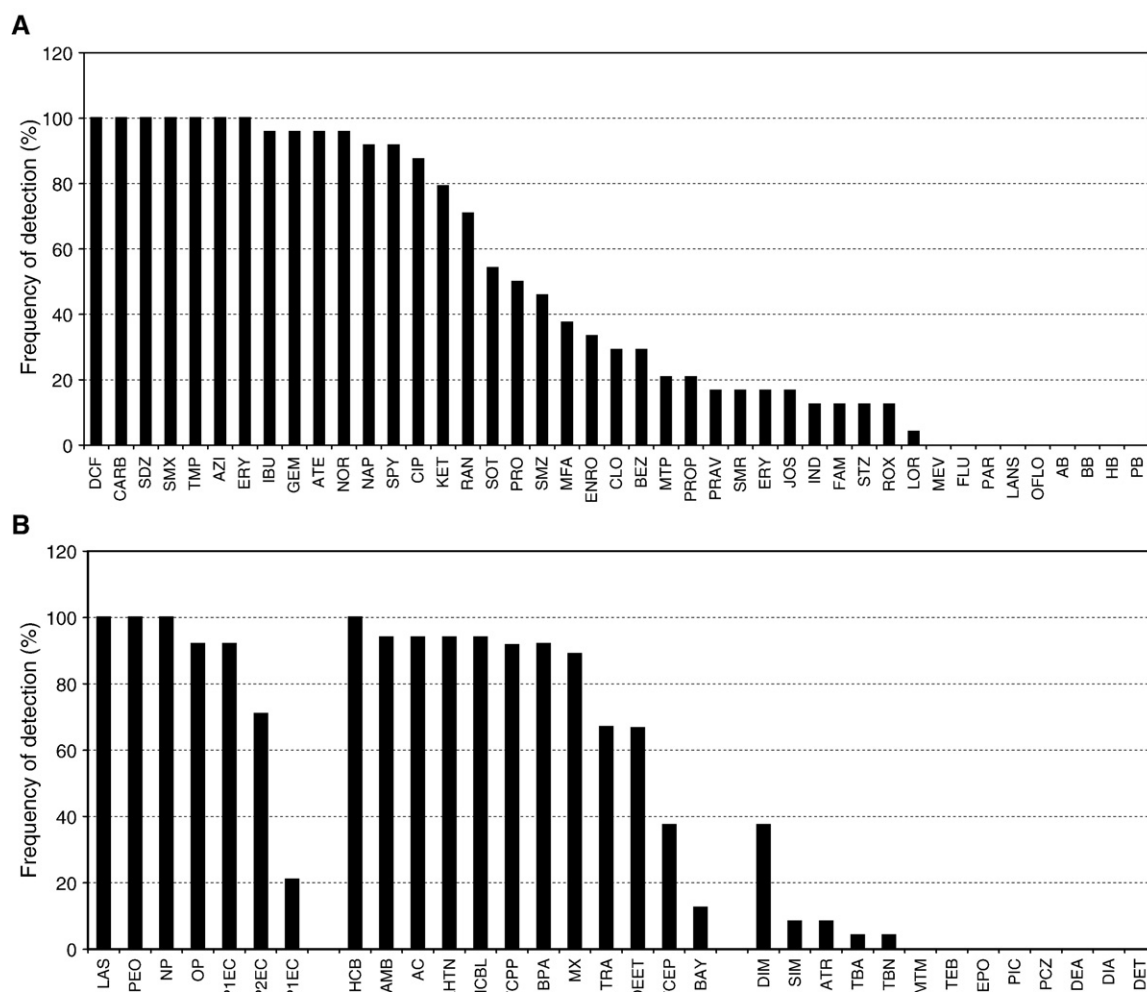


Fig. 1—Frequency of detection for individual emerging contaminants (%). A) Pharmaceuticals; B) Surfactants, fragrances, flame retardants, insect repellents and pesticides.

This is important for the assessment of the endocrine disrupting potential associated with APEO surfactants and their metabolites, because OP is 4 times more potent endocrine disrupting compound (EDC) as NP (Jobling et al., 1996). On the other hand, another widespread alkylphenolic xenoestrogen, bisphenol A (BPA), was found in the concentrations, ranging typically from 60 to 300 ng/l with only three samples with concentrations above 1 µg/l. This compound is applied as plasticizer and thus has a different origin from NP, but their similar modes of action in biological systems justifies considering possible additive effects. The measured concentration of BPA was lower than in Austrian sewage where the concentration in most of the samples exceeded 1 µg/l (Clara et al., 2005).

3.1.1.2. Pharmaceuticals. Except surfactants, all other compounds were present in much lower concentrations, being mainly in the range of low ng/l to few µg/l, with pharmaceuticals and fragrances being the most abundant groups. Thirty one (31) out of forty four (44) analysed pharmaceutical compounds were detected at concentration above the detection limit (typically 1–10 ng/l). The most abundant drug groups included analgesics and antiinflammatories, antimicrobials, β -blockers and lipid regulators (Fig. 1A).

The concentration of analgesics and antiinflammatories, was relatively high as compared to other pharmaceutical compounds as it can be usually expected for non-prescription over-the-counter drugs (Reemtsma et al., 2006). The most abundant compounds in this group were diclofenac (DCF; 0.050–4.20 µg/l) and ibuprofen (IBU; <LOD — 11.9 µg/l). These levels seem to be a bit lower than those reported in Western Europe (see the compilation by Fent et al., 2006), indicating lower usage rates of pain-killers in WB countries. Some other analgesic compounds, including ketoprofen (KET), naproxen (NAP), indomethacin (IND), mefenamic acid (MFA) and propyphenazone (PRO) were also found in detectable concentrations. The levels of PRO (<LOD — 461 ng/l) are in agreement with an earlier study in Croatia (Jelić and Ahel, 2003), based on GC/MS determinations and reflect its widespread use in WB countries. It should be noted that phenazone analgesics are still used in pain-killer pills produced by the local pharmaceutical industries in WB countries although they were phased-out in some countries due to the therapeutical side-effects.

Among different antimicrobials, the most abundant ones were sulfonamides, in particular sulfamethoxazole (SMX; 0.019–11.6 µg/l) and sulfapyridine (SPY; <LOD — 0.93 µg/l) as the most prominent representatives. It should be stressed that the main form of SMX in raw influent wastewater is its metabolite *N*-acetylsulfamethoxazole (Goebel et al., 2005), so that the concentration levels of the free SMX often underestimate the total load. Expectedly, SMX was accompanied by significant levels of trimethoprim (TMP; 0.035–2.55 µg/l) since these two antimicrobials are used in the same drug. Other detectable sulfonamides included sulfadiazine (SDZ) and sulfamethazine (SMZ), while sulfathiazole (STZ) and sulfamerazine (SMR) were below the detection limit in all samples. The concentration levels of sulfonamide antimicrobials were significantly higher than those reported for some other European countries (Goebel et al., 2005).

Two types of antibiotics, fluoroquinolones (FQ) and macrolides (MAC), were encompassed by this study, showing their widespread use in the WB region. The analyses of FQ antibiotics confirmed a widespread use of norfloxacin (NOR; 0.016–2.94 µg/l) and ciprofloxacin (CIP; <LOD — 2.61 µg/l), while ofloxacin (OFL) was not found in any of the analysed samples and apparently is not being used in the region. Veterinarian drug, enrofloxacin (ENR), was detected, but at rather low concentrations (<LOD — 20 ng/l).

Observed levels of NOR (average concentration 979 ng/l) were higher than those reported for Swiss raw sewage (Golet et al., 2002), while the levels of CIP (average concentration 400 ng/l) were very similar. A significantly different NOR-to-CIP ratio in the WB indicates probably some region specific usage pattern.

Significant differences in the usage patterns between WB and the Western Europe were even more pronounced for MAC antibiotics. MAC are an important group in Croatia, reflecting the fact that one of the most important world manufacturers of AZI, pharmaceutical industry PLIVA, is located in Zagreb (Croatia). Consequently, the most prominent representatives of MAC antibiotics were azithromycin (AZI; 0.006–1.14 µg/l) and erythromycin (ERY; 0.024–0.420 µg/l), while only traces of other MAC, including tylosin (TYL), josamycin (JOS) and roxithromycin (ROX) were detected. The composition of MAC antibiotics in WB region was significantly different from the one observed in Switzerland where the most abundant MAC was clarithromycin (CLA), while ERY and AZI were significantly lower (Goebel et al., 2005).

The drugs belonging to the class of β -blockers were identified in all analysed samples and the most abundant ones were atenolol and metoprolol with average concentrations of 1.88 and 0.95 µg/l, respectively, while lower levels of sotalol (SOT; 0.22 µg/l) and propranolol (PROP; 0.13 µg/l) were also detected. The levels of the selected β -blockers appear to be significantly lower than those reported in some earlier studies in Western Europe (see compilation by Diaz-Cruz and Barcelo, 2004) or in the USA (Vanderford and Snyder, 2006).

Among five different lipid regulators and cholesterol lowering drugs monitored, the most frequent lipid-regulating drug was gemfibrozil (GEM; <LOD — 1.7 µg/l), which was detected in almost all samples. Clofibrate acid (CLO) and bezafibrate (BEZ) were detected in less than 30% of the samples with concentrations rarely exceeding 100 ng/l, while pravastatin (PRAV) and mevastatin (MEV) were never detected. The observed composition of lipid regulators is rather different and the concentrations lower than those from some earlier reports in Western Europe (see review by Diaz-Cruz and Barcelo, 2004) indicating the prevalence of older types of lipid-lowering drugs.

Analyses of psychiatric drugs confirmed the presence of carbamazepine (CARB) in all analysed samples (0.120–1.55 µg/l), with an average concentration of 0.42 µg/l. The widespread occurrence of CARB in municipal wastewaters was confirmed by many other studies in Europe (see review by Diaz-Cruz and Barcelo, 2004) and North America (Metcalfe et al., 2003). The other two selected representatives of psychiatric drugs, fluoxetine (FLU) and paroxetine (PAR), were not detected in any of analysed samples. Barbiturates, as a special category of

psychiatric drugs, were also not detectable in wastewaters from WB, since they were phased out from the use in most of the European countries. Their occurrence on some locations in Germany was shown to be associated with an old disposal site (Peschka et al., 2006b).

The most prominent antihistaminic drug was ranitidine (RAN), which was detected in 70% of the samples and reached average concentration of 250 ng/l. The other related drugs, anti-histaminic loratadine (LOR) and the ulcer-healing lansoprazole (LANS), were not detected in any of the analysed samples.

3.1.1.3. Personal care products, flame retardants and pesticides. As to the personal care products, fragrance compounds exhibited a widespread occurrence in municipal waters with maximal concentrations, ranging from 0.337 µg/l for traseolide (TRA) to 16.7 µg/l for amberonne (AMB). Most of the determined fragrances were detected at high frequencies (>90%). Among polycyclic musks, galaxolide (HHCB) was the most abundant representative with average levels of 630 ng/l. A lactone metabolite of HHCB and tonalide (TON) were also detected in the samples. Other prominent fragrances included AMB, acetyl cedrene (AC) and musk xylene (MX) with average concentrations of 2.8 µg/l, 1.6 µg/l and 0.13 µg/l, respectively. The observed levels and composition of fragrances in wastewaters of WB countries confirm findings from some other studies (Mitjans and Ventura, 2005).

Another widespread class of personal care products determined in this study were insect repellents, including *N*, *N*-diethyl-*m*-toluamide (DEET) and Bayrepel. Unlike in Germany, where DEET has been almost completely substituted by Bayrepel since 1999 (Knepper, 2004), DEET is still the main insect repellent in WB region. It was detected in 67% of the samples with average concentration of 840 ng/l, while Bayrepel was detected in only 3 samples. The maximum concentrations of both repellent types (6.7 µg/l DEET and 2.2 µg/l Bayrepel) were determined in the samples from eastern part of Croatia (Osijek and Beliše), which is known to have problems with mosquitoes.

The two organophosphate flame retardants, including Tris (chloroisopropyl)phosphate (TCPP) and Tris(2-chloroethyl)phosphate (TCEP), were also determined in most of the WB municipal wastewaters. TCPP was detected more frequently and its average concentration (460 ng/l) was somewhat higher than that of TCEP (190 ng/l). A very similar concentration levels were recently reported as a result of a Western European survey (Reemtsma et al., 2006).

This study encompassed also several classes of pesticides, including triazines and their metabolites, dimethoate (DIM) and triazole fungicides and postemergence herbicide picolinafen (PIC). The most frequently detected class was chlorotriazine herbicides but even this class was, generally, not very abundant in analysed municipal wastewaters. Atrazine (ATR), simazine (SIM), terbutylazine (TBA) and terbutryn (TBN) were present usually in rather low concentrations (<250 ng/l). This is probably a consequence of the fact that sampling campaigns were performed out of the main pesticide application season. High concentration of ATR (28 µg/l) was observed only in the wastewater of the city of Sisak (Croatia), probably due to the contribution of industrial waste from the herbicide manufacture at that location. All other pesticide classes were not detected.

3.1.2. Industrial wastewaters

As can be seen in Table 1, wastewater from different industries, including pharmaceutical industry, tannery, iron smelter, textile industry, cellulose production, dishes factory, pulp and paper factory, were analysed. It should be stressed that this study was not directed to perform a detailed screening of the main contaminants typical for each of the individual industries, but the samples were analysed for preselected compound classes as described for municipal wastewaters. As expected, most of the industrial effluents contained very low levels of pharmaceuticals, mainly few over-the-counter analgesics. However, it is interesting to look for the presence of selected pharmaceutical compounds in wastewater effluents from the pharmaceutical industries, since these may represent significant specific sources of

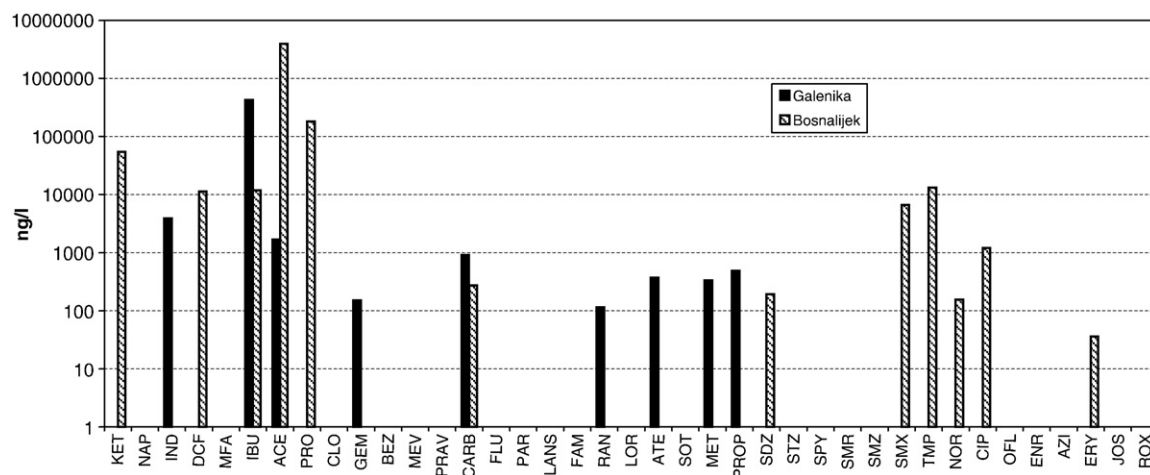


Fig. 2—Occurrence of pharmaceuticals in wastewaters of pharmaceutical industries Galenika (Serbia) and Bosnalijek (Bosnia and Herzegovina).

such contaminants. The results for pharmaceutical industries Bosnalijek in Sarajevo (Bosnia and Herzegovina) and Galenika in Belgrade (Serbia) are presented in Fig. 2. As can be seen, composition of the detectable pharmaceuticals is much simpler than in the municipal wastewater, and reflects production assortments of the given industry. However, the concentrations for most of the selected target compounds were relatively low in terms of expected strongly enhanced values, which can occur periodically in industrial effluents. Only few compounds such as acetaminophen (ACE; up to 4 mg/l), ibuprofen (IBU; 0.42 mg/l) and propyphenazone (PRO; 0.18 mg/l), were present in concentrations above 0.1 mg/l, while some other less abundant compounds (KET, DCF, TMP and SMX) were still present in rather high concentrations (5–50 µg/l) as compared to municipal wastewaters. Such a picture indicates very likely that the discharges from the different production facilities are not continuous.

Due to their widespread use in various industrial applications, surfactants are supposed to be relatively common constituents of industrial wastewater effluents. The results of the analyses of aromatic surfactants in effluents of five different industries from Bosnia and Herzegovina are presented in Fig. 3. The concentrations of both LAS and NPEO vary over wide ranges with LAS being significantly higher in all effluents. The LAS concentration was the highest in effluents from the textile (16.9 mg/l) and pharmaceutical industry (7.7 mg/l), while effluents from the cellulose production and iron smelter showed relatively low levels (0.04 and 0.22 mg/l). The distribution of NPEO surfactants showed also the lowest abundance in the effluents from the cellulose production and iron smelter however their concentration was significantly enhanced in the effluents from the textile industry and tannery. This is in a good agreement with the reported most common industrial applications of NPEO. With respect to the transformation products of NPEO, the most abundant ones were NP and NP1EC. The concentrations of NP in the effluents from the textile industry (Viteks Visoko) reached very high

levels, exceeding 100 µg/l, which suggests that this location requires a particular attention, since such concentrations are considered harmful for aquatic life (see review by Servos, 1999).

3.1.3. Removal during wastewater treatment

Unlike surfactants, which behaviour in WWTPs has already been well-described in the literature (Ahel et al., 1994; Di Corcia et al., 1999; Clara et al., 2005) elimination efficiency of pharmaceuticals in WWTPs is still a matter of intensive research (e.g. Clara et al., 2005; Lindqvist et al., 2005; Santos et al., 2007). The concentrations of the most prominent representatives of pharmaceuticals in raw influent water and secondary effluent as well as resulting removal rates in the WWTP Čakovec (Croatia) are presented in Fig. 4. This WWTP was chosen for detailed assessment of removal efficiencies because it includes both mechanical and biological treatment and allows collection of flow-proportional composite samples of wastewater effluents. The only pharmaceutical compound that exhibited very high elimination rate of over 95% during both sampling periods was IBU. This finding is in agreement with several previously published reports indicating that IBU, although widely present wastewater contaminant, is readily eliminated in WWTPs (Lindqvist et al., 2005; Santos et al., 2007). On the contrary, most of the other pharmaceutical compounds exhibited much lower (DCF, CLO, CARB, ATE, SOT, TMP, AZI, ERY) or rather variable (SMX, KET) elimination efficiency. For some of these compounds a similar behaviour has already been reported. Goebel et al. (2005) reported on rather low elimination efficiency of macrolide antimicrobials and TMP in Swis WWTPs, while other authors found that CARB and DCF were inadequately eliminated during waste water treatment (Clara et al., 2005; Lindqvist et al., 2005). It should be mentioned that in some cases (ATE, DFC, TMP, AZI, ERY), effluent concentrations were higher than in the influents, which could be explained either by sampling inaccuracy (erroneous estimate of hydraulic retention time) or also by deconjugation or retransformation of conjugated compounds during

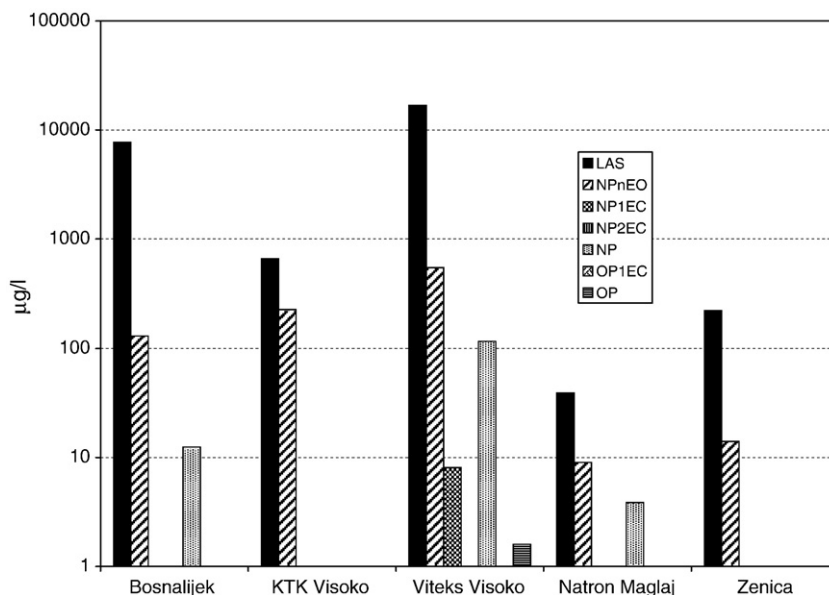


Fig. 3 – Concentration of different types of surfactants and surfactant-derived compounds in several types of industrial waters in Bosnia and Herzegovina (see Table 1).

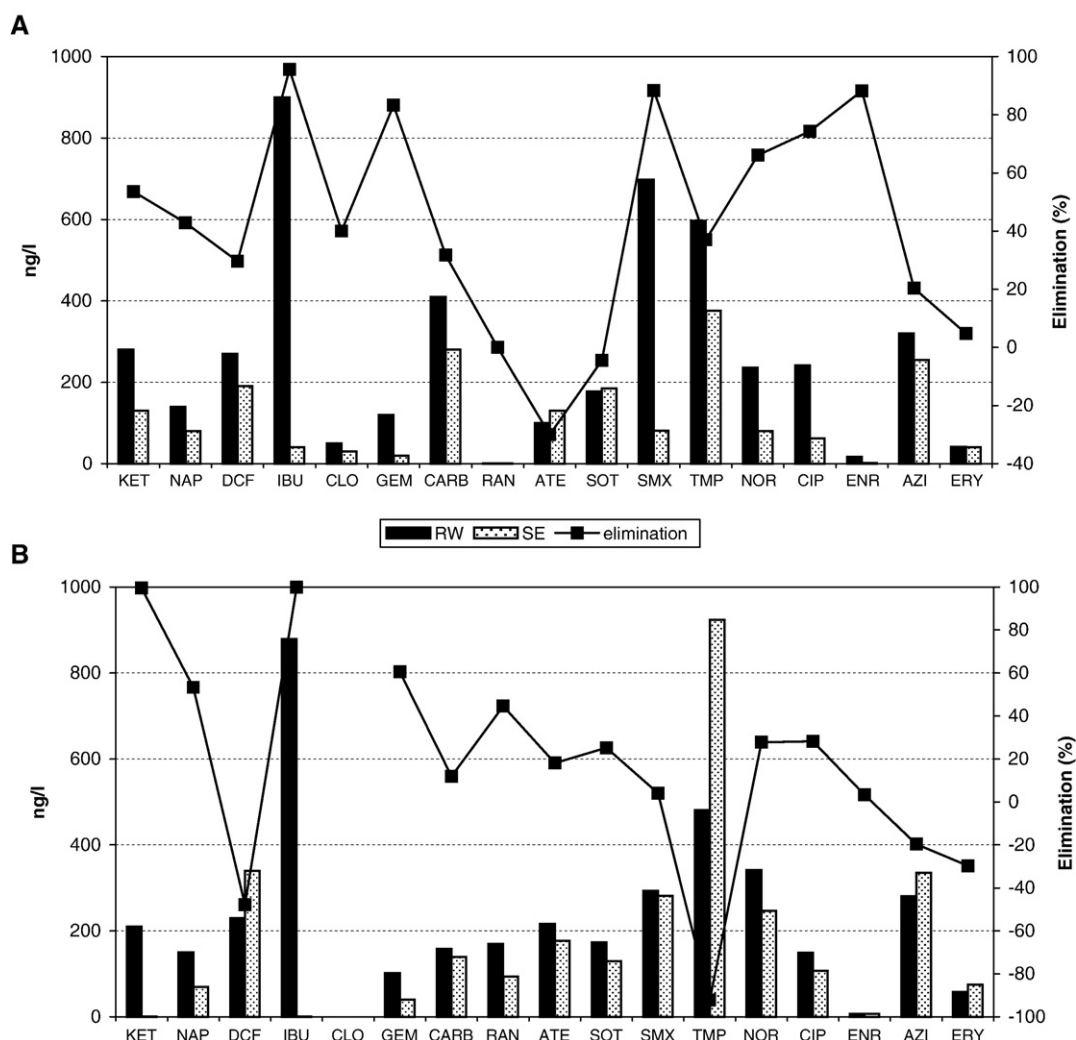


Fig. 4–Occurrence and elimination efficiencies of pharmaceuticals in the municipal WWTP of the city of Čakovec (Croatia). A) October 2004; B) May 2005.

treatment into the original compounds. Since these conjugates were not included in the analysis, no reliable conclusion about their biotransformation could be made.

Acknowledgements

This work was performed within the framework of the EU FP6 STREP project on the Reduction of Environmental Risks, Posed by Emerging Contaminants, through Advanced Treatment of Municipal and Industrial Wastes (EMCO) (INCO-CT-2004-509188). The financial support of Croatian Ministry of Science, Education and Sports (Project No. 098-0982934-2712) is also acknowledged.

REFERENCES

- Ahel M, Jeličić I. Phenazone analgesics in soil and groundwater below a municipal solid waste landfill. In: Daughton CG, Jones-Lepp TG, editors. ACS Symposium Series, Pharmaceuticals and Personal Care Products in the Environment. Scientific and Regulatory Issues. Washington, D.C.: American Chemical Society; 2001. p. 100–15.
- Ahel M, Giger W, Koch M. Behaviour of alkylphenol polyethoxylate surfactants in the aquatic environment-I. Occurrence and transformation in sewage treatment. *Water Res* 1994;28:1131–42.
- Ahel M, Mikac N, Čosović B, Prohić E, Soukup V. The impact of contamination from a municipal solid waste landfill (Zagreb, Croatia) on underlying soil. *Water Sci Technol* 1998;37:203–10.
- Ahel M, Giger W, Molnar E, Ibrić S. Determination of nonylphenol polyethoxylates and their lipophilic metabolites in sewage effluents by normal-phase high-performance liquid chromatography and fluorescence detection. *Croat Chem Acta* 2000;73:209–27.
- Ahel T, Mijatović I, Matošić M, Ahel M. Nanofiltration of a landfill leachate containing pharmaceutical intermediates from vitamin C production. *Food Technol Biotechnol* 2004;42:99–104.
- Clara M, Strenn B, Gans O, Martinez E, Kreuzinger N, Kroiss H. Removal of selected pharmaceuticals, fragrances and endocrine disrupting compounds in a membrane bioreactor and conventional wastewater treatment plants. *Water Res* 2005;39:4797–807.

- Dalmacija B, Ivančev-Tumbas I, Zejak J, Djurendić M. Case study of petroleum contaminated area of Novi Sad after NATO bombing in Yugoslavia. *Soil Sediment Contam* 2003;12(4):591–611.
- Daughton CG. Non-regulated water contaminants: emerging research. *Environ Impact Asses Rev* 2004;24(7–8):711–32.
- Daughton CG, Ternes TA. Pharmaceuticals and personal care products in the environment: agents of subtle change? *Environ Health Perspect* 1999;107:907–38.
- Diaz-Cruz S, Barcelo D. Occurrence and analysis of selected pharmaceuticals and metabolites as contaminants present in waste waters, sludge and sediments. In: Barcelo D, editor. *The Handbook of Environmental Chemistry*, vol. 5(I). Berlin Heidelberg: Springer-Verlag; 2004. p. 227–60.
- Di Corcia A, Capuani L, Casassa F, Marcomini A, Samperi R. Fate of linear alkyl benzenesulfonates, coproducts, and their metabolites in sewage treatment plants and in receiving river waters. *Environ Sci Technol* 1999;33:4119–25.
- Fent K, Weston AA, Caminada D. Ecotoxicology of human pharmaceuticals. *Aquat Toxicol* 2006;76:122–59.
- Gašić S, Budimir M, Brkić D, Nešković N. Residues of atrazine in agricultural areas of Serbia. *J Serb Chem Soc* 2002;67(12):887–92.
- Goebel A, McArdeall CS, Suter MJ-F, Giger W. Trace determination of macrolide and sulfonamide antimicrobials, a human sulfonamide metabolite, and trimethoprim in wastewater using liquid chromatography coupled to electrospray tandem mass spectrometry. *Anal Chem* 2004;76(16):4756–64.
- Goebel A, Thomsen A, McArdeall CS, Joss A, Giger W. Occurrence and sorption behaviour of sulfonamides, macrolides, and trimethoprim in activated sludge treatment. *Environ Sci Technol* 2005;35:3981–9.
- Golet EM, Alder AC, Giger W. Environmental exposure and risk assessment of fluoroquinolone antibacterial agents in wastewater and river water of the Glatt Valley watershed, Switzerland. *Environ Sci Technol* 2002;36(17):3645–51.
- Gonzalez S, Petrović M, Barcelo D. Advanced liquid chromatography/mass spectrometry (LC-MS) methods applied to wastewater removal and the fate of surfactants in the environment. *Trends Anal Chem* 2007;26(2):116–24.
- Gros M, Petrović M, Barcelo D. Development of a multi-residue analytical methodology based on liquid chromatography-tandem mass spectrometry (LC-MS/MS) for screening and trace level determination of pharmaceuticals in surface and wastewaters. *Talanta* 2006b;70:678–90.
- Gros M, Petrović M, Barcelo D. Multi-residue analytical methods using LC-tandem MS for the determination of pharmaceuticals in environmental and wastewater samples: a review. *Anal Bioanal Chem* 2006a;386(4):941–52.
- Grung M, Lichtenthaler R, Ahel M, Tollefsen KE, Langford K, Thomas KV. Effects-directed analysis of organic toxicants in wastewater effluent from Zagreb, Croatia. *Chemosphere* 2007;67(1):108–20.
- Jeličić I, Ahel M. Occurrence of phenazone analgesics and caffeine in Croatian municipal wastewaters. *Fres Environ Bull* 2003;12:46–50.
- Jobling S, Sheahan D, Osborne JA, Matthiessen P, Sumpter JP. Inhibition of testicular growth in rainbow trout (*Oncorhynchus mykiss*) exposed to estrogenic alkylphenolic chemicals. *Environ Toxicol Chem* 1996;15:194–202.
- Kaštelan-Macan M, Ahel M, Horvat AJM, Jabučar D, Jovančić P. Water resources and waste water management in Bosnia and Herzegovina, Croatia and the State Union of Serbia and Montenegro. *Water Policy* 2007;9:319–43.
- Knepper TP. Analysis and mass spectrometric characterisation of the insect repellent Bayrepel and its main metabolite Bayrepel acid. *J Chromatogr A* 2004;1046:159–66.
- Kolpin DW, Furlong ET, Meyer MT, Thurman EM, Zaugg SD, Barber LB, Buxton HT. Pharmaceuticals, hormones, and other organic wastewater contaminants in US streams, 1999–2000: a national reconnaissance. *Environ Sci Technol* 2002;36(6):1202–11.
- Kvešćak R, Terzić S, Ahel M. Input and distribution of alkylphenol polyethoxylates in a stratified estuary. *Mar Chem* 1994;46:89–100.
- Lindqvist N, Tuhkanen T, Kronberg L. Occurrence of acidic pharmaceuticals in raw and treated sewage and in receiving waters. *Water Res* 2005;39:2219–28.
- Metcalfe CD, Koenig BG, Bennie DT, Servos M, Ternes TA, Hirsch R. Occurrence of neutral and acidic drugs in the effluents of Canadian sewage treatment plants. *Environ Toxicol Chem* 2003;22:2872–80.
- Meyer J, Bester K. Organophosphate flame retardants and plasticizers in wastewater treatment plants. *J Environ Monit* 2004;6:599–605.
- Mitjans D, Ventura F. Determination of fragrances at ng/L levels using CLSA and GC/MS detection. *Water Sci Technol* 2005;52(10–11):145–50.
- Peschka M, Müller J, Knepper TP. Trends in pesticide transport into the River Rhine, the Rhine. In: Knepper TP, editor. *The Handbook of Environmental Chemistry, Water Pollution*, vol. 5 (I). Berlin Heidelberg: Springer-Verlag; 2006a. p. 155–76.
- Peschka M, Eubeler JP, Knepper TP. Occurrence and fate of barbiturates in the aquatic environment. *Environ Sci Technol* 2006b;40(23):7200–6.
- Petrović M, Barcelo D, Diaz A, Ventura F. Low nanogram per liter determination of halogenated nonylphenols, nonylphenol carboxylates, and their non-halogenated precursors in water and sludge by liquid chromatography electrospray tandem mass spectrometry. *J Am Soc Mass Spectrom* 2003;14:516–27.
- Reemtsma T, Weiss S, Mueller J, Petrović M, Gonzalez S, Barcelo D, Ventura F, Knepper TP. Polar pollutants entry into the water cycle by municipal wastewater: a European perspective. *Environ Sci Technol* 2006;40:5451–8.
- Richardson SD. Water analysis: emerging contaminants and current issues. *Anal Chem* 2007;79(12):4295–323.
- Santos JL, Aparicio I, Alonso E. Occurrence and risk assessment of pharmaceutically active compounds in wastewater treatment plants. A case study: Seville city (Spain). *Environ Int* 2007;33:596–601.
- Senta I, Terzić S, Ahel M. Simultaneous determination of sulfonamide, fluoroquinolone and macrolide antimicrobials in wastewater using solid-phase extraction and liquid chromatography/tandem mass spectrometry (LC/MS/MS). In: Barcelo D, Petrovic M, editors. *1st EMCO Workshop on Analysis and Removal of Contaminants from Wastewaters for the Implementation of the Water Framework Directive (WFD)*, 20–21 October 2005; Dubrovnik, Croatia; 2005. p. 87.
- Servos MR. Review of the aquatic toxicity, estrogenic responses and bioaccumulation of alkylphenols and alkylphenol polyethoxylates. *Water Qual Res J Can* 1999;34(1):123–77.
- Ternes TA. Occurrence of drugs in German sewage treatment plants and rivers. *Water Res* 1998;32(11):3245–60.
- Terzić S, Ahel M. Organic contaminants in Croatian municipal wastewaters. *Arh Hig. Rada Toksikol* 2006;57:297–307.
- Vanderford BJ, Snyder SA. Analysis of pharmaceuticals in water by isotope dilution liquid chromatography/tandem mass spectrometry. *Environ Sci Technol* 2006;40:7312–20.
- Zuccato E, Castiglioni S, Fanelli R, Reitano G, Bagnati R, Chiabrando C, Pomati F, Rossetti C, Calamari D. Pharmaceuticals in the environment in Italy: causes, occurrence, effects and control. *Environ Sci Pollut Res* 2006;13(1):15–21.