The SOLUTIONS project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no. 603437

Solutions for present and future emerging pollutants in land and water resources management

THEME

ENV.2013.6.2-2

Toxicants, environmental pollutants and land and water resources management

Start date of project: 1st October 2013 Duration: 5 years

D1.2 Integrated publications on novel solutions for risks of mixtures of emerging pollutants in water resources

Due date of deliverable: 31.07.2018

Actual submission date: 30.11.2018

Author(s)

Werner Brack, Rolf Altenburger, Christin Müller (UFZ, Leipzig, Germany)

Dissemination Level		
PU	Public	x
PP	Restricted to other programme participants (including EC)	
RE	Restricted to a group specified by the consortium (including EC)	
CO	Confidential, only for members of the consortium (including EC)	

1.1 [readable] Summary

SOLUTIONS allocated major efforts towards the integration and digestion of scientific findings of the project in order to provide this knowledge in a way that it can be understood and used by the scientific community, practitioners in the field of water and chemicals monitoring, assessment, prioritization and management as well as by regulators and decision makers. Twenty integrated papers have been published in international scientific journals being well-known for considering science-policy interfacing as an important task and being well recognised by the type of readers mentioned above. In these papers involving the diversity of experts in the field within the SOLUTIONS consortium and beyond, SOLUTIONS provided a novel conceptual framework for targeting the needs of different reader groups and stakeholder needs with different entry points namely societal developments, chemicals, environmental observations, and abatement options. A specific focus in the integrated papers has been on novel methods for monitoring and concepts and guidance to integrate them in a way that they can be used most efficiently in practice. This includes chemical screening techniques as well as effect-based monitoring and toxicity driver identification. Finally, the upcoming review of the WFD triggered two integrated recommendation papers as well as a series of policy briefs that will be also published as integrated papers in a scientific journal.

1.2 Graph

Science of the Total Environment 576 (2017) 720–737

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Towards the review of the European Union Water Framework Directive: Recommendations for more efficient assessment and management of chemical contamination in European surface water resources

Werner Brack[a,b,*], Valeria Dulio[c], Marlene Ågerstrand[d], Ian Allan[e], Rolf Altenburger[a,b], Markus Brinkmann[b], Dirk Bunke[f], Robert M. Burgess[g], Ian Cousins[d], Beate I. Escher[a,h], Félix J. Hernández[i], L. Mark Hewitt[j], Klára Hilscherová[k], Juliane Hollender[l], Henner Hollert[b], Robert Kase[m], Bernd Klauer[a], Claudia Lindim[d], David López Herráez[a], Cécil Miège[n], John Munthe[o], Simon O'Toole[p], Leo Posthuma[q,r], Heinz Rüdel[s], Ralf B. Schäfer[r], Manfred Sengl[u], Foppe Smedes[k], Dik van de Meent[v], Paul J. van den Brink[w,x], Jos van Gils[y], Annemarie P. van Wezel[z,aa], A. Dick Vethaak[y,ab], Etienne Vermeirssen[l], Peter C. von der Ohe[ac], Branislav Vrana[k]

2. List of Contents

3. List of Abbreviations

BQE	Biological Quality Element
EDA	Effect-directed analysis
EQS	Environmental Quality Standard
MoA	Mode of action

NORMAN	Network of reference laboratories, research centres and related organisations for monitoring of emerging environmental substances
NTS	Non-target screening
UBA	Umweltbundesamt (German Environment Agency)
WFD	Water Framework Directive

4. Section(s)

4.1 Introduction

The SOLUTIONS consortium published up to now more than 100 highly ranked publications in peer-reviewed scientific journals. Moreover, a further 30 manuscripts are in preparation or already submitted and under review. These publications and drafts comprise of cutting edge scientific studies on specific issues from all SOLUTIONS subprojects that are of major interest for the scientific community. In addition to this documented scientific progress, SOLUTIONS produced and is still producing integrated papers that are reporting on the general concepts of SOLUTIONS as well as digesting scientific project results into overarching findings and recommendations. The focus lies on the particular relevance for decision makers and practitioners in the field of environmental monitoring, assessment and management. In SOLUTIONS, this digestion process has been performed in most cases as a joint exercise involving many different SOLUTIONS partners but also experts from closely related networks such as NORMAN. Typically, the efforts resulted in multi-author papers that reflect the consented opinion of a group of widely acknowledged experts rather than showing individual scientific results. A selection of integrated papers of this type is highlighted and put in perspective in this deliverable.

4.2 Conceptual papers

The basic ideas of SOLUTIONS, following the ambitious goals of the WFD and addressing important gaps in the implementation of this regulatory framework have been published at the very beginning of the project [1]. In this paper, the objectives and the structure of SOLUTIONS have been presented together with a layout of the conceptual framework for the planned project work. It elaborates a solutions-oriented assessment with four different entry points as shown in Figure 1.

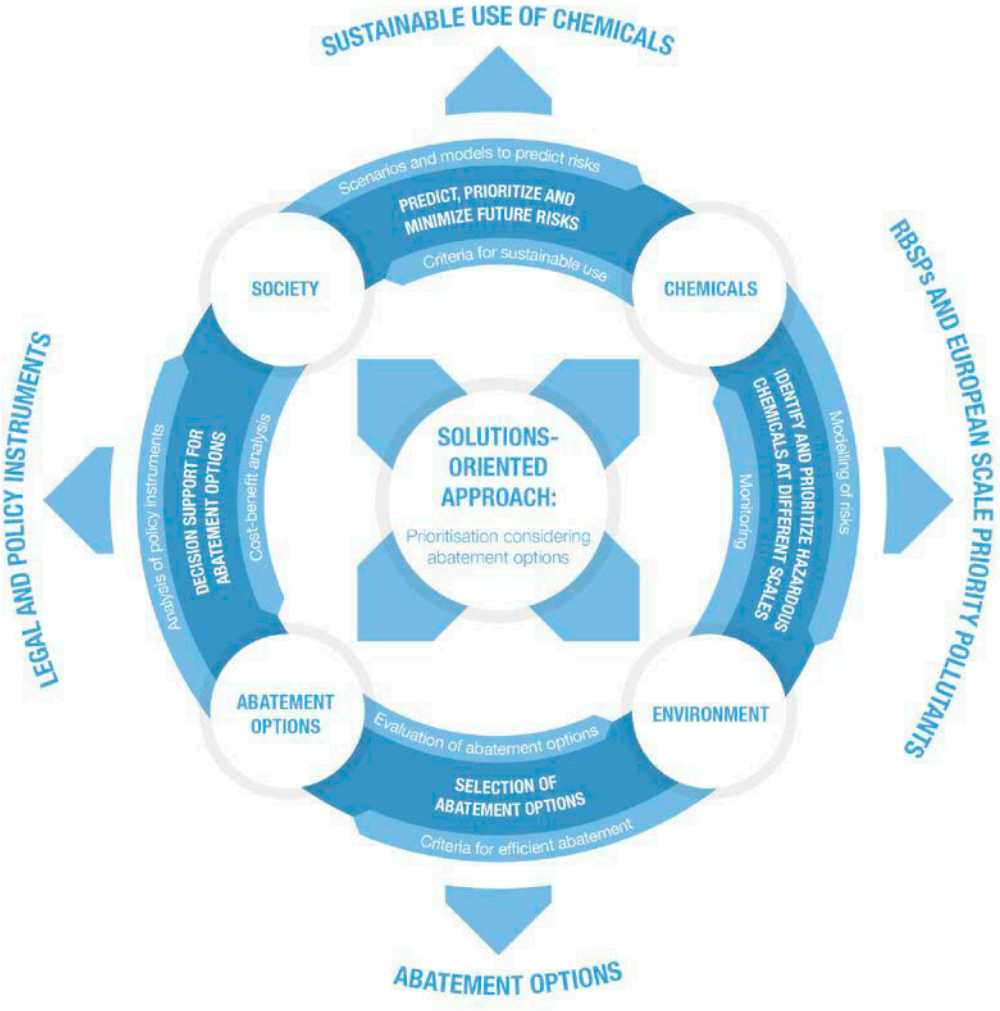

Figure 1: SOLUTIONS conceptual framework

This conceptual framework guided the work in the project over the whole project run-time and was used as the basis of the user-friendly decision support system RiBaTox, which is one of the central products of SOLUTIONS. The SOLUTIONS workflow and sub-project structure (Figure 2) had been designed to optimally serve the conceptual framework. Key priorities of the approach followed in SOLUTIONS have been also defined already in this first concept paper comprising of (1) the use of solution-oriented approaches that consider abatement options already for assessment and prioritization, (2) the integration of human health and ecological risks, (3) the integration of legacy, present use and future chemicals, (4) the integration of modelling approaches, chemical analytics and effect-based tools, (5) the improved identification of emerging pollutants and hazardous transformation products, (6) the identification of priority mixtures, (7) the identification of drivers of toxicity, (8) a prioritization process taking into account existing knowledge gaps as a way to highlight priorities for research, (9) the consideration of technical and non-technical abatement options, (10) the identification of synergies and conflicts between

the WFD and other regulatory frameworks, and (11) the operationalization of the conceptual framework in terms of an end-user friendly decision support system and a toxicant knowledge base. All tools should be demonstrated in trans-European case studies in the Danube and Rhine river and in several Spanish river basins.

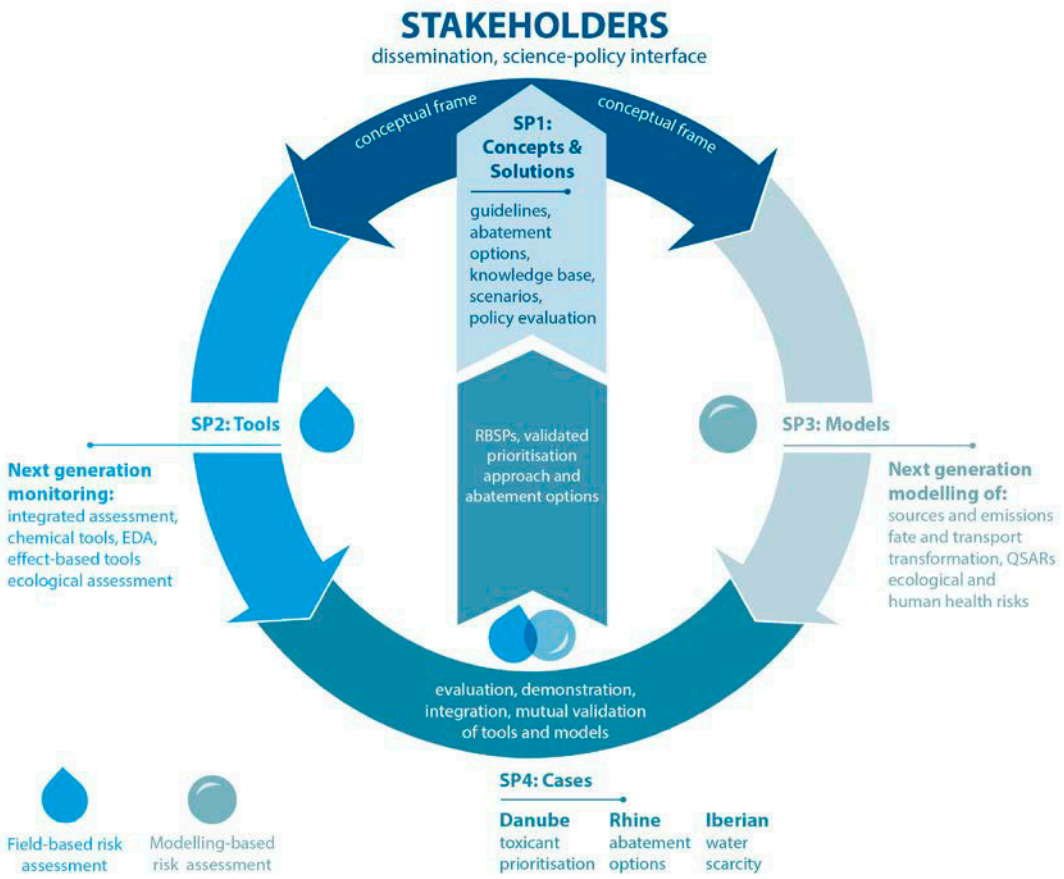

Figure 2: SOLUTIONS workflow and sub-projects

In a follow up publication [2] major approaches were further elaborated putting a particular focus on integrated modelling, selecting relevant and efficient abatement options, an overview of relevant policies for hazardous emerging chemicals (Figure 3), the prediction and prioritization of future chemical risks and the evaluation and communication of solutions-focused scenarios applying chemical footprints.

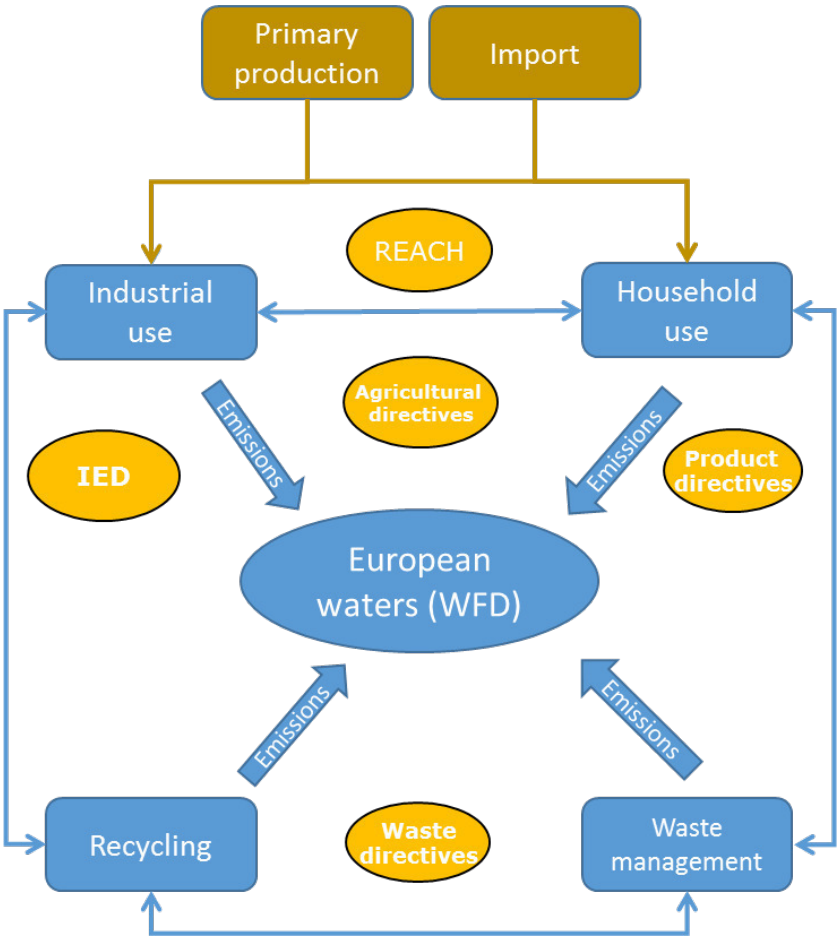

Figure 3: Schematic substance flow analysis for chemicals including examples of where policies interact in the system

The development of experimental and observational tools for water quality monitoring that is designed to cope with complex mixtures of pollutants in water resources management has been one of the key tasks of SOLUTIONS. The approach of SOLUTIONS to address this challenge has been discussed in an integrated paper by Altenburger et al. [3]. This conceptual paper is based on the understanding that mixtures of contaminants are not an exception but the rule in European river basins, while current monitoring approaches address few prioritized individual chemicals individually and thus largely ignoring mixture toxicity. The paper elaborates a new mixture-directed approach of solutions-oriented monitoring involving three complementary approaches including (1) the identification of priority mixtures as chemicals that typically co-occur and need to be addressed together, (2) the direct monitoring of the impact of mixtures using effect-based methods anchored in adverse outcome pathways (Figure 4) and (3) the identification of mixture toxicity drivers following the approach of a tiered effect-directed analysis.

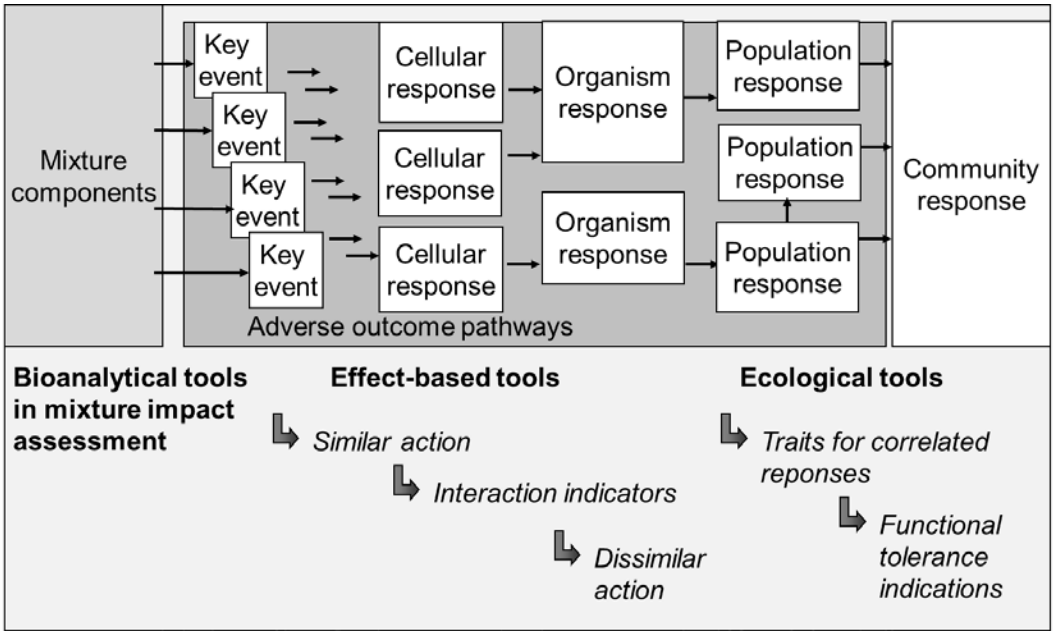

Figure 4: Conceptual framework for bioanalytical tools illustrating their place in an adverse outcome pathway network.

Prioritization of emerging pollutants has been adressed in an Environmental Toxicology and Chemistry Perspectives paper, which provides an excellent format to discuss the different perspectives of regulators, science and business [4]. In this paper Heiss and Küster from the German Environmental Agency (UBA) elaborated that a coordinated approach to generate data and to prioritize emerging pollutants is lacking, while chemical stress in a number of member states is still underestimated due to the lack of data. Particularly the monitoring results from small rivers exposed to intensive agriculture provide strong indications from a regulator perspective that chemical stress is not adequately addressed based on Priority Substances alone. The authors concluded that prioritization tended to affirm regulated, well-known substances and experienced significant difficulties in addressing emerging substances. This problem has been addressed from the SOLUTIONS/NORMAN perspective recommending a prioritization approach that actually helps to fill data gaps in a systematic way (Figure 5). From a business consultant perspective it was highlighted that environmental quality standards for single pollutants are not sufficiently protective against toxic mixture effects. Instead it was suggested to base the definition of priority mixtures on co-occurrence of compounds and their mode-of-action and to apply a tiered approach for risk assessment starting with default assumption of concentration addition for all substances co-occurring in a scenario. This perspectives paper prepared the ground for the further advancement of prioritisation by SOLUTIONS and increased awareness on conceopts and bottlenecks.

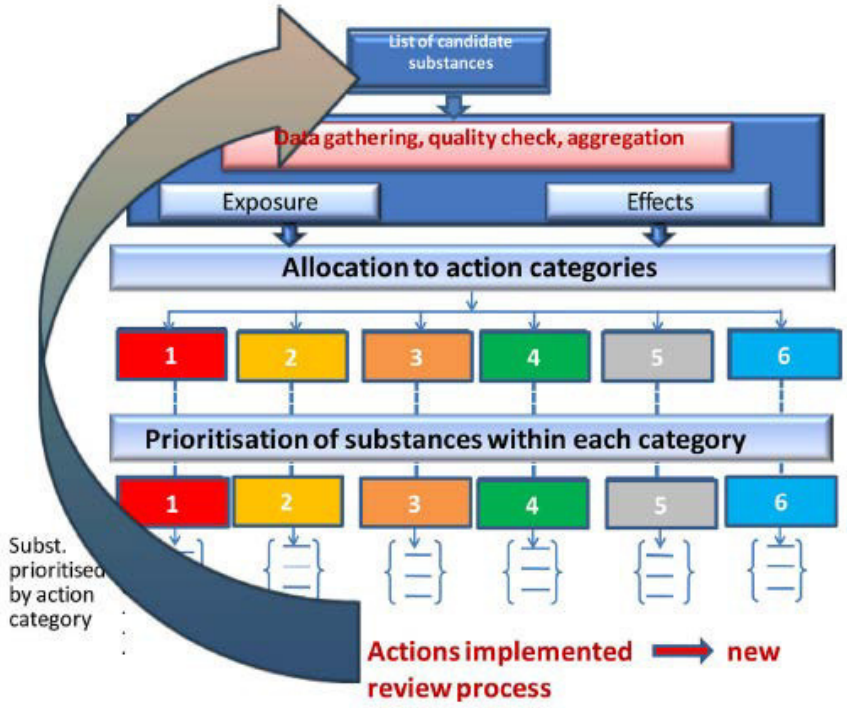

Figure 5: Overview on the NORMAN/SOLUTIONS categorization/prioritization scheme.

4.3 Integrated papers on key components of the SOLUTIONS toolbox

The SOLUTIONS toolbox on holistic and solutions-oriented water monitoring includes advanced technologies for sampling, multi- and non-target screening (NTS), effect-based monitoring, effect- and ecology-directed analysis for the identification of effect-drivers. All major approaches have been addressed in integrated papers exploring the opportunities of these tools but also addressing pitfalls and bottlenecks.

An integrated paper on non-target screening used a dataset from a collaborative non-target screening trial organized by NORMAN to review the state-of-the-art and to discuss future perspective of non-target screening using high-resolution mass spectrometry in water analysis [5]. The comprehensive dataset revealed that non-target screening analytical techniques, workflows and criteria for identification confidence (Figure 6) are already substantially harmonized but that data processing still remains a bottleneck. Although the objective of a fully-automated identification workflow remains elusive in the short term, important steps in this direction have been taken. Major recommendations to improve non-target screening were made, suggesting the better integration and connection of desired features into software packages, the exchange of target and suspect lists, and the contribution of more spectra from standard substances into openly accessible databases.

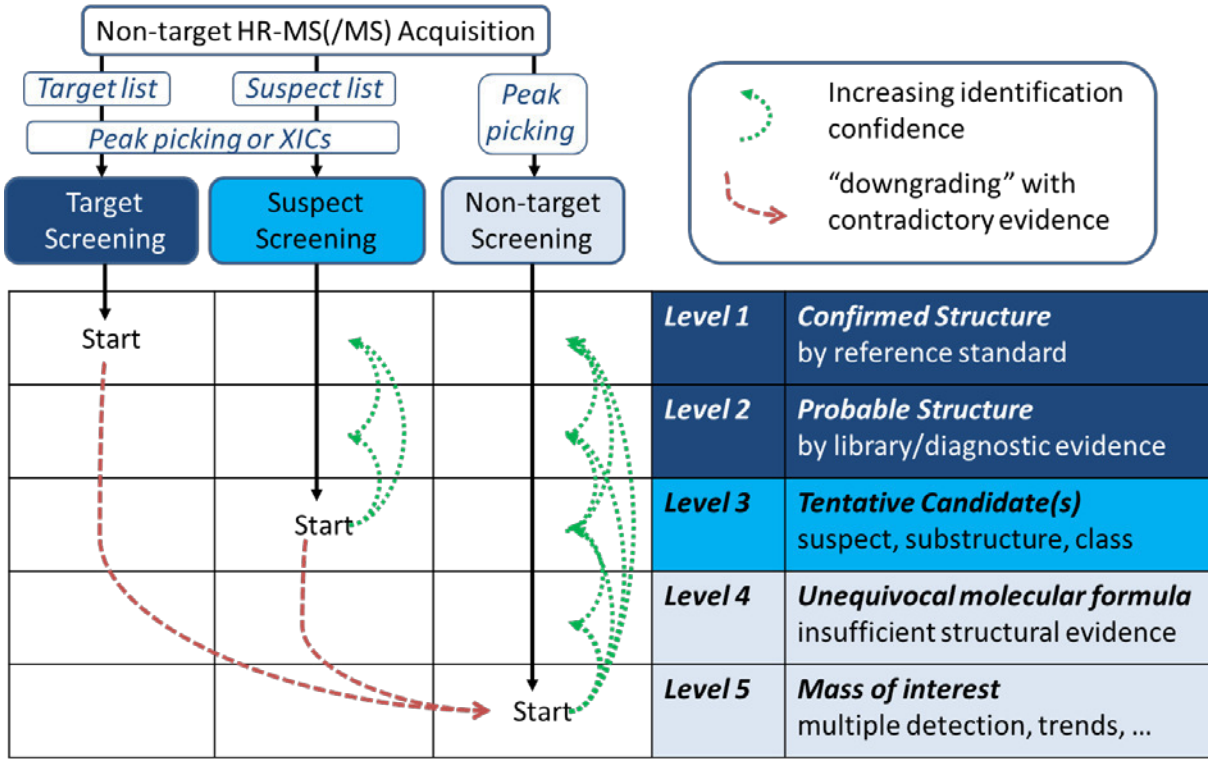

Figure 6: Matrix of identification approach vs. identiofication confidence

The perspectives of NTS have been further explored by Hollender et al. [6]. Based on the experience with NTS in the case study River Rhine the authors highlighted the potential of NTS to detect novel compounds and accidental spills in NTS routine monitoring with 10 major spills of previously undetected compounds documented in 2014. The NTS technology proposed by SOLUTIONS has been published in a book chapter of the renowned Handbook Comprehensive Analytical Chemistry [7]. A critical assessment of computer tools for small molecule identification complemented the evaluation and recommendation of NTS tools [8].

One of the key recommendation of SOLUTIONS is the implementation of effect-based methods for diagnosis of the likelihood of pollution impacts on water quality goals within WFD impact assessment and for monitoring of groups if chemicals with similar effects. This is propagated in order to provide a more realistic picture of mixture risks and to avoid substitutions by chemicals with similar risks, which are not listed as Priority Substances yet. From the diagnostic point of view, biotest batteries would be preferential that cover and discriminate major modes of action with specific high-throughput *in vitro* assays. This potential has been explored by Busch et al. [9] by evaluating almost 1000 typical water contaminants identifying 31 mode-of-actions (MoA) categories. Of these MoAs, however, only to a minor degree can are captured *in vitro* bioassays that are ready for use in water monitoring. We thus suggest that combinations of *in vitro* and *in vivo* tests should be applied jointly in bioassay panels for monitoring.

SOLUTIONS made major efforts to develop, test and validate such bioassay batteries and to provide guidance on the concept as well as the selection and application of the needed test protocols resulting in several complementary integrated papers. Since robustness and inter-laboratory consistency of bioassays results are key criteria for their application, an inter-laboratory investigation of the detectability of emerging contaminants in spiked water extracts with *in vitro* and *in vivo* bioassays was an important step and resulted in an integrated paper [10]. The authors concluded that differences in experimental protocols, model organisms, and data analysis can be sources of variations that demand for harmonized standard procedures. A second inter-laboratory study with a much larger battery of 19 bioassays has been performed with a specific focus on mixtures [11]. This integrated paper strongly supported the application of such effect-based methods demonstrating that the majority of the cell- and organism-based endpoints produced responses that are well in agreement with the additivity expectation of concentration addition. The majority of bioassays were able to quantitatively detect the predicted non-interactive combined effect of the specifically bioactive compounds against a background of complex mixture of other chemicals in the sample. The potential of a bioanalytical test battery, selected according to the principles discussed above, to fingerprint identified micropollutants and their contribution to effects in surface waters has been demonstrated in an integrated paper by Neale et al. [12]. Effect-based monitoring of steroidal estrogens has been identified as one of the most urgent requirements due to the enormous challenge to detect the very frequently occurring Watchlist compounds and natural and synthetic steroids 17α-ethinyl estradiol, 17β-estradiol and estrone. These compounds are extremely potent and very challenging to be detected with chemical analysis at their very low EQS concentration values. At the same time, their bioanalytical detection is most advanced. Thus, in two integrated papers the power of effect-based monitoring of these compounds has been demonstrated and guidance on available methods and tools was provided [13, 14]. For practical application in monitoring, the development of effect-based trigger values supporting the EQS of the WFD are of outmost importance. Different options how to derive such trigger values in a consistent way for many different effect-based methods have been discussed by Escher et al. [15].

The application of effect-based methods for monitoring is believed to be of substantial added value for the identification of hot spots of contamination and of major endpoints and thus adverse outcome pathways and BQEs that might be under risk. However, effect-based tools as well as analytical tools by themselves lack the capability to identify the drivers of possible risks and effects. Driver identification and the establishment of cause-effect relationships require a smart way to combine both methods. SOLUTIONS put major efforts into the establishment, advancement and evaluation such tools that may be summarized under the term effect-directed analysis (EDA). An in-depth overview on available concepts, approaches and methods for most efficient EDA has been published as integrated paper

involving a large number of leading experts from the SOLUTIONS consortium and beyond [16]. In this paper EDA has been presented as a tiered approach making use of existing information as far as ever possible and focusing laborious site-specific investigations on those sites with significant effects that cannot be explained by known chemicals (Figure 7). Extensive guidance is given on all steps and tools from problem formulation via study development, toxicity testing, sampling strategies and extraction, fractionation and chemical analysis up to the analytical and toxicological confirmation of the identified drivers.

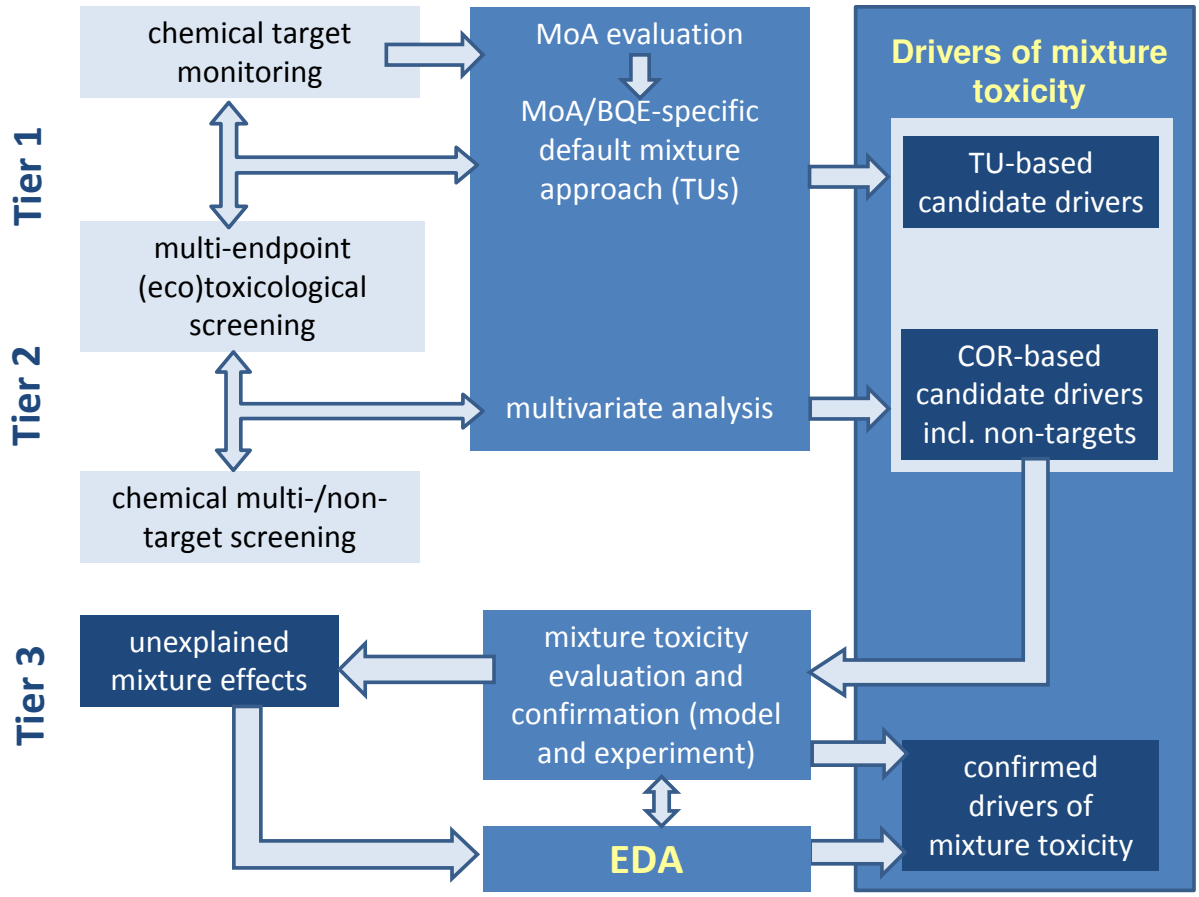

Figure 7: Scheme of a conceptual framework for driver identification in terms of a tiered approach

Finally, all concepts and methods on chemical and effect-based monitoring and toxicity driver identification together with ecological approaches to detect impacts of toxic pollution have been condensed in a guidance paper on future water quality monitoring for pollutant mixtures submitted to Environmental Sciences Europe, which is a renowned journal with a specific focus on science-policy-interfacing [17]. The paper builds on the WFD demand calling for "Member States shall use the information collected above, and any other relevant information including existing environmental monitoring data, to carry out an assessment of the likelihood that surface waters bodies within the river basin district will fail to meet the environmental quality objectives set for the bodies". Guidance is

provided for the use of tools for the identification of River Basin Specific Pollutants, the impact assessment and the establishment of cause-effect relationships in order to open new perspectives for water quality monitoring.

4.4 Recommendation papers and policy briefs

Currently, the WFD is under review and awareness is increasing in science as well as in regulation that an advancement of this ambitious regulatory framework would be helpful to adequately address complex mixtures of pollutants that may be found in European water bodies potentially posing risks to human health and ecosystems. This would require a more holistic and solution-oriented monitoring, including explicit assessment and abatement of mixtures. At the same time, efficient tools and guidance for impact assessment and diagnosis are underdeveloped, thus hampering the achievement of the goals of WFD. The experts of the SOLUTIONS consortium therefore compiled a set of ten recommendations under the umbrella of three major requirements, namely (1) Improve monitoring and strengthen comprehensive prioritization, (2) Foster consistent assessment and (3) Support solution-oriented assessment [18]. These recommendations have been summarized in Figure 8 and address the most pressing issues.

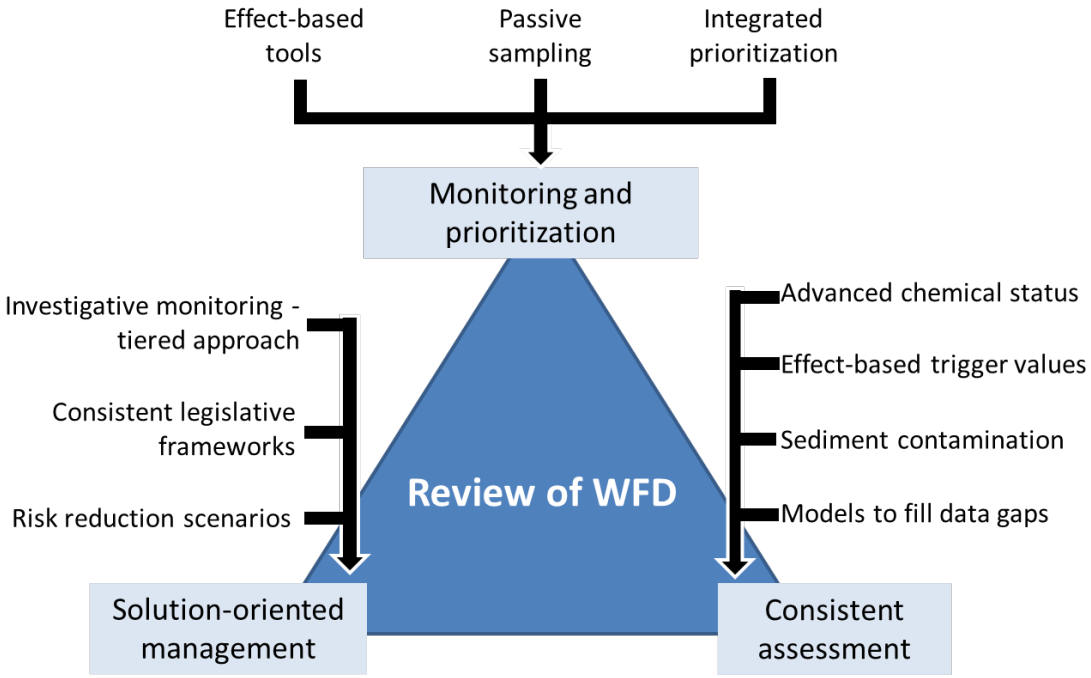

Figure 8: Major issues addressed by recommendations for the review of WFD

While the Ecological Status according to WFD is already based on a holistic approach focusing on deviations of the overall status from reference situations and whole communities represented by four BQEs (fish, macroinvertebrates, algae and macrophytes) as key organism groups in surface waters, the Chemical Status is still defined by a small group of so-called Priority Substances out of tens of thousands

of chemicals present as components of highly complex mixtures. In a further recommendations paper, roads towards a more holistic and solution-oriented monitoring of a chemical status have been provided. These address real world contaminations in order to support the EU strategy for a non-toxic environment [19]. Based on the finding that state-of-the-art chemical and effect-based screening is able to provide chemical and toxicological fingerprints that can be used to bridge the gap between ecological monitoring and assessment and management comprehensive but also realistic approaches on chemical status monitoring are suggested (Figure 9).

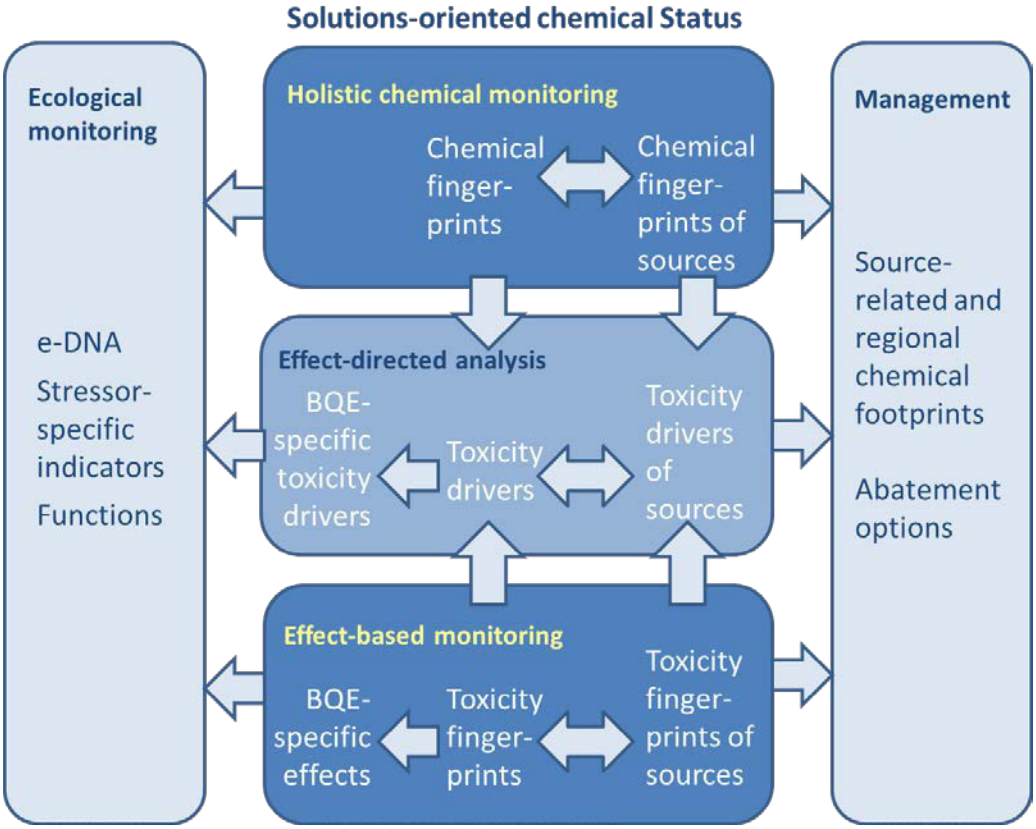

Figure 9: Scheme on a solution-oriented chemical status that can bridge the gap between the ecological status and management in water bodies impacted by toxic stress

SOLUTIONS policy briefs are designed as a major instrument for dissemination of SOLUTIONS findings and recommendations in a targeted enduser- and stakeholder-oriented way. A set of policy briefs has been defined (see Deliverable D8.3) and a first policy brief called "Effect-based methods are key. SOLUTIONS recommends to integrate effect-based methods to diagnose and monitor water quality" has been finalized and distributed among relevant stakeholders. Ten others are in preparation. All SOLUTIONS policy briefs shall be published in an adapted format as a special series of integrated papers in the journal Environmental Sciences Europe. The first of these policy briefs has been submitted for publication [20].

5. Conclusions

The project SOLUTIONS made major efforts to go beyond high quality science by individual groups and published in individual scientific papers that are typically perceived by a limited number of specialists in the field. Through intensive collaboration among all partners on the one hand and the strong focus on a well-organized and participatory stakeholder dialogue on the findings of SOLUTIONS on the other hand an intellectual reflection of the achieved progress was possible. This resulted in the publication of twenty integrated papers so far, including various stakeholders. These papers are characterized by a (1) focus on integration and digestion of results, (2) the involvement of large numbers of co-authors who substantially contributed to the manuscripts, which, thus, represent the consented opinion of groups of experts rather than individual views and (3) the attempt to address burning questions of stakeholders in an understandable and practice-oriented manner. SOLUTIONS integrated papers so far nicely cover major conceptual developments, guidance on novel and integrated approaches and tools for holistic and solution-oriented monitoring as well as on recommendations papers particularly in the context of WFD review. The visibility of these efforts is already emerging in terms of high citation rates. In addition, several integrated papers on modelling approaches to support monitoring are in preparation that will be published after the official termination of the project, however, acknowledging SOLUTIONS and being uploaded on to the SOLUTIONS website. Published policy briefs will complement this selection with papers and a sustained web-presence, which are fully dedicated to the digestion of science to user-oriented guidance.

6. References

1. Brack, W., et al., *The SOLUTIONS project: Challenges and responses for present and future emerging pollutants in land and water resources management.* Science of The Total Environment, 2015. **503–504**(0): p. 22-31.
2. Munthe, J., et al., *An expanded conceptual framework for solution-focused management of chemical pollution in European waters.* Environmental Sciences Europe, 2017. **29**(1): p. 13.
3. Altenburger, R., et al., *Future water quality monitoring - Adapting tools to deal with mixtures of pollutants in water resource management.* Science of the Total Environment, 2015. **512**: p. 540-551.
4. Brack, W., et al., *The Challenge: Prioritization of emerging pollutants.* Environmental Toxicology and Chemistry, 2015. **34**(10): p. 2181-2187.
5. Schymanski, E.L., et al., *Non-target screening with high-resolution mass spectrometry: critical review using a collaborative trial on water analysis.* Analytical and Bioanalytical Chemistry, 2015. **407**(21): p. 6237-6255.

6. Hollender, J., et al., *Nontarget Screening with High Resolution Mass Spectrometry in the Environment: Ready to Go?* Environmental Science & Technology, 2017. **51**(20): p. 11505-11512.
7. Krauss, M., *Chapter 15 - High-Resolution Mass Spectrometry in the Effect-Directed Analysis of Water Resources*, in *Comprehensive Analytical Chemistry*, S. Pérez, P. Eichhorn, and D. Barceló, Editors. 2016, Elsevier. p. 433-457.
8. Schymanski, E.L., et al., *Critical Assessment of Small Molecule Identification 2016: automated methods.* Journal of Cheminformatics, 2017. **9**(1): p. 22.
9. Busch, W., et al., *Micropollutants in European rivers: A mode of action survey to support the development of effect-based tools for water monitoring.* Environ. Toxicol. Chem., 2016. **DOI:10.1002/etc.3460**.
10. Di Paolo, C., et al., *Bioassay battery interlaboratory investigation of emerging contaminants in spiked water extracts – Towards the implementation of bioanalytical monitoring tools in water quality assessment and monitoring.* Water Research, 2016. **104**: p. 473-484.
11. Altenburger, R., et al., *Mixture effects in samples of multiple contaminants – An inter-laboratory study with manifold bioassays.* Environment International, 2018. **114**: p. 95-106.
12. Neale, P.A., et al., *Development of a bioanalytical test battery for water quality monitoring: Fingerprinting identified micropollutants and their Contribution to effects in surface water.* Water Research, 2017. **123**: p. 734-750.
13. Könemann, S., et al., *Effect-based and chemical analytical methods to monitor estrogens under the European Water Framework Directive.* TrAC Trends in Analytical Chemistry, 2018. **102**: p. 225-235.
14. Kase, R., et al., *Screening and risk management solutions for steroidal estrogens in surface and wastewater.* Trac-Trends in Analytical Chemistry, 2018. **102**: p. 343-358.
15. Escher, B.I., et al., *Effect-based trigger values for in vitro and in vivo bioassays performed on surface water extracts supporting the environmental quality standards (EQS) of the European Water Framework Directive.* Science of The Total Environment, 2018. **628-629**: p. 748-765.
16. Brack, W., et al., *Effect-directed analysis supporting monitoring of aquatic environments - An in-depth overview.* Science of the Total Environment, 2016. **544**: p. 1073-1118.
17. Altenburger, R., et al., *Future water quality monitoring – Improving the balance between exposure and toxicity assessments of real world pollutant mixtures.* Environ. Sci. Europe, submitted.
18. Brack, W., et al., *Towards the review of the European Union Water Framework Directive: Recommendations for more efficient assessment and management of chemical contamination in European surface water resources.* Science of The Total Environment, 2017. **576**: p. 720-737.
19. Brack, W., et al., *Towards a holistic and solution-oriented monitoring of chemical status of European water bodies: how to support the EU strategy for a non-toxic environment?* Environmental Sciences Europe, 2018. **DOI: 10.1186/s12302-018-0161-1**.
20. Brack, W., et al., *Effect-based methods are key. The European Collaborative Project SOLUTIONS recommends integrating effect-based methods in order to diagnose and monitor water quality.* Environ. Sci. Europe, submitted.