

REVIEW

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# Developments in society and implications for emerging pollutants in the aquatic environment

Dirk Bunke<sup>1\*</sup> , Susanne Moritz<sup>1</sup>, Werner Brack<sup>2,3</sup>, David López Herráez<sup>2</sup>, Leo Posthuma<sup>4,5</sup> and Margarita Nuss<sup>1</sup>

## Abstract

Pollutant emissions in river basins may be subject to change. How can we succeed in predicting future pollutant emissions and risks? The approach presented here is based on the hypothesis that the existing scenarios on developments in society may provide useful indications on future pollutants. To begin with, the results of four societal scenario-based analyses showed that some developments are directly connected to consumption and the emission of specific substances. Second, it appeared that the effects of other development scenarios are more complex, such as those associated with climate change. Quantitative statements with regard to the implications of such scenarios on future pollutants can be particularly difficult. A third important group of changes are technological developments. Frequently observed changes in this respect are substitutions of problematic substances by substances with a similar structure. When the pollutant consequences of future development scenarios are taken together it will be possible to explore political, societal, or technical mitigation efforts which can be undertaken now or in the near future to counteract the effects of developments that are considered as extremely hazardous for man and the environment. Thereby, a careful monitoring of developments in society can help to develop appropriate strategies which should include preemptive emission and impact reduction efforts. Finally, we developed recommendations how to manage future emerging pollutants in river basins.

**Keywords:** Emerging pollutants, Surface water, Developments, Scenarios, Prediction, Substitution

## Background and objectives of the review

Pollutants in river basins can change with time. Over the last few decades, increasing numbers of pollutants have been found in European waterbodies [1, 2] and globally, not only via better detection techniques, but also regarding the really enriched composition of the combined exposures. In this review, the term “emerging pollutants” (EPs) is used as defined by the NORMAN Network, an international institution which enhances the exchange of information on emerging environmental substances, and encourages the validation and harmonization of common measurement methods and monitoring tools [3].

“*Emerging pollutants*” Substances currently not included in routine environmental monitoring programs and which may be candidates for future legislation due to their adverse effects and/or persistency [4].

Up to now, around 970 emerging pollutants have been detected by the NORMAN Network group during the last 10 years [4]. It has been shown that EPs affect ecosystems and human health and reduce the quality of water bodies [1, 5, 6]. The most important sources of EPs including hospitals, animal husbandries, household discharges, companies manufacturing drugs, and wastewater- and sewage-treatment plants are shown in [1, 5]. Inputs of disposal of municipal, industrial, and agricultural wastes, excretion of pharmaceuticals, and accidental spills also play an important role [6]. A summary about emissions of emerging contaminants found in the urban water cycle is given by Pal et al. [7]. The analysis of global trends in the chemical sector as

\*Correspondence: d.bunke@oeko.de

<sup>1</sup> Oeko-Institut e.V. Institut für angewandte Ökologie, Institute for Applied Ecology, Merzhauserstr 173, 79100 Freiburg, Germany  
Full list of author information is available at the end of the article

given in the Global Chemicals Outlook [8] shows that these emissions will continue and increase even further. Therefore, management strategies to ensure a good water quality should try to address the risks of future pollutants next to those of current concern. How can we predict them? The approach presented here is based on the hypothesis that existing scenarios on developments in society can give useful indications on future pollutants, and—in turn—provide information that might be useful for the design of preemptive management strategies that can prevent environmental deterioration even for novel compounds that will be designed and emitted in the future.

Recent developments in society and technology are described in a broad range of scenarios. Scenarios on climate change are well known and published by the Intergovernmental Panel on Climate Change (IPCC). IPCC is the international body for assessing the science related to climate change [9, 10]. The UNESCO (United Nations Educational, Scientific and Cultural Organization)—WWAP (World Water Assessment Program) refers to future trends in water consumption and water resources [11]. Other scenarios address demographic changes in European and global population growth, economic and technological changes. We reviewed the options to translate future societal scenarios into chemical emission scenario expectations, thereby including aspects of emissions, exposure levels, and expected impacts on human health and the environment, starting from a solution-focused paradigm of risk assessment. That is, we evaluate the scenarios with a view on derivation of mitigation measures that may support limiting current and future emissions, exposures, and risks, even for chemicals not yet designed, used, or produced.

The review presented here has three objectives:

- Overview on developments which are expected in society in the coming two, three decades;
- Analysis to what extent these predictions can be used as an information source to qualify and/or quantitate the ‘pollutants of tomorrow’;
- Application of a solution-focused approach to the results, so as to discuss general mitigation options.

Existing scenarios for developments of society are identified and analyzed as to whether causal links exist between societal development and emissions of new or already known substances to the environment. For specific areas, expected developments are discussed in more detail with the aim to support the development of appropriate management options for risk management.

## Approach

Which pollutants can be expected to occur if future developments in society and climate are taken into account? Such developments are described in a broad range of scenarios. The scenarios on climate change are well known and published by the IPCC [9, 10]. Other studies focus on economic, technological, and demographic developments. These changes in society can cause releases of new or already known substances to the environment.

The following sections give a review of developments in society which can be foreseen. In addition, they describe potential causal links between changes in society, use of chemicals/materials, and emissions of pollutants. This analysis refers to 33 publicly available studies with a large number of scenarios from different sectors (see Table 1).

The scenarios can be grouped as follows:

- *Scenarios for middle- and long-term developments in society, caused by multiple drivers* (e.g., the UNEP GEO 5—Global Environmental Outlook [12]; the UN Millennium Ecosystem Assessment (MA) [13]; the European Environment—State and Outlook 2010 [14]; the Planetary Boundary Approach [15]);
- *Predictions for water use and water cycle* (e.g., The World Water Vision of Earthscan [16]; Water in a changing world (e.g., The United Nations World Water Development Report [11]); Water resources across Europe (European Environmental Agency) [17]);
- *Predictions for industrial chemicals and hazardous waste* (e.g., Costs on Inaction on the sound management of chemicals (UNEP) [18]; Trace Contaminants in Water Cycles (Acatech) [19]);
- *Developments due to climate change* (e.g., the IPCC Special Report Emission Scenarios from UNEP [20]; the SCARCE project [21]);
- *Developments due to demographic change* (e.g., OECD Environmental Outlook to 2050 [22]);
- *Developments due to technological and/or economic changes* (e.g., THOUGHTS Megatrends [23]) and
- *Predictions for food production and nutrients* (e.g., The Global River Nutrient Report [24]).

In addition to the aspects listed above, some of the studies analyzed address a number of related aspects such as a retrospective analysis of technological changes (EEA, Late lessons from early warnings [25]) and EU Environmental Policy Targets for 2010–2050 [26]. In some cases, studies refer to several of the items mentioned above (see comment fields in Table 1).

Most of the scenarios which have been analyzed refer to five important developments:

**Table 1 Documents on developments in society and scenarios analyzed**

No.	Title	Institution/author	Years	References	Main topics/comments
(1)	Scenarios for middle- and long-term developments in society, caused by multiple drivers				
1.1	GEO 5 for business—impacts of a changing environment on the corporate sector	UNEP—United Nation Environment Programme	2013	[12]	Environmental change—because of two main drivers population growth and economic development
1.2	GEO 5—global environmental outlook	UNEP—United Nation Environment Programme	2012	[70]	Climate change population growth urbanization Water scarcity—and its impacts
1.3	Millennium ecosystem assessment (MA)	Alcamo et al.	2003	[13]	The four MA Scenarios and their direct and indirect drivers
1.4	Measuring progress—environmental goals and gaps	UNEP—United Nation Environment Programme	2012	[104]	Climate change chemicals waste, water
1.5	The European environment—state and outlook 2010	European Environment Agency, Jock Martin, Thomas Henrichs, and many more	2010	[14]	Climate change nature and biodiversity natural resources and waste Environment, health, and quality of life these are directly/indirectly linked
1.6	Planetary boundaries: exploring the safe operating space for humanity	Rockström et al.	2009	[15]	Seven planetary boundaries
(2)	Developments in water use and water cycles				
2.1	World water vision—making water everybody's business	World Water Council	2000	[16]	Future scenarios for water, water business
2.2	Charting our water future Economic framework to inform decision-making	McKinsey 2030 water resources group	2009	[105]	Economic framework
2.3	Water in a changing world The United Nations World Water Development Report 3	UNESCO	2009	[11]	Drivers of water changes of water cycle
2.4	GLOWA—global change and the hydrological cycle	Federal Ministry of Education and Research (BMBF)	2008	[106]	Influence of demographic and technological change for water use, climate change
2.5	Future long term changes in global water resources driven by socioeconomic and climate changes	Alcamo et al.	2007	[107]	Global water resources, global change, water scenarios, water availability, water stress, climate change, and water
2.6	Water for men. Water for life	UNESCO World water assessment programme	2003	[108]	World water assessment
2.7	Water resources across Europe—confronting water scarcity and drought	European Environment Agency	2009	[17]	Future water use, main drivers
(3)	Developments in use and impact of chemicals				
3.1	Chemicals action plan 2010–2013. safety in Denmark	Government of Denmark	2010–2013	[109]	Use of chemicals on a global scale
3.2	Costs on inaction on the sound managements of chemicals	UNEP	2013	[18]	Impacts of chemicals for health, environmental, and development effects
3.3	Harmful substances and hazardous waste	United Nation Environment Programme		[110]	Hazardous wastes
3.4	Ökotoxikologische Bewertung von anthropogenen Stoffen	Thomas Knacker, Anja Coors, Acatech	2011	[19]	Pollutants in river systems and effects
3.5	Organische Spurenstoffe im Wasserkreislauf	Axel Bergmann, Acatech	2011	[111]	Pollutants in water cycles
(4)	Specific driver: climate change				
4.1	IPCC special report: emissions scenarios, summary for policymakers	Intergovernmental panel on climate change (IPCC) working group	2000	[20]	Climate change

**Table 1 (continued)**

No.	Title	Institution/author	Years	References	Main topics/comments
4.2	SCARCE—assessing and predicting effects on water quality and quantity in Iberian Rivers caused by global change	Spanish Council for Scientific Research	2009–2014	[21]	Change of water quality/quantity
4.3	WATCH—water and global change	Richard Harding Tanya Wamaars	2011	[112]	Introduction to the achievements of the WATCH Project Water cycle and its changes
4.4	Modell Deutschland: Klimaschutz bis 2050	Prognos, Öko-Institut e.V.	2009	[113]	Climate protection, focus Germany
(5)	Specific driver: demographic change				
5.1	Die demografische Zukunft Europas—wie sich Regionen verändern	Berlin Institut für Bevölkerung und Entwicklung	2008	[114]	Demographic change in Europe
5.2	OECD environmental outlook to 2050—the consequences of inaction	OECD	2012	[22]	Demographic change and its impact
(6)	Specific driver: technological/economical changes				
6.1	Trend Report Convenience—Machen Sie es sich bequem	SevenOne media	2007	[115]	Changing living standard, food, trade, human care products, e-commerce, consumer electronics
6.2	THOUGHTS megatrends	Roland Berger, School of Strategy and Education		[23]	Different perception—see changes in economic/technology sector because of the scenarios
(7)	Sector-specific topic: development in food production				
7.1	Fisheries and aquaculture in Europe	European Commission	2012	[116]	Aquaculture
7.2	The food gap—the impacts of climate change on food production 2020	FEU-US	2011	[117]	Impacts of climate change on food production in 2020
(8)	Sector-specific topic: nutrients				
8.1	Global river nutrient report: a scenario analysis of past and future trends	Seitzinger et al.	2009	[24]	Nutrient flows, MA scenarios included
8.2	World water vision—making water everybody's business	World Water Council	2000	[16]	Future scenarios for water and waste water
(9)	Further aspects				
9.1	Late lessons from early warning: the precautionary principle 1896–2000	European Environment Agency	2002	[25]	Retrospective analysis
9.2	Towards a green economy in Europe—EU environmental policy targets and objectives 2010–2050	European Environment Agency	2013	[26]	Green economy in Europe with laws and implementations
9.3	World social science report—changing global environment	UNESCO and ISCC	2013	[118]	Social developments
9.4	zPunkt megatrends	zPunkt GmbH	2012	[119]	Abstract of different megatrends

- Climate change;
- Demographic change;
- Global population growth and urbanization;
- Substitution of problematic chemicals due to regulation;
- Technological developments with new uses of chemicals.

For each of these developments, it has been analyzed whether the described developments could have consequences for the emissions of substances and for the occurrence of emerging pollutants in surface waters. The following figure illustrates the implications of future developments in society on emerging pollutants (Fig. 1).

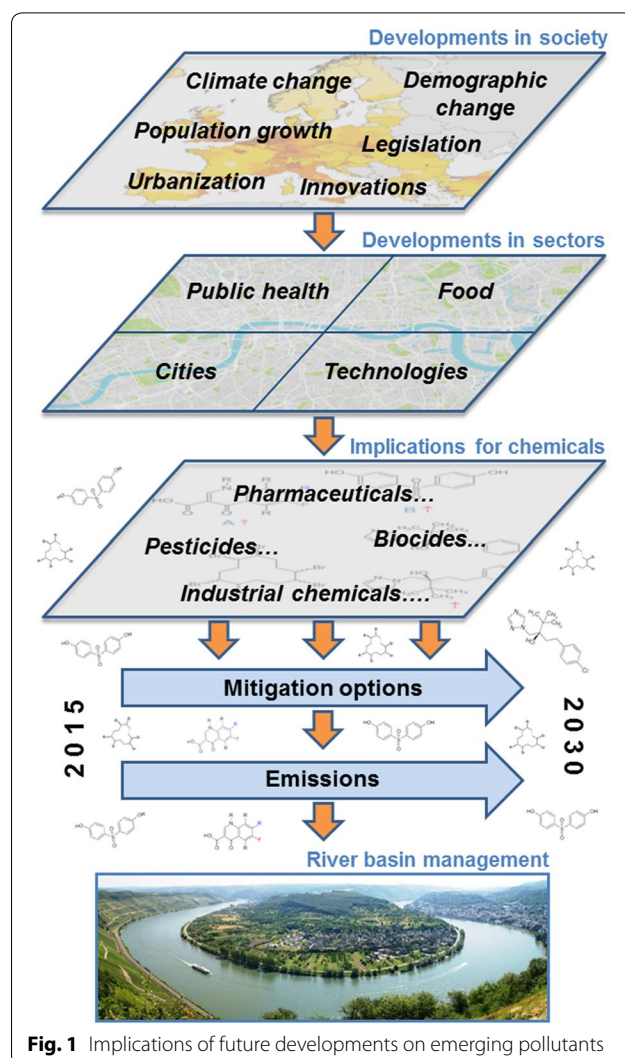
The figure shows that certain developments in society (first level) and in sectors of society (second level) influence the use and emissions of chemicals and groups of chemicals (third level). These emissions affect the future water quality in river basins.

## Results

### Climate change

Climate change is one of the main future developments currently being discussed. Main references are the emission scenarios published by the Intergovernmental Panel on Climate Change (IPCC), IPCC Working Group III [9]. “Climate change is an increasingly urgent problem with potentially far reaching consequences for life on earth and also reports unequivocal global warming with evidence of increases in global mean air and ocean temperatures, widespread snow and ice melt, and rising global sea level” [27]. Droughts, floods, and water scarcity are the most important impacts which affect the behavior of pollutants in water. Changes in precipitation directly affect water dilution volumes, and thus concentration variability in space and time—while the net result of chemical load and water volume determines the concentrations that are eventually the key predictors of risks and impacts. These developments can be seen in the Mediterranean basin, one of the regions of the world that are most vulnerable to global change [28]. Predictions show that upcoming problems in water availability can be clearly seen in this region [29, 30]. IPCC forecasts that this region will have rising temperatures in summer, more droughts, and also stronger rainfall. In addition, the average river flow will decrease [31]. In these respects, freshwater ecosystems like the ones of the Mediterranean basin are particularly vulnerable to global change [32–34]. Water temperature and the frequency of large floods will increase in future [31].

Droughts and floods, water scarcity, changes in water temperature, and also storm intensity will have consequences on the occurrence and concentrations of



**Fig. 1** Implications of future developments on emerging pollutants

EPs. Climate change also affects the transport of contaminants, their transfer between compartments of the ecosystems and also their transformation. In addition, climate change has significant adverse consequences for the incidences of diseases and the related use of drugs. These impacts of climate change on EPs are described in more detail in the following sections.

### Water scarcity and droughts: consequences of climate change

Due to climate change, water scarcity as well as droughts will increase. This development could have negative impacts on the flow river regime [28] and also on the chemical quality of water systems [31, 34].

Even without changes in the mass of pollutants emitted, water scarcity leads to a higher concentration of nutrients, pesticides, surfactants, pharmaceuticals, and estrogenic compounds [35, 36]. Dilution capacity



during droughts decreases. Therefore, the risk of pollutants in the environment increases. This might affect the functioning of the river ecosystem [3]. At present, this is a phenomenon particularly serious in arid or semi-arid regions as the Mediterranean basin. Due to climate change, this problem might become more severe in other regions of the world, too. In arid regions, the contaminants could be concentrated in river waters even more than hitherto [37].

The main uses of water by man are the production of drinking water and agricultural use. If water scarcity will increase, wastewaters must be reused for these applications. Pollutants from wastewater might be emitted to river waters, because the required purification of emerging pollutants in waste water before reuse is insufficiently effective, or often does not take place at all [28, 38–40].

#### **Torrential rainfalls and floods: consequences of climate change**

Extreme weather events like rainfalls will affect river flows and thus cause an increasing shear stress [41]. Sediments may be mobilized and deposited in lakes and reservoirs. Problems with pollutants in floodplains are expected after possible flooding of sewage plants, extruded agriculture land, or waste dumps behind dams in which EPs are stored [42, 43]. So far, immobilized pesticides or other EPs can enter surface waters in the event of torrential rainfalls and floods. For example, concentrations of the insecticides carbaryl and imidacloprid increased with the increasing storm intensity [27, 44]. Changes in the hydrological regime can mobilize stored contaminants [42]. Furthermore, contaminated water can deposit pollutants to agriculture land. Productive livestock or agriculture plants could absorb these contaminants originating from sediments or contaminated water [45]. Finally, these EPs could enter the (human) food chain.

#### **Elevated water temperatures: consequences of climate change**

Under changing climatic conditions, the water temperature at low river flow conditions will probably increase [28, 31]. This may lead to a synergistic effect of two stressor types: increasing amounts of emerging pollutants due to reuse of wastewater (see above) and also rising water temperatures. Wildlife will suffer from this second stress factor as well as from multiple other stress factors.

Climate change is expected to have further manifold implications on terrestrial and aquatic ecosystems. A constant increase of surface water temperature can alter or influence the environmental fate of chemicals, e.g., bioaccumulation, degradability, and mobility. Due to

these changes, the exposure of biota to these contaminants can change. Elevated water temperatures may alter the biotransformation of contaminants to more bioactive metabolites, and impair homeostasis. In addition, the toxicity of contaminants may be enhanced with increasing temperatures [27, 46–48]. Higher water temperature has long been known to modify the chemistry of a number of pollutants, resulting in significant alterations in their toxicities, e.g., in that of fish [42].

Higher water temperature is a further stressor for aquatic animals, but at the same time, will influence the uptake rate of pollutants by higher ventilation and the metabolic rate in fish, for example [49]. Another example for a synergistic effect has been reported for the Baltic amphipod *Monoporeia affinis*. Combined exposure to increased water temperature and the fungicide fenarimol resulted in an increased numbers of females with dead eggs [42].

Additional overviews about the interactions between various classes of chemicals and different environmental factors as temperature in aquatic organisms are given by Schiedeck, Heugens, and their colleagues [42, 50].

#### **Environmental behavior and fate of chemicals: consequences of climate change**

Climate change can have a large effect on the environmental fate and behavior of chemicals [27]. Several biotic and abiotic factors influencing the behavior and the fate of chemicals [42] show a temperature dependency. Examples are air–surface exchange, wet/dry deposition, and reaction rates as photolysis, biodegradation, or oxidation in air [27]. Solar irradiations are expected to increase in intensity. This results in an intense photo degradation of chemicals such as pharmaceuticals (e.g., diclofenac and ibuprofen) or the X-Ray contrast medium iopromid [51–53]. An example is the photo transformation of the anti-inflammatory drug diclofenac. Its photo transformation products have been shown to be more stable as well as more toxic than parent diclofenac [52–54]. Similarly, the photo products of anti-inflammatory drugs showed an increase in toxicity [51, 55–57].

#### **Incidence of diseases and drug consumption: consequences of climate change**

Climate-related environmental alterations are expected to be associated with an increase in chronic diseases already common in the Northern Hemisphere—such as cardiovascular, respiratory, and mental health problems. It is reasonable to assume that this will lead to a greater need for chemical medications, such as vasodilators, anticoagulants, anti-inflammatories, antidepressants, and analgesics, which then will potentially be emitted to the environment [58].

Changes in climate are also expected to result in an increase in pathogens and invertebrate vectors (such as mosquitos) for infectious diseases. As new disease threats emerge, higher pharmaceutical use seems inevitable. It is likely that medical drugs not commonly employed at present such as antiprotozoal are prescribed in future to treat, for example, malaria, amebiasis, and other diseases [58].

### Demographic change in Europe

Demographic changes may be important for future chemical emissions. According to demographic predictions for the next 40 years, the total population in Europe will remain relatively constant [59]. In parallel, the growth of the share of people older than 65 in the whole population will exhibit an increase by 38% until 2030, while the fraction of people under 20 years old will decrease by 17% until 2030 [60, 61]. As a consequence, disease incidences will increase for those diseases that are typical for elderly people. Examples are heart and circulation diseases, cancer, or diabetes, the frequency of which is likely to increase [58, 62]. There will also be an increasing demand for pharmaceuticals that are used in association with the increasing mean age [62].

Due to these developments, it is foreseeable that the consumption of pharmaceuticals will increase mostly in hospitals [63] and elderly homes, but also in privately owned homes. Pharmaceuticals like lipid regulators (e.g., bezafibrates), anti-inflammatory drugs (e.g., diclofenac), diabetic medications, and antibiotics are most frequently used by elderly people [49, 62, 63]. X-ray contrast medium and antineoplastic used in chemotherapy are further examples for groups of pharmaceuticals mostly consumed in hospitals but also in practical surgeries [64]. It is reasonable to assume that the consumption of these pharmaceuticals will further increase. Demographic change and pharmaceutical consumption are linked together [62]. Pharmaceuticals enter aquatic and terrestrial ecosystems [64], and have even been detected in drinking water in small concentrations [65].

### World population growth and urbanization

The world population is projected to grow from 7.7 billion in 2015 to 9.7 billion in 2050 [66]. This increase will mainly take place in developing countries such as Africa, South America and Asia. The trend of a declining population in Europe is noticeable (see “[Demographic change in Europe](#)”). In the scenario of population growth, the trend could be observed that the number of inhabitants in big cities will increase rapidly. In 1975, only 38% of the world population lived in cities. Presently, around 50% of the people live in cities while around two-thirds of the

global population is predicted to live in cities in 2030 [59, 67, 68]. This process of “urbanization” will entail many problems for the environment. It can result in increased concentrations of EPs in surface waters.

As a result of urbanization, the management of water, waste, and waste water as well as traffic regulation in cities will gain in importance. Urban development means also an increase of ground sealing (e.g., pavement, roads, and industrial areas) with negative impacts for the environment [69]. Natural land surfaces are transformed into impervious surfaces, such as streets, parking lots, and roofs. Percolation of rainwater and snowmelt through the soil is blocked [59, 11]. Ground sealing can increase the frequency and intensity of floods. Floods can transport pesticides, surfactants, pharmaceuticals, and other emerging pollutants to river systems, resulting in local pollution problems [11].

Urbanization requires a proper management of waste water to avoid contamination of local freshwater resources [11]. The rising share of the population living in cities results in an increase in waste water volume. Purification systems are a requirement that has become more essential than ever to ensure good water quality. Growing cities require the conduction of rainfall and flood prevention, an effective waste water treatment, a decrease of pollution, and, in many cases, an integrated management of the water system for households and industry [68].

Another important topic in big cities with impact on emerging pollutants is waste management [70, 71]. Waste and waste dumps are problematic stocks of contaminants. On a global scale, suitable waste management is not in place. Disposal flows with emerging pollutants such as plasticizers or deposits from pharmaceuticals can directly enter ecosystems and surface water [11].

Some substances used for insulation materials in house walls are pollutants of emerging concern. Examples are the flame retardant hexabromocyclododecane (HBCDD) and biocides, such as terbutryn (used as a herbicide) and 2-octyl-2*H*-isothiazol-3-on [72]. These substances have already been found in surface waters. Terbutryn can be released by rain water from insulation mats. It contaminates the ground, surface, and drinking water. At present, no purification methods are yet available for these substances in waste water treatment plants. After having passed through the sewage-treatment plants, they are emitted to the receiving water bodies [73].

These substances can become important future emerging pollutants, if buildings are replaced or renovated. This is likely to happen within the next 30–50 years. In a best-case scenario, all the renovation waste materials will be disposed as toxic waste. Or else, HBCDD and also terbutryn from historical uses will contaminate ecosystems, groundwater, and surface water for a long time, even if

the future use of substances such as HBCDD will be prohibited by virtue of REACH, the European Regulation on Registration, Evaluation, Authorization and Restriction of Chemicals (<https://eur-lex.europa.eu/legal-content/en/TXT/?qid=1532936325230&uri=CELEX:02006R1907-20180509>).

A growing world population requires enough food for all, a condition which has not yet been fulfilled. The major source of providing food comes from agriculture within farming, cattle breeding, aquaculture, and forestry [68]. Water management is one of the biggest challenges for this development, good water quality being of high importance. As a result of the reuse of sewage water, a future circulation of agrochemicals and other emerging pollutants is expected in regions with water scarcity [3, 35]. Reduction of meat consumption, sustainable agriculture with a reduced use of pesticides, as well as a sustainable use of land and soil are necessary elements for a food production system which respects the planetary boundaries [74].

### Technological changes

Technological developments take place in a large number of sectors on a continuous basis. New products or new functions of existing products are generated. In many cases, these innovations are based on the use of specific substances. An example for such functionality is the permanent water resistance of outdoor textiles. It has been realized with the use of per- and polyfluorinated chemicals (PFCs) [75]. Such new developments can result in the emergence of new contaminations of surface water, if these substances are released during production, service life, recycling, reuse, or disposal of the products. For PFOA, PFOS, and several other PFCs, adverse properties (toxicity, ecotoxicity, persistence, bioaccumulation) have been confirmed [76–80].

Technological changes are difficult to predict and are found in all branches. In the following sections, some examples are given for pollutants that have been emerging in response of such changes. In respect of these changes, two drivers can be distinguished:

- Regulation of problematic substances;
- Technological developments with new uses of chemicals and materials.

### *Substitution of problematic substances due to regulation*

The use of substances with very problematic properties may be prohibited by regulatory measures. Examples are restrictions for specific uses of substances under chemical legislation or the process of authorization under REACH [81]. Experience of the last decades has

shown that very often regulated substances are substituted by substances which belong to the same structural group. Often, these substitutes show a similar behavior in the environment. Recent examples for EPs which have been “triggered” by regulatory measures are phthalates and per- and polyfluorinated compounds. A third example is brominated flame retardants.

Recent monitoring studies show an increase in the concentrations of phthalates [diisononyl phthalate (DINP) and diisodecyl phthalate DIDP]), used as substitutes for low molecular weight phthalates which have been restricted by law throughout the EU [36, 82]. It can easily happen that phthalates are released out of a product because they are not chemically bound. They are semivolatile organic compounds. They can evaporate, be washed out, or abraded out of products [82, 83]. For several phthalates, severe adverse effects on humans and animals have been confirmed [84–86]. Phthalates are EPs frequently found in surface water [87].

Similarly, restrictions on long-chain (C8) per- and polyfluorinated hydrocarbons (PFCs) lead to the replacement of these substances by short-chain 2–4 PCFs [82, 88]—which continue to be detected in the environment in increasingly high levels [89].

These “new” phthalates and short-chain PFCs are not yet all regulated under a legal framework such as REACH. Therefore, producers can place these critical substances on the market.

Specific brominated flame retardants are the third example of substitutes triggered by regulatory measures. Hexabromobenzene (HBB) and bis(2,4,6-tribromophenoxy)ethene (BTBPE) are new, i.e., emerging pollutants—and substitutes for polybrominated biphenyls which have been forbidden by chemical legislation. The main emissions from these flame retardants result from the production of plastic materials over point sources. There are also diffuse sources such as migration from articles and elution of the flame retardant out of the products during production, use, or depollution. The persistent and bio-accumulative substances can be found in sediments, dust, in wild animals and humans [73, 90]. Their presence in surface water has furthermore been established by analysis. A review paper stated that there were increasing concentrations of brominated flame retardants in environmental waters [91].

The flame retardant hexabromocyclododecane is another example of a substance for which substitutes can be expected in water in the near future. HBCDD has been identified under REACH as a substance of very high concern. Since August 2015, the future use of this substance has been prohibited, unless authorization should be granted for specific uses (REACH Title VII, Art. 56).



### **Technological developments with new uses of chemicals**

Approximately 70% of all product innovations in Europe are based on new material developments. Materials innovations comprise new substances, substance and material modifications (e.g., surface functionalization), new material combinations (e.g., multimaterial systems, composites), and new applications of established substances. Substitutions can be triggered by many different reasons: replacement of rare or cost-intensive raw materials, replacement of hazardous and toxic substances, and use of materials which allow for a better product performance [92].

The VDI Technology Center has identified more than a hundred innovative technologies and materials, selecting 20 of them for a deeper analysis [92]. They belong to the following six groups: new production technologies (such as 3D printing), electronics (such as OLEDs and printable electronics), construction and lightweight engineering, energy, and environmental engineering (as organic photovoltaics), textile technologies, and functional materials and coatings (as polymeric foams) [92]. Many of the 470 substances compiled for these new technologies were polymers (polymers are exempted from the registration of REACH. However, the related monomers have to be registered). Convenience products are another product group in which many innovations have been generated in the last few years—resulting in EPs.

Convenience food and convenience in human care products are two groups of convenience lifestyle products [93]. Consumption of these products has been steadily increasing over the last decade. Often, they contain substances as sucralose or aspartame, used as food additives (sweeteners and aroma). Annual consumption rates are higher for products containing these substances [93–95]. Demographic change and urbanization further support the application of sucralose and other sweeteners. As described in “[Demographic change in Europe](#)”, the percentage of older people increases, resulting in higher rates of diseases such as diabetic. Popular diabetic products are made with sucralose or other sweeteners instead of sugar. This could increase the consumption of sucralose in the future. Sucralose as well as triacetin have already been detected as contaminants in surface waters [94]. It is reasonable to assume that their concentrations will increase, if the consumption rates will continue to increase.

### **Conclusion**

Future developments in society can result in the emission of new substances to the environment. In this review, an investigation on many reports on trends in society has

been carried out in terms of their potential implications on future emerging pollutants.

Scenarios on the development of society can give valuable indications on changes in future pollutants in river basins. Some developments are directly connected to the consumption and emission of specific substances, e.g., the demographic change in Europe. Due to the higher life expectancy in the following decades, it is reasonable to assume that the amount of pharmaceuticals circulating in sewage-treatment plants and the related concentrations in the environment will increase.

For specific product groups related to societal behaviors, there have been a growing number of indications for increased emissions. Examples are chemicals used for convenience products.

Other developments, such as climate change, are more complex. Its implications on future pollutants are much more difficult to predict in quantitative terms. The IPCC expects a rise in temperature as well as the increase of extreme weather events. As a result, the behavior of chemicals in water will change. The mobilization of chemicals from sediments might be facilitated by erosion, flood events, or rising water levels. Climate change will also affect behavior and risk attitudes of humans. All these aspects are linked and cannot be separated from each other.

Another important group of changes are technological developments. Substitutions of hazardous substances by substances with a similar structure are frequently observed. “New” phthalates as well as per- and polyfluorinated hydrocarbons (PFCs) are monitored in surface waters in increasing quantities after the regulatory control of a restricted number of substances of these classes.

Some of the developments described here could be mitigated by political, societal, or technical efforts. A careful monitoring of developments in society can help to develop appropriate strategies which should include preemptive emission and impact reduction efforts. Recommendations for future work are described in the following section: “[Recommendations: How to manage future emerging pollutants in river basins?](#)”

Future technological progress can contribute to delivering suitable alternatives for the currently used EPs as phthalates, PFCs, flame retardants, or nanomaterials. However, these new substances too might have a negative impact on the ecosystem. A preliminary examination of the risks associated with these substances together with a minimization of these risks from the very beginning has revealed its potential to become a selling point for novel technologies. In a Dutch project called *Nano next*, a specific method for Risk Analysis and Technology Assessment—termed RATA—has been developed. It includes a specific tool set to check new business ideas

for risks—really at the beginning [10]. It could be an important tool to avoid the introduction of new emerging pollutants as a result of new technologies.

More dedicated research on the linkages between society, climate change, and production and consumption of chemicals will be needed. The ongoing horizon-scanning activity of the EU shows the importance of monitoring future development in society. This can help to predict and to manage future emerging pollutants [96]. The monitoring of developments has to be supplemented by a scientific analysis of causal links between trends in society and the use of chemicals and the resulting emissions.

Based on the analysis of scenarios presented here, we identified the following areas which are likely to undergo considerable changes in the next two decades: public health, food, urbanization, and technologies.

### **Recommendations: How to manage future emerging pollutants in river basins?**

The following recommendations represent conclusions for a successful management of future emerging pollutants in river basins. They are based on the analysis of developments in society and their implications for emerging pollutants.

*Note* The following recommendations are quantitative. Within the project SOLUTIONS, information on tools have been provided which allow for the quantitation of future trends. Such tools can help to transform the following recommendations into quantitative objectives for a specific region or a specific river basin. They refer to the modeling of chemicals and risks, to the identification of priority pollutants and priority mixtures, to monitoring tools such as effect-based monitoring, to a solution-focused management of chemicals and risk, to abatement and mitigation options, and other important elements for the river basin management of emerging pollutants. Comprehensive information on these elements is provided in a user-friendly manner in the decision support system, RiBaTox. It is the main result of the SOLUTIONS project. It helps decision makers to find the appropriate instruments for the management of future pollutants in river basins and to implement the necessary efforts (RiBaTox, Version 2018, <https://solutions.marvin.vito.be/>).

### **Increase in pressure and change of pollutant pattern**

#### **Recommendation 1: Expect a future increase of the chemical burden in European river basins**

Several developments in society will lead to increased emissions of future emerging pollutants to river basins. Examples are increased releases of biocides from building facades due to an increase in heavy rainfall events, increase of drugs against antiprotozoal due to an increase

in the incidence of vector-borne diseases and an increase in emissions from the use of rodenticides in urban areas due to the growth of cities. This increase refers to the total emission, to the number of substances as well as to the complexity of the pollution pattern. Concentrations are expected to temporarily increase as a result of more extreme low river discharges.

#### **Recommendation 2: Expect a future decrease of chemicals which are under strict regulatory control**

A number of industrial chemicals which have been identified as substances of very high concern already exhibits decreasing concentrations in environmental media (e.g., DEHP and PFOS). It can be expected that this trend will continue. If such chemicals have been used in articles or buildings in the past, larger stocks of these chemicals may still be present in the urban environment. The REACH candidate list contains the substances that have been identified in Europe as substances of very high concern. It can be foreseen that for these substances substitutes will be placed on the market. This development is supported by the fact that the safety of chemicals increasingly became the focus of controversial debate in society—as one reason to place more chemicals under strict regulatory control, e.g., endocrine disrupting chemicals.

#### **Recommendation 3: Expect a future increase of substitutes for strictly regulated chemicals**

In general, strictly regulated substances are replaced by other chemicals which have a similar function. Only in rare cases, changes in product design are made to avoid the use of a substance at all. In many cases, these substitutes also have problematic properties and can become future emerging pollutants. For several of such regrettable substitutes, increasing concentrations in the environment are found, e.g., for Bisphenol S.

### **More demand for integrated (waste) water management**

#### **Recommendation 4: Enlarge the capacity of integrated water management systems in urban areas**

The ongoing growth of cities will lead to an increase in soil sealing in these urbanized areas. Climate change is expected to cause an increase in the frequency of heavy rain falls and stormy weather events in some regions, and increased droughts in others. Untreated storm water run-off has been found as an important source of urban pollutants: suspended solids, heavy metals, traffic-related micropollutants, plasticisers, flame retardants, and biocides. A combination of centralized and de-centralized technologies will be required to manage these emissions.

### **Recommendation 5: Improve water management systems in rural areas**

In regions with climate-induced increases in precipitation, an increase of surface water levels with possible flooding of sewage plants or extruded agriculture land can be expected. It is becoming increasingly important to implement an advanced storm water management in order to avoid an untreated overflow of sewage-treatment plants and to prevent mobilization of pesticides from agricultural land.

### **Recommendation 6: Prevent/avoid reuse of untreated waste water in areas of water scarcity**

Climate change is expected to cause an increase of areas and time periods with water scarcity. As a consequence, the need to use wastewater for irrigation will increase. This leads to an additional emission of contaminants to river basins, if the wastewater is not treated properly. Purification of waste water before reuse will become an even greater challenge in the years to come. In addition, if urban areas are adapted to a more circular economy and higher reuse rates of water, this adaptation should include a safe and circular design to prevent “recycling of risks” during reuse.

### **Regional development planning**

#### **Recommendation 7: Include scenarios on future regional developments in the river basin management plans**

Climate change as well as urbanization will result in changes in land use. Emission profiles from urban areas are quite distinct from rural areas. Changes in agricultural farming will lead to changes in the emission of pesticides and other agrochemicals which greatly influence the chemical burden and the appropriate abatement measures. The magnitudes of these effects strongly depend on regional conditions. Regional development plans should include predictions of these developments in order to find the most appropriate management option to avoid future emerging pollutants.

### **Monitor the total burden: chemicals and effects**

#### **Recommendation 8: Use monitoring approaches which allow for an assessment of the total chemical burden and its effects**

The complexity of the pattern of pollutants will further increase in the future (see “[Recommendation 1: Expect a future increase of the chemical burden in European river basins](#)”). Therefore, monitoring approaches are needed which allow for an integrated assessment of the total chemical burden and its effects. Advanced effect monitoring could address specific biological endpoints as well as modes of actions which are expected for future

emerging pollutants. The expected increase of emissions of pharmaceuticals should stimulate the monitoring of drug-specific endpoints relevant for both human and ecosystem health, e.g., behavioral changes in fish.

### **Risk reduction and abatement**

#### **Priority setting in risk reduction**

#### **Recommendation 9: Identify drivers of chemical pressure and predict their future development**

Due to a continuous increase in the complexity of the exposure situation, priority setting in risk reduction is required. In general, emission profiles of cities, industrial areas, and of rural areas are dominated by a limited number of chemicals. Identification of these drivers can support the application of efficient abatement strategies. Future development of these drivers should as far as possible be predicted by quantitative trend indications. The placement of risk reduction measures should relate to the expected future placement of critical or susceptible types of water use.

#### **Abatement technologies, solutions-oriented approach**

#### **Recommendation 10: Apply abatement technologies in a solution-focused approach to also take into account future emerging pollutants**

Complex patterns of pollutants need an integrated approach for emission reduction. The selection of tools to identify and prioritize pollutants for further action should be guided by the regional or local chemical fingerprints, not on individual substances. Furthermore, risk reduction measures are required to address multiple exposures to legacy, present, and emerging pollutants in a solution-focused approach [97]. Site-specific abatement packages are required to address the priority pollutants on a regional or local scale [98].

The following recommendations are addressed to national competent authorities and research institutions.

### **Reduce complexity**

#### **Recommendation 11: Support strategies to reduce the number and the total amount of critical substances**

Many technologies are at hand to reduce the total amount of a substance needed for a given purpose, e.g., precision farming and personalized medicine. These options should be supported to reduce the quantity of emissions and the total burden of chemicals in river basins. In addition to the reduction of the total amount used, attention should be given to the requirement of reducing the complexity of the pollutant pattern by minimizing the number of problematic substances which are used.

### Track consumption of chemicals of high concern

#### Recommendation 12: Monitor the total volumes of critical substances in use

Data on the total use volume and the related uses can be drawn upon to predict critical emissions. Such data (as from the Nordic product registers) furthermore allow us to monitor the success of substitution measures over time. National or EU-wide use data should be requested and used to monitor high-priority groups of chemicals. Such data can be aggregated to obtain the total burden related to substances or substance groups with specific modes of actions or with critical properties (e.g., persistent mobile organics) and to predict transformation products. For critical substances, it is crucial to better understand main drivers of consumption (e.g., the role of marketing) and options to influence these drivers.

### Look into the future: horizon scanning and more. What comes up?

#### Recommendation 13: Predict future emerging pollutants

By 2030, several developments in society will have severe implications on the water quality of river basins. An analysis of these developments provides important indications for future emerging pollutants, e.g., an increase of rodenticides in urban areas. Therefore, developments in society should be systematically analyzed, as they are able to reveal future EPs on the basis of which water management strategies can be adjusted. Horizon scanning, sector-specific analyses, and substitution checks for strictly regulated substances are important instruments available for the prediction of future emerging pollutants and the decision which of them should be used.

#### Recommendation 14: Screen ongoing technological innovations regarding new materials and chemicals

The majority of innovations is based on new materials. The horizon scanning of technologies helps identify new materials and chemicals which can be expected to be used in the future. This work should be accomplished together with materials scientists, involving the industries concerned by these developments at an early stage.

### Prevent from the beginning: conduct technology assessments at an early stage/design by benign

#### Recommendation 15: Conduct risk and benefit assessments of new technologies at an early stage

New technologies often entail the use of new chemicals. However, an assessment of potential releases and an identification of more sustainable chemicals have been carried out only very rarely in the early stages of technology development or product development. At a later point in the development process, it can be more difficult

to replace problematic substances than in the beginning. Therefore, such an assessment should become a key step early in the design process. If risks are checked in advance and minimized from the very beginning, a powerful sales argument for novel technologies could be built up. The Risk Analysis and Technology Assessment—termed RATA—is an example for such an early assessment [98]. It includes a specific tool set to check new business ideas for risks—at the very beginning.

#### Recommendation 16: Support design and use of better degradable and more sustainable chemicals

The production and use of more sustainable chemicals should be promoted. The use of better degradable and less hazardous substances avoids problematic emissions at an early stage. This contributes significantly to the avoidance of complex emissions [99].

### Model future chemical burdens

#### Recommendation 17: Use quantitative trend indications to model and to predict future emerging pollutants

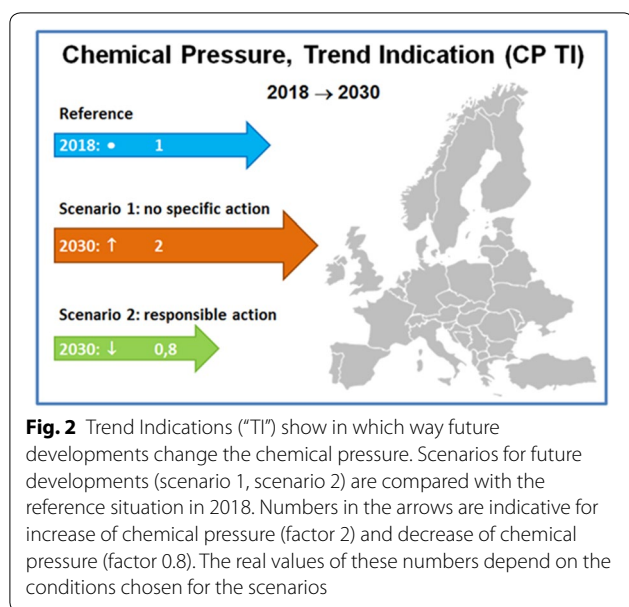
Due to differences in land use, population density, climate conditions, and other factors, large regional differences can be expected in future chemical burdens [100]. Impacts of developments in society on future emerging pollutants can be integrated in exposure and risk modeling. Examples are predictions on demographic change and changes in the consumption pattern of pharmaceuticals during their life-time. The modeling of future emerging pollutants contributes to the identification of appropriate management measures and strategies. Two approaches can be used to model future emerging pollutants: site-specific modeling of future pollutants and chemical footprints.

Site-specific modeling can use Trend Indications (TIs) to show in which way future developments will change chemical pressure. Trend Indications also illustrate the effects of different options to act (see the following Fig. 2).

To model future chemical burdens, scenarios that are combinations of several trends described above will be developed. They furthermore include assumptions on emission reduction measures taken and on their efficiency.

Chemical footprints visualize chemical burdens, based on the modeling of complex mixtures of pollutants. Chemical footprints are calculated and discussed in relation to planetary boundaries. These calculations reveal the main drivers for chemical burdens. Using the Trend Indications described above, an analysis how developments in society affect these drivers can be made. Scenarios can reflect important objectives as circular economy and different options to reach these goals. This makes it





possible to compare present and future chemical burdens—including future emerging pollutants [101, 102].

### Grouping and functional substitutes

#### Recommendation 18: Avoid regrettable substitution by grouping approaches

Problematic substances are frequently replaced by substances with other problematic properties. Future technological progress may help identify suitable alternatives for emerging pollutants that are currently used, such as phthalates, PFCs, flame retardants, or nanomaterials. These new substances, however, can also have negative impacts on the ecosystem.

Therefore, structurally related substances with similar problematic properties should be placed together in a group. Voluntary activities as well as—if necessary—regulatory actions should address such groups of substances instead of focussing on single substances. Chemicals within a group can have similar structural characteristics or can show the same mode of action (MoA). Grouping helps avoid regrettable substitutions (by chemicals of the same groups) and support functional substitutions.

#### Recommendation 19: Support identification and use of functional substitutes

Common substitutes for problematic substances should be systematically assessed regarding their hazard potential and related risks. For important chemicals that are strictly regulated, the development of less hazardous substitutes or nonchemical solutions should be stimulated.

### Information and behavioral changes

#### Recommendation 20: Inform downstream users about critical substance properties and critical substances

Downstream users of chemicals have several options to reduce their emissions. They need to be provided with clear information as to which substances are of concern in terms of water quality. For substances of very high concern, identified under REACH, this information is available. For other chemicals with problematic properties such information is still missing, e.g., for the group of persistent and mobile organic chemicals (PMOCS), and the group of persistent, mobile, and toxic chemicals (PMT substances). It is very important for formulators and end users of chemicals to be fully informed about the type of substances which belong to these groups—and should be replaced by less problematic ones.

#### Recommendation 21: Support awareness-raising actions for consumers

Remarkable reduction of critical emissions could be brought about by behavioral changes, e.g., in drug consumption. Industrialized countries show an increasing prevalence of obesity, diabetes, cancer, and depression. This usually results in an increased use of the related pharmaceuticals. In the newly industrialized countries an easier access to pharmaceuticals is given. Novel chemical treatments could support a more effective use of pharmaceuticals with lower emission levels. Between various countries, however, there are large differences regarding the consumption patterns of drugs. Higher emissions are found in the case of over-the-counter drugs which do not require a prescription. Awareness-raising actions for consumers are considered to provide a significant potential for emission reduction in order to support behavioral changes.

### Outlook

Our analysis on developments in society revealed that many changes can be expected with regard to future emerging pollutants. It is considered very likely that at least a part of them will occur. This makes it possible to decide on political, societal, or technical mitigation efforts to reduce the chemical pressure on river systems.

A careful monitoring of developments in society is needed to develop appropriate mitigation strategies. End-of-pipe technologies, however, are not sufficient to achieve this aim. There is a need for enhanced input reduction and prevention measures. Furthermore, there is a need for horizontal instruments which include approaches for the design and production of more sustainable chemicals and products. A broad variety of abatement technologies is still available with regard to

pollutants [103]. To achieve an effective and successful management of river basins, mitigation options for chemicals of major concern have to be applied in a prioritized and solution-focused approach. An extended conceptual framework for the solution-focused management of chemical pollution in European waters has been developed and applied within the SOLUTIONS project on emerging pollutants [97]. The decision support system, RiBaTox, may serve as guidance to decision makers regarding the identification of appropriate instruments to select and implement these efforts (RiBaTox, Version 2018, <https://solutions.marvin.vito.be/>). It includes recommendations how to predict future chemical burdens by modeling the emission profiles and chemical footprints of pollutants [8, 102].

#### Abbreviations

EPs: emerging pollutants; IPCC: Intergovernmental Panel on Climate Change; NORMAN: network of reference laboratories, research centers, and related organizations for monitoring of emerging environmental substances; OECD: organization for economic cooperation and development; PFC: per- and polyfluorinated hydrocarbons; REACH: registration, evaluation, authorization and restriction of chemicals; UNESCO: United Nations Educational, Scientific and Cultural Organization.

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#### Authors' contributions

SM, DB, WB, DLH, and LP were substantially involved in the conception and design of the study. All the authors drafted the manuscript. All the authors read and approved the final manuscript.

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#### Competing interests

The authors declare that they have no competing interests.

#### Author details

<sup>1</sup> Oeko-Institut e.V. Institut für angewandte Ökologie, Institute for Applied Ecology, Merzhauserstr 173, 79100 Freiburg, Germany. <sup>2</sup> Helmholtz Centre

for Environmental Research—UFZ, Permoserstraße 15, 04318 Leipzig, Germany.

<sup>3</sup> Department of Ecosystem Analysis, Institute for Environmental Research, ABBt—Aachen Biology and Biotechnology, RWTH University of Aachen, Aachen, Germany. <sup>4</sup> Centre for Sustainability, Environment and Health, RIVM—Dutch National Institute for Public Health and the Environment, P.O. Box 1, 3720 BA Bilthoven, The Netherlands. <sup>5</sup> Department of Environmental Science, Institute for Water and Wetland Research, Radboud University Nijmegen, Heyendaalseweg 135, 6525 AJ Nijmegen, The Netherlands.

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#### References

1. Stefanakis AI, Becker JA (2016) A review of emerging contaminants in water: classification, sources, and potential risks in: impact of water pollution on human health and environmental sustainability. *IGI Glob*. <https://doi.org/10.4018/978-1-4666-9559-7.ch003>
2. Zwiener C, Frimmel I (2004) LC-MS analysis in the aquatic environment and in water treatment—a critical review. Part II. Applications for emerging contaminants and related pollutants, microorganisms and human-acids. *Anal Bioanal Chem* 378:862–874
3. Navarro-Ortega A, Acuna V, Batalla RJ, Blasco J, Conde C, Elorza FJ, Elozeigi A, Frances F, La-Roca F, Munoz I, Petrovic M, Pico Y, Sabater S, Sanchez-Vila X, Schuhmacher M, Barcelo D (2012) Assessing and forecasting the impacts of global change on Mediterranean rivers. The SCARCE Consolider project on Iberian basins. *Environ Sci Pollut Res Int* 19:918–933. <https://doi.org/10.1007/s11356-011-0566-5>
4. NORMAN (2016) NORMAN Network group. <http://www.norman-network.net/?q=node>. Accessed 21 May 2019
5. Pal A, Gin KYH, Lin AYC, Reinhard M (2010) Impacts of emerging organic contaminants on freshwater resources: review of recent occurrences, sources, fate and effects. *Sci Total Environ* 408:6062–6069. <https://doi.org/10.1016/j.scitotenv.2010.09.026>
6. La Farré M, Pérez S, Kantiani L, Barceló D (2008) Fate and toxicity of emerging pollutants, their metabolites and transformation products in the aquatic environment. *Trends Anal Chem* 27:991–1007. <https://doi.org/10.1016/j.trac.2008.09.010>
7. Pal A, He Y, Jekel M, Reinhard M, Gin KYH (2014) Emerging contaminants of public health significance as water quality indicator compounds in the urban water cycle. *Environ Int* 71:46–62. <https://doi.org/10.1016/j.envint.2014.05.025>
8. United Nations Environment Programme (UNEP) (2017) Global chemicals outlook II. From legacies to innovative solutions. [https://wedocs.unep.org/bitstream/handle/20.500.11822/27651/GCOII\\_synth.pdf?sequence=1&isAllowed=y](https://wedocs.unep.org/bitstream/handle/20.500.11822/27651/GCOII_synth.pdf?sequence=1&isAllowed=y). Accessed 8 Apr 2019
9. Stocker TF (2013) Climate change 2013: the physical science basis; summary for policymakers, a report of Working Group I of the IPCC, technical summary, a report accepted by Working Group I of the IPCC but not approved in detail and frequently asked questions; part of the Working Group I contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, New York
10. Nanonextnl (2016) <http://www.nanonextnl.nl/programme/1b-envir-onmental-risks/>. Accessed 28 July 2016
11. UNESCO (ed) (2009) World Water Assessment Programme. The United Nations World Water Development Report 3. <http://www.unesco.org/new/en/natural-sciences/environment/water/wwap/wwdr3-2009/>. Accessed 21 May 2019
12. United Nations Environment Programme (UNEP) (ed.) (2013) GEO-5 for business. Impacts of a changing environment on the corporate sector. <https://www.unenvironment.org/resources/geo-5-business>. Accessed 21 May 2019
13. Alcamo J, van Vuuren D, Cramer W et al. (2005) Ecosystems and human well-being: scenarios, volume 2—chapter 9: changes in ecosystem services and their drivers across the scenarios. <https://www.millenniumassessment.org/documents/document.333.aspx.pdf>. Accessed 21 May 2019

14. European Environment Agency (EEA) (ed) (2010) The European environment—state and outlook 2010. <https://www.eea.europa.eu/soer/synthesis/synthesis>. Accessed 21 May 2019
15. Rockström J, Steffen W, Noone K, Persson A, Chapin FS et al (2009) Planetary boundaries: exploring the safe operating space for humanity. In: *Ecology & society*, vol. 14, no. 2. <http://www.ecologyandsociety.org/vol14/iss2/art32/>. Accessed 21 May 2019
16. World Water Council; Earthscan Publications (eds) (2000) World water vision: making water everybody's business. <http://www.worldwatercouncil.org/en/vision-report>. Accessed 21 May 2019
17. European Environment Agency (EEA) (ed) (2009) Water resources across Europe—confronting water scarcity and drought (EEA Report, 2). <https://www.eea.europa.eu/publications/water-resources-across-europe>. Accessed 21 May 2019
18. United Nations Environment Programme (UNEP) (2013) Costs of inaction on the sound management of chemicals. Technical Report. <http://wedocs.unep.org/handle/20.500.11822/8412>. Accessed 21 May 2019
19. Knacker T, Coors A (2011) Ökotoxikologische Bewertung von anthropogenen Stoffen. Diskussionspapier für die acatech Projektgruppe Georesource Wasser – Herausforderung Globaler Wandel". In: *acatech Materialien*, vol. 10
20. Fernández-Alba AR (2000) Emissions scenarios—summary for policy-makers. IPCC Special Report. IPCC, WMO und UNEP (eds). <https://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf>. Accessed 21 May 2019
21. IDAEA-CSIC (ed) (n.y.) SCARCE—assessing and predicting effects on water quantity and quality in Iberian rivers caused by global change (2009–2014). <http://www.idaea.csic.es/scarceconsolider/publica/P000M ain.php>. Accessed 21 May 2019
22. OECD Publishing (ed) (2012) OECD environmental outlook to 2050. The Consequences of Inaction
23. Schwenker B, Raffelt T (2012) THOUGHTS—megatrends. Roland Berger School of Strategy and Economics (ed). <http://www.inur.de/cms/wp-content/uploads/news/2012/2012-07-Studie-Roland-Berger-Weltk-arte-der-Chancen.pdf>. Accessed 21 May 2019
24. Seitzinger SP, Mayorga E, Bouwman AF, Kroeze C, Beusen AHW, Billen G, van Drecht G, Dumont E, Fekete BM, Garnier J, Harrison JA (2010) Global river nutrient export—a scenario analysis of past and future trends. *Glob Biogeochem Cycles* 24:67. <https://doi.org/10.1029/2009gb003587>
25. European Environment Agency (EEA) (ed) (2002) Late lessons from early warning: the precautionary principle 1896–2000. A retrospection of scenarios (Environmental issue report, 22/2001). [https://www.eea.europa.eu/publications/environmental\\_issue\\_report\\_2001\\_22](https://www.eea.europa.eu/publications/environmental_issue_report_2001_22). Accessed 21 May 2019
26. European Environment Agency (EEA) (ed) (2013) Towards a green economy in Europe—EU environmental policy targets and objectives 2010–2050 (EEA Report, 8/2013). <https://www.eea.europa.eu/publications/towards-a-green-economy-in-europe>. Accessed 21 May 2019
27. Noyes PD, McElwee MK, Miller HD, Clark BW, van Tiem LA, Walcott KC, Erwin KN, Levin ED (2009) The toxicology of climate change: environmental contaminants in a warming world. *Environ Int* 35:971–986. <https://doi.org/10.1016/j.envint.2009.02.006>
28. Barceló D (2010) Water quality and assessment under scarcity: prospects and challenges in mediterranean watersheds. *J Hydrol* 383(1):1–4
29. García-Ruiz JM, López-Moreno JL, Vicente-Serrano SM, Lasanta-Martínez T, Beguería S (2011) Mediterranean water resources in a global change scenario. *Earth Sci Rev* 105:121–139. <https://doi.org/10.1016/j.earscirev.2011.01.006>
30. Giorgi FLP (2008) Climate change projections for the Mediterranean region. *Glob Planet Change* 63:90–104. <https://doi.org/10.1016/j.gloplacha.2007.09.005>
31. Sabater S, Barceló D, Castro-Catala N, Ginebreda A, Kuzmanovic M, Petrovic M, Pico Y, Ponsati L, Tornes E, Munoz I (2016) Shared effects of organic microcontaminants and environmental stressors on biofilms and invertebrates in impaired rivers. *Environ Pollut* 210:303–314. <https://doi.org/10.1016/j.envpol.2016.01.037>
32. Dudgeon D, Arthington AH, Gessner MO, Kawabata ZI, Knowler DJ, Leveque C, Naiman RJ, Prieur-Richard AH, Soto D, Stiassny MLJ, Sullivan CA (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. *Biol Rev Camb Philos Soc* 81:163–182. <https://doi.org/10.1017/S1464793105006950>
33. Ormerod SJ, Dobson M, Hilderw AG, Townsend CR (2010) Multiple stressors in freshwater ecosystems. *Freshw Biol* 55:1–4. <https://doi.org/10.1111/j.1365-2427.2009.02395.x>
34. Jackson MC, Loewen CJG, Vinebrooke RD, Chimimba CT (2016) Net effects of multiple stressors in freshwater ecosystems: a meta-analysis. *Glob Change Biol* 22:180–189. <https://doi.org/10.1111/gcb.13028>
35. Munoz I, Lopez-Doval JC, Ricart M, Villagrasa M, Brix R, Geiszinger A, Ginebreda A, Guasch H, Lopez Jose-, de Alda M, Romani AM, Sabater S, Barcelo D (2009) Bridging levels of pharmaceuticals in river water with biological community structure in the Llobregat River basin (northeast Spain). *Environ Toxicol Chem* 28:2706–2714. <https://doi.org/10.1897/08-486.1>
36. Bayrisches Landesamt für Umwelt (2012) Stoffinformationen zu besonders besorgniserregenden Stoffen- Phthalate
37. Navarro-Ortega A, Tauler R, Lacorte S, Barceló D (2010) Occurrence and transport of PAHs, pesticides and alkylphenols in sediment samples along the Ebro River Basin. *J Hydrol* 383:5–17. <https://doi.org/10.1016/j.jhydrol.2009.12.031>
38. Umweltbundesamt (UBA) (2015) Organische Mikroverunreinigung in Gewässern. Vierte Reinigungsstufe für weniger Einträge, Dessau
39. Abegglen A, Siegrist H (2012) Mikroverunreinigungen aus kommunalem Abwasser. Verfahren zur weitergehenden Elimination auf Kläranlagen, Bern
40. Navarro-Ortega A, Sabater S, Barcelo D (2012) Understanding effects of global change on water quantity and quality in river basins—the SCARCE project. *Environ Sci Pollut Res Int* 19:915–917. <https://doi.org/10.1007/s11356-012-0894-0>
41. Whitehead PG, Wilby RL, Battaabre RW, Kernan M, Wade AJ (2009) A review of the potential impacts of climate change on surface water quality. *Hydrol Sci J* 54:101–123. <https://doi.org/10.1623/hysj.54.1.101>
42. Schiedek D (2007) Interactions between climate change and contaminants. *Mar Pollut Bull* 54:1845–1856
43. Hoepffner N (2006) Marine and coastal dimension of climate change in Europe a report to the European water director
44. Chiovarou ED, Siewicki TC (2008) Comparison of storm intensity and application timing on modeled transport and fate of six contaminants. *Sci Total Environ* 389:87–100. <https://doi.org/10.1016/j.scitotenv.2007.08.029>
45. Böhme M, Krüger F, Ockenfeld K, Geller W (2005) Schadstoffbelastung nach dem Elbe-Hochwasser 2002, Magdeburg
46. Boone MD, Bridges CM (1999) The effect of temperature on the potency of carbaryl for survival of tadpoles of the green frog (*Rana clamitans*). *Environ Toxicol Chem* 18(7):1482–1484
47. Capkin E, Altinok I, Karahan S (2006) Water quality and fish size affect toxicity of endosulfan, an organochlorine pesticide, to rainbow trout. *Chemosphere* 64(10):1793–1800
48. Gaunt P, Barker SA (2000) Matrix solid phase dispersion extraction of triazines from catfish tissues; examination of the effects of temperature and dissolved oxygen on the toxicity of atrazine. *Int J Environ Pollut* 13(1–6):284–312
49. Daughton CG TTA. Environmental tobacco smoke: risk assessment. Environmental tobacco smoke: risk assessment, monograph based on papers developed from ETS Risk Assessment Workshop held 9–10 July 1998 in Baltimore, Maryland, Samet, Jonathan, vol. 107, no. Suppl.6. National Inst. of Environmental Health Sciences, Research Triangle Park, NC
50. Heugens EH, Hendriks AJ, Dekker T, Straalen NMV, Admiraal W (2001) A review of the effects of multiple stressors on aquatic organisms and analysis of uncertainty factors for use in risk assessment. *Crit Rev Toxicol* 31(3):247–284
51. Fatta-Kassinos D, Vasquez MI, Kümmerer K (2011) Transformation products of pharmaceuticals in surface waters and wastewater formed during photolysis and advanced oxidation processes—degradation, elucidation of byproducts and assessment of their biological potency. *Chemosphere* 85:693–709. <https://doi.org/10.1016/j.chemosphere.2011.06.082>
52. Schmitt-Jansen M, Bartels P, Adler N, Altenburger R (2007) Phytotoxicity assessment of diclofenac and its phototransformation products. *Anal Bioanal Chem* 387(4):1389–1396
53. Schneider C (2005) Synthetische organische Spurenstoffe in der aquatischen Umwelt und ihr Verhalten im Klärprozess

54. Agüera A, Perez Estrada LA, Ferrer I, Thurman EM, Malato S, Fernández-Alba AR (2005) Application of time of flight mass spectrometry to the analysis of phototransformation products of diclofenac in water under natural sunlight. *J Mass Spectrom* 40(7):908–915
55. Isidori M, Lavorgna M, Nardelli A, Parrrella A, Previtara L, Rubino M (2005) Ecotoxicity of naproxen and its phototransformation products. *Sci Total Environ* 348(1):93–101
56. Isidori M, Nardelli A, Parrrella A, Pascarella L, Previtara L (2006) A multi-species study to assess the toxic and genotoxic effect of pharmaceuticals: furosemide and its photoproduct. *Chemosphere* 63:785–793. <https://doi.org/10.1016/j.chemosphere.2005.07.078>
57. DellaGreca M, Fiorentino A, Isidori M, Lavorgna M, Previtara L, Rubino M, Temussi F (2004) Toxicity of prednisolone, dexamethasone and their photochemical derivatives on aquatic organisms. *Chemosphere* 54(5):629–637
58. Redshaw CH, Stahl-Timmins WM, Fleming LE, Davidson I, Depledge M (2013) Potential changes in disease patterns and pharmaceutical use in response to climate change. *J Toxicol Environ Health B Crit Rev* 16:285–320. <https://doi.org/10.1080/10937404.2013.802265>
59. United Nations (2011) Department of Economic and Social Affairs, Population Division, World population prospects: the 2010 revision, Volume I: comprehensive tables. ST/ESA/SER.A/313
60. OECD (2012) OECD environmental outlook to 2050. OECD Publishing. <https://doi.org/10.1787/9789264122246-en>
61. Berkermann U, Eckert-Kömen J, Heffels A, Kramer-Huber K, Matuschke M, Steiner M (2007) Die Gesundheitsbranche Dynamisches Wachstum im Spannungsfeld von Innovation und Intervention. Prognos-Studie, Brügglen
62. Schwabe UPD (ed) (2015) *Arzneiverordnungs-Report 2015: Aktuelle Zahlen, Kosten, Trends und Kommentare, 2016th edn*. Springer, Berlin
63. Pinnekamp J (2013) Innovative Konzepte und Technologien für die separate Behandlung von Abwasser aus Einrichtungen des Gesundheitswesens
64. Heberer T (2002) Occurrence, fate, and removal of pharmaceutical residues in the aquatic environment: a review of recent research data. *Toxicol Lett* 131(1):5–17
65. Kümmerer K (2008) *Pharmaceuticals in the environment: sources, fate, effects and risks*. Springer, Berlin
66. United Nations (2015) Department of Economic and Social Affairs, Population Division, World population prospects: the 2015 revision. [https://esa.un.org/unpd/wpp/Publications/Files/World\\_Population\\_2015\\_Wallchart.pdf](https://esa.un.org/unpd/wpp/Publications/Files/World_Population_2015_Wallchart.pdf). Accessed 01 Aug 2016
67. United Nations (2015) Department of Economic and Social Affairs, Population Division, World Urbanization Prospects: The 2014 Revision
68. UNESCO (2003) *Wasser für Menschen, Wasser für Leben* [http://www.dgyn.de/fileadmin/user\\_upload/PUBLIKATIONEN/UN\\_Berichte\\_HDR/World\\_Water\\_Report\\_exsum\\_ger.pdf](http://www.dgyn.de/fileadmin/user_upload/PUBLIKATIONEN/UN_Berichte_HDR/World_Water_Report_exsum_ger.pdf). Accessed 01 Aug 2016
69. Scalenghe R, Marsan FA (2009) The anthropogenic sealing of soils in urban areas. *Landscape Urban Plan* 90:1–10. <https://doi.org/10.1016/j.landurbplan.2008.10.011>
70. United Nations Environment Programme (UNEP) (ed) (2012) *GEO-5: global environmental outlook—summary for policy makers*. <https://www.unenvironment.org/resources/global-environment-outlook-5>. Accessed 21 May 2019
71. United Nations Environment Programme (UNEP) (2015) *Global Waste Management Outlook*
72. Walser A (2008) *Gewässerbelastung durch Biozide aus Gebäudefasaden*. GWA Gas Wasser Abwasser 8:639–647
73. Umweltbundesamt (UBA) (2008) *Brominated flame retardants: guardian angels with a bad streak?* <https://www.umweltbundesamt.de/publikationen/brominated-flame-retardants-guardian-angels-a-bad>. Accessed 10 Apr 2019
74. European Environment Agency (2015) *The European environment: state and outlook 2015; synthesis report*. European Environment Agency, Copenhagen
75. Greenpeace e.V (2012) *Chemistry for any weather. Greenpeace tests outdoor clothes for perfluorinated toxins report*
76. Lau C, Butenhoff JL, Rogers JM (2004) The developmental toxicity of perfluoroalkyl acids and their derivatives. *Toxicol Appl Pharmacol* 198(2):231–241
77. Buck RC, Franklin J, Berger U, Conder JM, Cousins IT, Voogt P, Jensen AA, Kannan K, Mabury SA, van Leeuwen SPJ (2011) Perfluoroalkyl and polyfluoroalkyl substances in the environment: terminology, classification, and origins. *Integr Environ Assess Manag* 7:513–541. <https://doi.org/10.1002/ieam.258>
78. Lau C, Anitole K, Hodes C, Lai D, Pfahles-Hutchens A, Seed J (2007) Perfluoroalkyl acids: a review of monitoring and toxicological findings. *Toxicol Sci* 99(2):366–394
79. DeWitt JC, Peden-Adams MM, Keller JM, Germolec DR (2012) Immunotoxicity of perfluorinated compounds: recent developments. *Toxicol Pathol* 40:300–311. <https://doi.org/10.1177/0192623311428473>
80. Grandjean P, Budtz-Jørgensen B (2013) Immunotoxicity of perfluorinated alkylates: calculation of benchmark doses based on serum concentrations in children. *Environ Health* 12:35. <https://doi.org/10.1186/1476-069X-12-35>
81. ECHA (2019) ECHA European chemical agency <https://www.echa.europa.eu/regulations/reach/understanding-reach>. Accessed 5 Apr 2019
82. Mavromati F, Pfeifer T (2007) Phthalates—useful plasticisers with undesired properties. Federal Environment Agency, <https://www.umweltbundesamt.de/publikationen/phthalates-useful-plasticisers-undesired-properties>. Accessed 5 Apr 2019
83. Gao DW, Wen ZD (2016) Phthalate esters in the environment: a critical review of their occurrence, biodegradation, and removal during wastewater treatment processes. *Sci Total Environ* 541:986–1001. <https://doi.org/10.1016/j.scitotenv.2015.09.148>
84. Bornehag CG, Sundell J, Weschler CJ, Sigsgaard T, Lundgren B, Hasselgren M, Hägerhed-Engman L (2004) The association between asthma and allergic symptoms in children and phthalates in house dust: a nested case-control study. *Environ Health Perspect* 112:1393–1397
85. Fukuwatari T, Suzuki Y, Sugimoto E, Shibata K (2002) Identification of a toxic mechanism of the plasticizers, phthalic acid esters, which are putative endocrine disruptors: time-dependent increase in quinolinic acid and its metabolites. *Biosci Biotechnol Biochem* 66(12):2687–2691
86. Mankidy R, Wiseman S, Ma H, Giesy JP (2013) Biological impact of phthalates. *Toxicol Lett* 217:50–58. <https://doi.org/10.1016/j.toxlet.2012.11.025>
87. Horn O, Nalli S, Cooper D, Nicell J (2004) Plasticizer metabolites in the environment. *Water Res* 38(17):3693–3698
88. Umweltbundesamt (2009) Do without per- and polyfluorinated chemicals and prevent their discharge into the environment. <https://www.umweltbundesamt.de/publikationen/do-without-per-polyfluorinated-chemicals-prevent>. Accessed 5 Apr 2019
89. Benskin JP, Muir DCG, Scott BF, Spencer C, Silva AO, Kylin H, Martin JW, Morris A, Lohmann R, Tomy G, Rosenberg B, Taniyasu S, Yamashita N (2012) Perfluoroalkyl acids in the Atlantic and Canadian Arctic Oceans. *Environ Sci Technol* 46:5815–5823. <https://doi.org/10.1021/es300578x>
90. Moskeland T (2009) Environmental screening of selected “new” brominated flame retardants and selected polyfluorinated compounds. Oslo. <https://docplayer.net/34737555-Environmental-screening-of-selected-new-brominated-flame-retardants-and-selected-polyfluorinated-compounds-2009.html>. Accessed 5 Apr 2019
91. Richardson SD (2009) Water analysis: emerging contaminants and current issues. *Anal Chem* 81:4645–4677. <https://doi.org/10.1021/ac9008012>
92. Eickenbusch H, Luther W, Brand L, Vorberg K (2015) Summary of the Project to identify Substances that are used in innovative Techniques and Materials Zusammenfassung des Rechercheprojektes zur Identifizierung von Stoffen, die für innovative Techniken und Materialien verwendet werden. <http://nbn-resolving.de/urn:nbn:de:101:1-201601282718>. Accessed 4 Aug 2016
93. Ziegler D, Reitbauer S, Rizzo L (2007) *TrendReport Convenience—Machen Sie es sich bequem*. [https://www.sevenonemedia.de/c/document\\_library/get\\_file](https://www.sevenonemedia.de/c/document_library/get_file). Accessed 26 July 2016
94. Loos R, Gawlik BM, Boettcher K, Locoro G, Contini S, Bidoglio G (2009) Sucralose screening in European surface waters using a solid-phase extraction-liquid chromatography-triple quadrupole mass spectrometry method. *J Chromatogr A* 1216:1126–1131. <https://doi.org/10.1016/j.chroma.2008.12.048>
95. Lange FT, Scheurer M, Brauch HJ (2012) Artificial sweeteners—a recently recognized class of emerging environmental contaminants:



- a review. *Anal Bioanal Chem* 403:2503–2518. <https://doi.org/10.1007/s00216-012-5892-z>
96. Sutherland WJ, Clout M, Depledge M, Dicks LV, Dinsdale J, Entwistle Abigail C, Fleishman E, Gibbons DW, Keim B, Lickorish FA, Monk KA, Nancy O, Peck Lloyd S, Pretty J, Rockstrom J, Spalding MD, Tonneijck FH, Wintle BC (2015) A horizon scan of global conservation issues for 2015. *Trends Ecol Evol* 30:17–24. <https://doi.org/10.1016/j.tree.2014.11.002>
  97. Munthe J, Brorström-Lundén E, Rahmberg M, Posthuma L, Altenburger R, Brack W, Bunke D, Engelen G, Gawlik BM, van Gils J et al (2017) An expanded conceptual framework for solution-focused management of chemical pollution in European waters. *Environ Sci Eur* 29(1):13. <https://doi.org/10.1186/s12302-017-0112-2>
  98. van Wezel AP, ter Laak TL, Fischer A, Bäuerlein PS, Munthe J, Posthuma L (2017) Mitigation options for chemicals of emerging concern in surface waters; operationalising solutions-focused risk assessment. *Environ Sci Water Res Technol* 3(3):403–414. <https://doi.org/10.1039/C7EW00077D>
  99. Arp HPH, Brown TN, Berger U, Hale SE (2017) Ranking REACH registered neutral, ionisable and ionic organic chemicals based on their aquatic persistency and mobility. *Environ Sci Process Impacts* 19(7):939–955. <https://doi.org/10.1039/c7em00158d>
  100. Lindim C, Cousins IT, vanGils J (2015) Estimating emissions of PFOS and PFOA to the Danube River catchment and evaluating them using a catchment-scale chemical transport and fate model. *Environ Pollut* 207:97–106. <https://doi.org/10.1016/j.envpol.2015.08.050>
  101. Posthuma L, Brown CD, de Zwart D, Diamond J, Dyer SD, Holmes CM, Marshall S, Burton GA (2017) Prospective mixture risk assessment and management prioritizations for river catchments with diverse land uses. *Environ Toxicol Chem*. <https://doi.org/10.1002/etc.3960>
  102. Zijp C, Posthuma L, van de Meent D (2014) Definition and applications of a versatile chemical pollution footprint methodology. *Environ Sci Technol* 48(18):10588–10597. <https://doi.org/10.1021/es500629f>
  103. van Wezel AP, van Lente H, van de Sandt JJ, Bouwmeester H, Vandenberg RL, Sips AJ (2018) Risk analysis and technology assessment in support of technology development. Putting responsible innovation in practice in a case study for nanotechnology. *Integr Environ Assess Manag* 14(1):9–16. <https://doi.org/10.1002/ieam.1989>
  104. United Nations Environment Programme (UNEP) (ed) (2012) Measuring progress: environmental goals & gaps. Report prepared within UNEP's GEO-5 reporting process. <https://www.unenvironment.org/resources/measuring-progress>. Accessed 21 May 2019
  105. McKinsey 2030 Water Resources Group (ed) (2009) Charting our water future—economic frameworks to inform decision-making. <https://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/charting-our-water-future>. Accessed 21 May 2019
  106. Bundesministerium für Bildung und Forschung [Federal Ministry of Education and Research] (BMBF) (ed) (2008) GLOWA—Global Change and the Hydrological Cycle. The German contribution to the International Hydrological Programme (IHP) of UNESCO and to the Hydrology and Water Resources Programme (HWRP) of WMO (IHP/HWRP-Berichte, 7), vol. 10. [https://www.pik-potsdam.de/glowa/pdf/glowaiii/GLOWA\\_Broschuere\\_2008.pdf](https://www.pik-potsdam.de/glowa/pdf/glowaiii/GLOWA_Broschuere_2008.pdf). Accessed 21 May 2019
  107. Alcamo J, Flörke M, Märker M (2007) Future long-term changes in global water resources driven by socio-economic and climatic changes. *Hydrol Sci J* 52(2):247–275. <https://doi.org/10.1623/hysj.52.2.247.11>
  108. UNESCO (2003) Wasser für Menschen, Wasser für Leben. Weltwasserentwicklungsbericht der Vereinten Nationen; Zusammenfassung; world water assessment programme. Vereinte Nationen. Bonn. [https://www.unesco.de/sites/default/files/2018-08/wasser\\_f%C3%BCr\\_mensch\\_hen\\_wasser\\_f%C3%BCr\\_leben.pdf](https://www.unesco.de/sites/default/files/2018-08/wasser_f%C3%BCr_mensch_hen_wasser_f%C3%BCr_leben.pdf). Accessed 21 May 2019
  109. Government of Denmark (ed) (2009) Chemicals action plan 2010–2013. Safety in Denmark. [http://eng.mst.dk/media/mst/69076/chemicals\\_action\\_plan\\_2010-2013.pdf](http://eng.mst.dk/media/mst/69076/chemicals_action_plan_2010-2013.pdf). Accessed 21 May 2019
  110. United Nations Environment Programme (UNEP) (ed) (2010) Harmful substances and hazardous waste. <http://wedocs.unep.org/handle/20.500.11822/7939>. Accessed 21 May 2019
  111. Bergmann A (2011): Organische Spurenstoffe im Wasserkreislauf. Diskussionspapier für die acatech Projektgruppe „Georessource Wasser—Herausforderung Globaler Wandel“. In: acatech Materialien (12), vol. 18
  112. EU WATCH (ed) (2011) WATCH—water and global change. Integrated project within the 6th Framework Programme of the European Union (2009–2011). <http://www.eu-watch.org/about>. Accessed 21 May 2019
  113. Kirchner A, Matthes F-C (2009) Modell Deutschland. Klimaschutz bis 2050: Vom Ziel her denken. Prognos & Öko-Institut für WWF Deutschland. [http://www.wwf.de/fileadmin/fm-wwf/Publikationen-PDF/WWF\\_Modell\\_Deutschland\\_Endbericht.pdf](http://www.wwf.de/fileadmin/fm-wwf/Publikationen-PDF/WWF_Modell_Deutschland_Endbericht.pdf). Accessed 21 May 2019
  114. Kröhnert S, Hoßmann I, Klingholz R (2008) Die demografische Zukunft von Europa. Wie sich die Regionen verändern: dtv. [https://www.berlin-institut.org/fileadmin/user\\_upload/Europa/Europa\\_d\\_online\\_kl.pdf](https://www.berlin-institut.org/fileadmin/user_upload/Europa/Europa_d_online_kl.pdf). Accessed 21 May 2019
  115. Ziegler D, Reitbauer S, Rizzo L (2007) TrendReport Convenience – Machen Sie es sich bequem. SevenOne Media GmbH. [https://www.sevenonemedia.ch/documents/1674869/1675398/TrendReport\\_Convenience.pdf/0c2829ca-cad6-b819-2613-7af2848bd8b3](https://www.sevenonemedia.ch/documents/1674869/1675398/TrendReport_Convenience.pdf/0c2829ca-cad6-b819-2613-7af2848bd8b3). Accessed 21 May 2019
  116. European Commission (2012) Fisheries and aquaculture in Europe. [https://ec.europa.eu/dgs/maritimeaffairs\\_fisheries/magazine/en](https://ec.europa.eu/dgs/maritimeaffairs_fisheries/magazine/en). Accessed 21 May 2019
  117. FEU-US (ed) (2011) the food gap—the impact of climate change on food production: a 2020 perspective. [https://www.eenews.net/asset/s/2011/01/19/document\\_cw\\_02.pdf](https://www.eenews.net/asset/s/2011/01/19/document_cw_02.pdf). Accessed 21 May 2019
  118. UNESCO; ISSC (eds) (2013) World social science report—changing global environments (OECD Publishing). <http://unesdoc.unesco.org/images/0022/002246/224677e.pdf>. Accessed 21 May 2019
  119. zPunkt GmbH (ed) (2012) zPunkt Megatrends (status: 2012; website continuously updated). <http://www.z-punkt.de/en/themen/artikel/megatrends>. Accessed 21 May 2019

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