Umweltwiss Schadst Forsch (2010) 22:217–228
DOI 10.1007/s12302-010-0137-2

EU PROJECTS

MODELKEY

Key findings and recommendations for reaching the EU Water Framework Directive's quality objectives

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Received: 30 March 2010 / Accepted: 1 April 2010 / Published online: 27 April 2010

Preamble A first paper on MODELKEY was published in Environ Sci Pollut Res (Brack et al. 2005, see online Appendix) and introduced the project. This article summarises the outcome of the project.

Abstract The EU Water Framework Directive (WFD) requires the achievement of good ecological and chemical status in European river basins. However, evidence is increasing that a majority of European water bodies will not achieve this goal. Nutrient emissions and related eutrophication together with hydromorphological alterations have been suggested as the major driving forces of this insufficient ecological status. MODELKEY (511237 GOCE, FP6) provides strong evidence that toxic chemicals also affect the ecological status of European rivers. This was demonstrated in the case study rivers Elbe, Scheldt and Llobregat on different scales.

This paper summarises key findings of MODELKEY including recommendations for WFD implementation. We

- provide evidence of toxic stress in aquatic ecosystems,
- provide evidence that impairment of ecological status results from impact of multiple stressors,
- suggest a tiered approach to assess impact of chemicals on ecological status,
- suggest a new approach for deriving candidate compounds for monitoring and prioritisation,
- call for consideration of bioavailability and bioaccumulation in chemical status assessments,
- suggest improvements for WFD water quality monitoring programmes,

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Electronic supplementary material The online version of this article (doi: 10.1007/s12302-010-0137-2) contains supplementary material which is opened up to interested users (doi: http://dx.doi.org/10.1065/espr2005.08.286).

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- provide new integrated tools for basin-scale risk assessment and decision making,
- developed a Decision Support System to support river basin management.

These key results will be presented in a series of ten integrated sections; for the scientific details please refer to publications listed on the MODELKEY website (http://www.modelkey.org/). This article also looks beyond MODELKEY and proposes a combination of MODELKEY diagnostic tools with recent ecological methods to further improve effectiveness of river basin management.

Keywords Aquatic ecosystems · Basin management · Basin-scale risk assessment · Chemical status assessments · Decision-making · Decision Support System · Ecological status · European river basins · Multiple stressors · Toxic stress · Water quality monitoring programmes

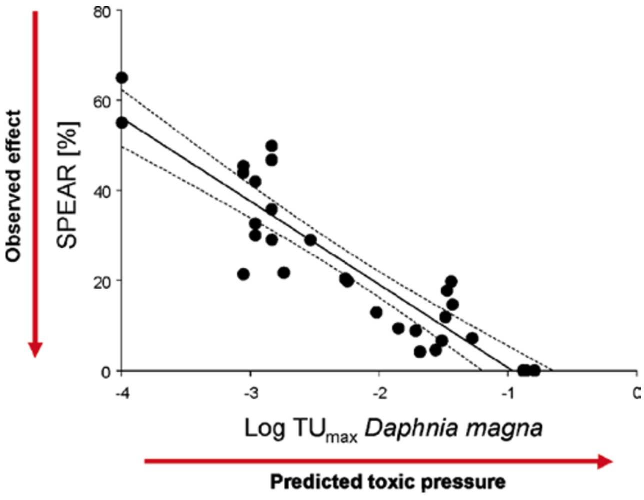


Fig. 1 Relation between observed effects from toxic stress, expressed by the SPEAR indicator, and the predicted toxic stress, expressed by TU (Llobregat River, Spain)

1 New evidences of toxic stress in aquatic ecosystems

Water managers who are concerned about the ecological status of European rivers often primarily think about the most obvious stressors: insufficient habitats due to hydromorphological alterations and excess eutrophication. However, research in MODELKEY provided strong evidence that contamination with toxic chemicals has a clear impact on aquatic communities and thus on the ecological status of a water body. This may be illustrated by the example of benthic invertebrates: In all of the three case study rivers (Elbe, Scheldt and Llobregat) those invertebrate species that are sensitive to chemicals and represented by the SPecies At Risk index (SPEAR), disappeared with increasing contamination, which is expressed as toxic units (TU) based on toxicity to water flea *Daphnia magna* (Fig. 1 for the Llobregat as an example) (von der Ohe et al. 2009).

This toxic stress could be confirmed for local communities in aquatic systems. We found evidence that benthic communities in the Llobregat were impacted by bioactive substances like pharmaceuticals. Multi-variate statistics revealed that the abundance and biomass of macroinvertebrates were correlated with concentrations of selected pharmaceuticals (e.g. *Chironomus* sp. with ibuprofen) (Munoz et al. 2009). Changes in physiological parameters of microalgal communities in the same field investigation were mainly correlated with the presence of pesticides (Ricart et al. 2009).

For the Scheldt basin, a tremendous alteration of the composition of macroinvertebrate communities has been detected downstream of the discharge of industrial and domestic waste water effluent at the river Schijn. This was especially the case for molluscs, where some species (e.g. *Potamopyrgus antipodarum*) were completely absent in parts of the river. In situ experiments with caged snails (*P. antipodarum*) revealed an unusual high reproduction potential at the downstream site, obviously resulting in a reduced competitiveness and thus disappearance of this species. Because of the fact that those snails are known to be very sensitive to endocrine-disrupting chemicals and that their reproduction is enhanced by xeno-estrogenic compounds (Duft et al. 2007), it was assumed that endocrine-disrupting compounds play an important role concerning the loss of species at this particular site. Additional experiments detected a high estrogenic equivalence concentration (using yeast estrogen screen [YES]) and a high concentration of the xeno-estrogen nonylphenol (0.91 ng/g sediment dw) at that site (Schmitt et al. 2010).

To be able to direct remediation efforts to improve the quality of European waters, a causal link is needed bridging contamination to impairment of aquatic communities. Thus, in situ experiments have been developed and applied during the project, as illustrated in the examples above. Moreover, MODELKEY demonstrated that communities (defined as assemblages of interacting species) are more sensitive towards toxicants than indicated by single species investigations. The concept of pollution-induced community tolerance (PICT) was applied to discriminate effects of key toxicants on a community level in the Elbe river basin, Germany. Algal communities from a contaminated site exhibited significantly higher tolerance to the herbicide prometryn, compared to the reference, indicating a loss of sensitive species caused by prometryn (McClellan et al. 2008).

These examples demonstrate that there is strong evidence of toxic stress impairing biological quality elements (BQEs). However, this can be seen only if appropriate diagnostic tools are applied that show stressor-specific responses rather than general degradation only.

2 Impairment of ecological status results from the impact of multiple stressors

The WFD requires the identification of significant anthropogenic pressures and the assessment of their impact on water bodies (Annex II, WFD). Relevant stressors include, among others, toxic chemicals arising from point source discharges or diffuse pollution, altered habitat properties due to hydromorphological changes, altered species interaction due to the invasion of alien species or disease and increased mortalities due to the presence of emerging pathogens (Fig. 2).

The risk imposed by multiple stressors to aquatic resources cannot be understood from assessing each individual stressor alone, but requires consideration of possible interactions and combination effects (Segner 2007). The ecological status integrates the impact of all stressors, regardless of whether they are present simultaneously or whether they are spatially and temporally separated. Importantly, the consequences of the combined impact are not only a function of stressor magnitude, frequency or duration, but also of the traits and characteristics of the biological receptors. This includes, for instance, the resilience of an ecosystem, the species composition of communities, or the genetically and physiologically determined resistance of resident species (see also Sect. 10).

Given such a complex situation, the challenge is to identify the hierarchy amongst the multiple stressors in order to prioritise remedial actions.

The MODELKEY project has taken different approaches to understand and assess the role of chemical stressors in relation to the impact of other stressors. These approaches included the development and application of

- diagnostic experimental techniques such as the use of bioassays, biomarkers, pollution-induced community tolerance (PICT) or toxicogenomics and -metabolomics to disentangle the role of toxic chemicals versus the impact of non-chemical stressors on aquatic species,
- mechanistic experimental studies to understand interactions between stressors and how they translate into trait- or density-mediated indirect effects on species and populations,
- mechanistically based models to predict interactions between stressors and how they translate into altered population growth and ecosystem structure (species composition) and functioning (processes such as primary production rate, etc.),
- multi-variate methodologies to identify those stressors that are major drivers of biological variability in an aquatic ecosystem,
- eco-epidemiological methodologies to quantify the intensity of stressors and to relate this to the biodiversity of river sites or river basins and
- stressor-specific indices to signify impairment of BQEs.

Research needs

Currently, assessing the role of multiple stressors in ecosystem impairment and inferring causative agents is largely done on an empirical, case-by-case approach. What is needed, however, are more conceptual approaches providing

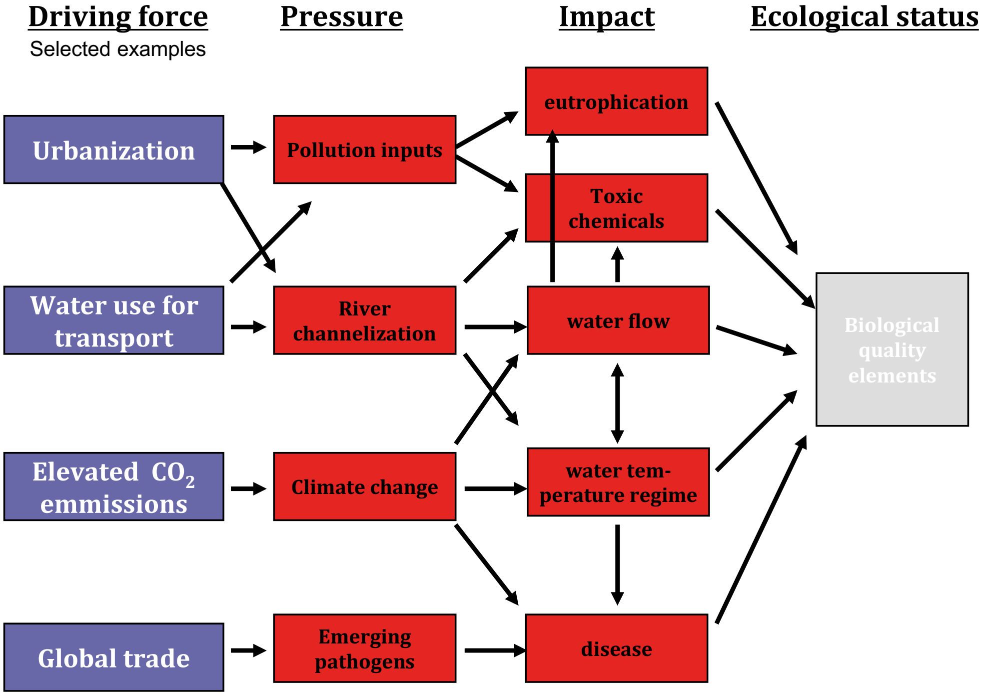


Fig. 2 DP(S)IR (Driving force – Pressure – State – Impact – Response) concept graph on multiple stress; in this schematised presentation, the S component was merged into P

a framework for an integrative – instead of solely chemical – risk assessment, i. e. the analysis, characterisation and possibly quantification of the combined risks to the environment from multiple stressors. MODELKEY has provided examples of how to tackle the problem of multiple stressor assessment. Future research should build on that and develop tools that enable water managers to

- set hierarchies on the relative importance of stressors,
- find evidence of cause–effect relationships,
- extrapolate multiple stressor effects across biological, spatial and temporal scales.

In developing these tools, it is important to keep in mind that multiple stressor assessment asks both for more understanding of the processes underlying stressor interactions and for more "ecological topping up" (see Sect. 10) of existing approaches.

3 "What to do if … ?" – A tiered approach to assess the impact of chemicals

The WFD forces water managers to invest in reaching a so-called "good" chemical and ecological status of its water bodies by the end of the year 2015. However, the list of priority substances used to define the chemical status, contains only a small fraction of the chemicals that can be present in the environment and as a consequence the qualification "good chemical status" can never guarantee that the BQEs are not affected by toxic compounds. In the case where the chemical status is good in terms of the WFD, but (some) BQEs are poor, it may be difficult to identify the real causes. This yields a potential problem for water managers since expensive measures, such as the improvement of hydromorphological characteristics of a water body, may be hardly effective if the BQEs are negatively affected by the presence of unknown toxic compounds. Actually, such site- or river basin specific toxic compounds should also be monitored in the frame of assessing the ecological status.

To deal with this problem, the approach developed within MODELKEY was converted into a practical flow chart that can be used as a guideline to assess whether toxic compounds affect the ecological status of a water body (Fig. 3). This flow chart can help water managers in terms of decision-making in regard to the most effective measure to improve the ecological status of a water body. For example, in the case of a "good" chemical status but insufficient ecological status (top, right), this approach suggests the application of available toxicological (and ecological) tools (e. g. various in vivo and in vitro assays) to verify chemicals as causative factors for the deterioration. Subsequently, with Effect-Directed Analysis studies (EDA), the responsible (group of) basin or site-specific toxic compounds can be determined (Brack et al. 2008), to be considered in future monitoring plans and programmes of measures.

4 MODELKEY suggests a field-evidence-based approach to derive candidates for monitoring and prioritisation

MODELKEY demonstrated that toxic compounds affect aquatic communities, by replacement of sensitive species (see Sect. 1). Significant effects were observed already at

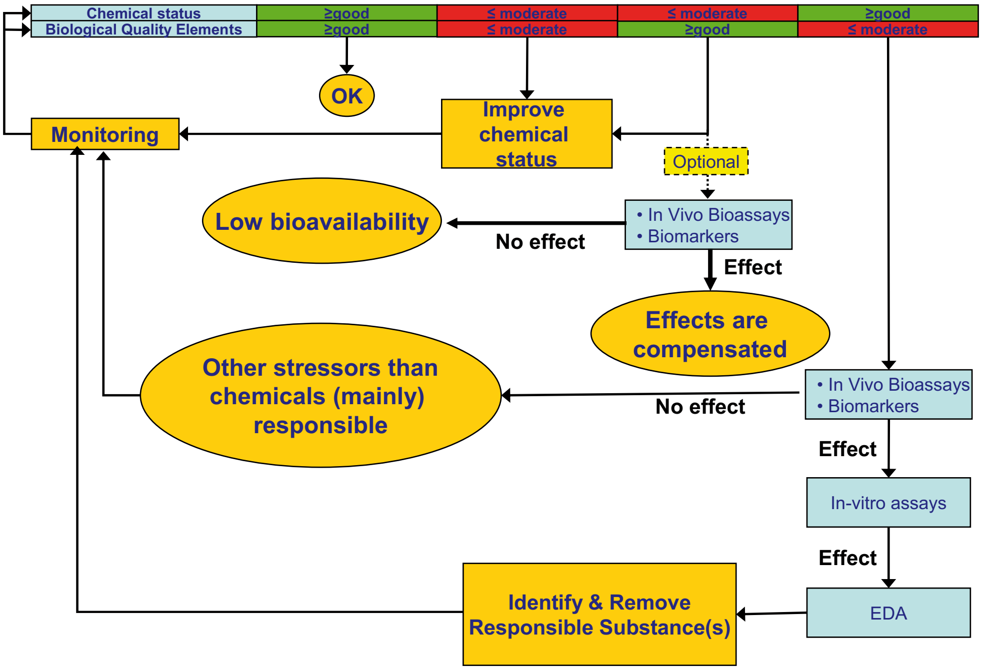


Fig. 3 Schematic overview of the tiered assessment approach

concentrations a thousand times lower than acute lethal concentrations (LC50 values) to *Daphnia magna*. And these are concentrations that frequently occur in our rivers. Thus, taking toxic contamination into account is crucial for successful management of rivers and the achievement of a good ecological status. However, the assessment of toxic effects on the BQEs is hampered by the enormous complexity of contamination. While only 41 priority and other hazardous chemicals together with some river-basin specific compounds are monitored in European river basins, screening analyses in environmental samples detect many thousands of compounds in each individual sample. These compounds are a subset of the 50 million chemicals we know today together with the even greater number of compounds we do not know yet. Thus, defining candidate compounds for monitoring and prioritisation is a challenging task.

The European Commission meets this challenge by applying two approaches. One approach applies PEC/PNEC ratios (ratio of Predicted Environmental Concentrations to Predicted No Effect Concentration) based on chemical monitoring data from the member states, while the other approach is based on modelled exposure data applying production volumes and usage patterns for the candidate compounds. Both approaches are complementary and powerful for compounds with a sufficient data basis. However, for many compounds present in the environment, neither monitoring nor reliable production data are available. Therefore, MODELKEY suggests involvement of a third approach based on field relevance applying effect-directed analysis (EDA, Fig. 4; Brack 2003). This approach is complementary to the others. It does not require any a priori knowledge on the chemicals we are looking for. It is based on measurable effects and thus specific for selected toxicological endpoints. Accordingly, it would combine ideally with effect monitoring based on biotests and biomarkers.

The EDA approach is site specific. Thus, the selection of sites representative and relevant for the river basin is important. We suggest that performing EDA downstream of major sources of pollution (intensive agriculture, industrial agglomerations, big cities …) but also in integrative sinks such as reservoirs, harbours or estuaries, particularly for sediment-associated compounds, would derive valuable candidates for prioritisation, monitoring and reduction.

EDA is based on selected toxicological endpoints and combines biotesting with fractionation to sequentially reduce complexity down to those compounds (or compound groups) causing observable effects. Finally, the components of the toxic fractions are analytically identified, quantified and confirmed as the cause of the effect. MODELKEY developed an extensive integrated toolbox for EDA including tools for exhaustive and bioaccessibility-directed extraction (Schwab and Brack 2007), clean-up and fractionation tools (Lübcke-von Varel et al. 2008; Meinert et al. 2010), biotests and bioavailability-directed dosing techniques (Bandow et al. 2009), and analytical and computer tools for structure elucidation (Schymanski et al. 2008). We applied this toolbox to sediments and waters at several sites in the three river basins mentioned above. The identified fractions and compounds bore little correspondence to what had been expected and to what are included in priority pollutant and river basin specific monitoring lists. This is illustrated using sediments as an example. Current assessment of sediment contaminants has a clear focus on nonpolar and highly hydrophobic compounds like for example polycyclic aromatic

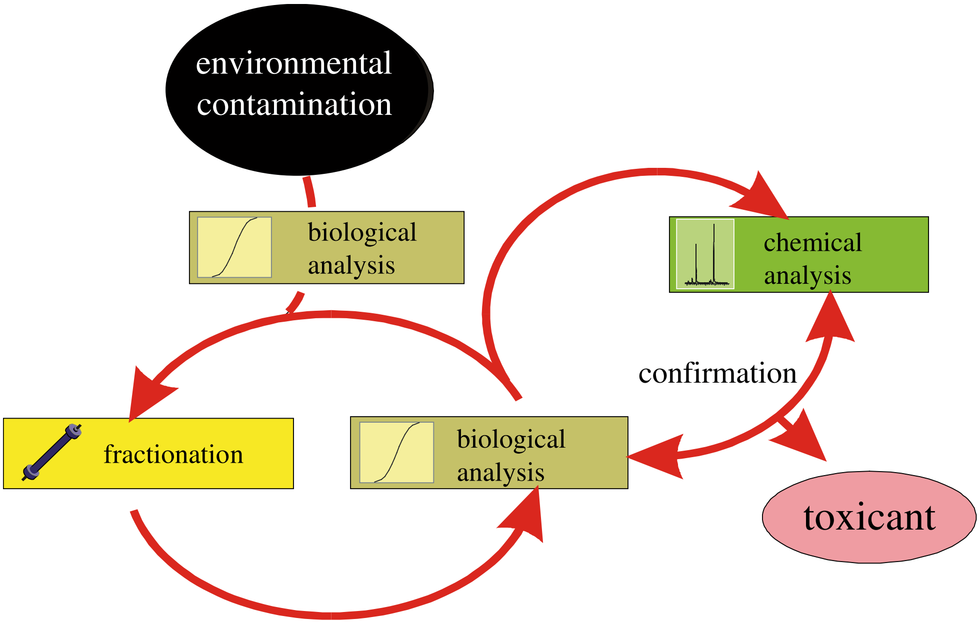


Fig. 4 EDA scheme (modified after Brack 2003)

hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polychlorinated dioxins and furans (PCDD/Fs) and chlorinated pesticides such as DDT, HCH, HCB, aldrin and dieldrin. EDA focusing on algal growth inhibition, mutagenicity, tumour promotion and endocrine disruption (estrogenic, androgenic, arylhydrocarbon-receptor mediated, thyroid hormone disturbing) as endpoints suggested a clear dominance of polar fractions causing these effects. These are thus likely relevant for different BQEs but possibly also for human health. This tendency towards attributing impacts to more polar compounds was further enhanced if bioavailability was considered in the EDA studies. Typical compounds identified as major toxicants in sediments were polar PAH-derivatives including nitro and keto-PAHs and PAH-quinones, the biocide triclosan used in personal care products, musk compounds such as galaxolide and tonalide or the flame retardant tri(2-chloroisopropyl)phosphate. None of these compounds is a priority pollutant or regularly monitored.

5 EQS values may be not protective for sensitive species

According to the EU Water Framework Directive, chemical contamination is assessed on the basis of environmental quality standards (EQS). Applying the SPecies At Risk (SPEAR) index MODELKEY clearly showed that sensitive invertebrate species are affected already at concentrations that are by a factor of 1,000 below the acute LC50 value for *Daphnia magna*, which is the most frequently used invertebrate test organism. This indicates that EQS closer to the acute lethal concentrations than a factor of 1,000 are not protective for invertebrate communities. These EQS have been derived from chronic or mesocosm experiments using a lower assessment factor on the observed effect concentrations. The priority pollutant chlorfenvinphos with an EQS of 0.1 µg/L and an LC50 of 0.3 µg/L may serve as an example. This compound is considered as less important and is rarely monitored because fortunately exceedances of the EQS are almost never observed when measured. However, already at concentrations far below the EQS an extensive disappearance of sensitive species will occur. On the basis of TU, chlorfenvinphos is among the most problematic compounds in the river basins investigated by MODELKEY.

6 Considering bioavailability and bioaccumulation improves the assessment of chemical stress

Traditional approaches in compliance monitoring and risk assessment of chemicals in the aquatic environment are based on the measurement and evaluation of total concentrations in water and sediment. Although it is well known that only a limited part of the contaminants bound to sediments, soils, suspended particulate matter, and colloids may be available for uptake by organisms, to date no standardised approaches exist that properly address bioavailability in monitoring and risk assessment.

A multitude of factors may determine the bioavailability of organic chemicals in sediments, including: (1) sediment characteristics, such as the type and quantity of organic matter (e. g. black carbon), grain size, ageing, (2) compound properties, such as lipophilicity, chemical structure (e. g. planarity), (3) organism-related factors, such as lipid content, body size, age, feeding habits, reproduction, habitat use, migration, biotransformation, and trophic position, and (4) environmental factors such as temperature and seasonal effects.

In MODELKEY much effort was dedicated to the assessment of bioavailability and bioaccumulation in integrated field, laboratory and modelling studies. The laboratory desorption and bioaccumulation studies with spiked contaminants demonstrated that, although our understanding of the factors involved is far from complete, the freely dissolved water concentrations, sediment characteristics, and – to a lesser extent – the rapidly exchanging fraction appeared to be the most predictive parameters for most of the compounds (Sormunen et al. 2009).

Bioaccumulation and trophic transfer were addressed in field studies, where in situ levels of a broad range of compounds were determined in sediments, suspended matter, water, biofilms, invertebrates and fish, sampled in the MODELKEY case study rivers Scheldt (estuary and freshwater tributaries), Elbe and Llobregat. The (more than 150) contaminants included: traditional PAHs, PCBs, dioxins, chlorinated pesticides to PCNs, brominated flame retardants, PFOS (Perfluorooctanesulfonic acid), alkyl phenols and ethoxylates, cationic surfactants, estrogens, pharmaceutical compounds, and polar pesticides. The results exhibited a large variation in biota-sediment accumulation factors (BSAF) between compounds, organisms and rivers, reflecting differences in uptake mechanisms, bioavailability and biotransformation. However, the results for dioxin-like compounds for example indicated that the assessment of bioaccumulation and trophic transfer is essential for assessing risks of secondary poisoning in predatory species (Fig. 5). These risks may be present even at concentrations in water that are orders of magnitude below what usually is measurable in current monitoring programmes for total water concentrations. Assessment and prediction of bioaccumulation and possible food web magnification may help to reveal unexpected properties of emerging compounds, and may be a useful tool to identify possible priority pollutants.

A rate-constant based first-order multi-compartment model was used for predicting bioavailability, bioaccumulation and food web transfer. The combined results of model-

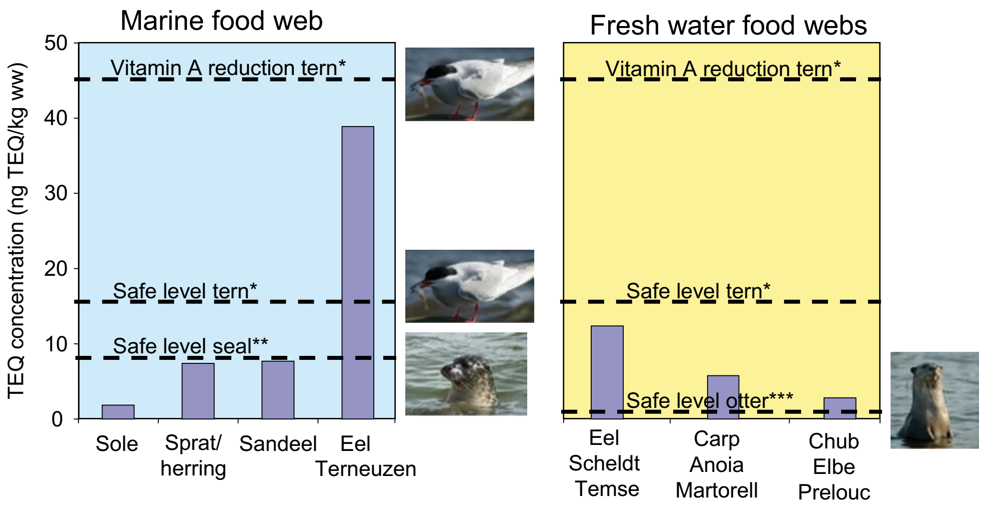


Fig. 5 Dioxin-like compounds (PCDDs, PCDFs, PCBs) in fish from a marine (Western Scheldt) and fresh water food webs (Scheldt, Anoia, Elbe) in relation to safe and critical body burden concentrations for tern, harbour seal and otter

ling, lab- and field investigations revealed that a combination of modelling partitioning to different organic carbon phases and applying assessment methods to estimate freely dissolved (pore) water concentrations or exchangeable sediment concentrations seems to be the most cost-effective approach for underpinning management decisions. Despite the still considerable uncertainties in current methods to assess bioavailability, MODELKEY investigations clearly showed that retrospective risk assessment (of supposedly contaminated water bodies) shall be based on extractable concentrations and freely dissolved concentrations rather than on total water or total sediment concentrations. These methods can also be useful for investigative monitoring studies.

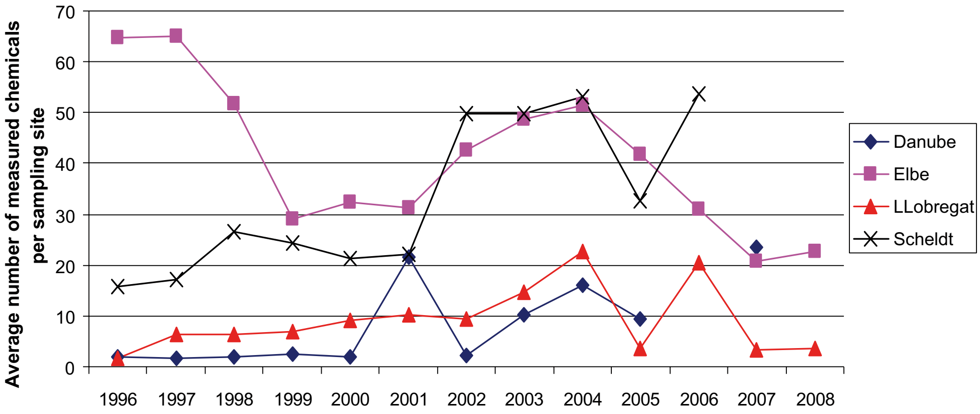
7 MODELKEY suggests improvements for surveillance and investigative monitoring

One of the goals of the WFD was to harmonise the monitoring strategies all over Europe, which differed among countries or even regions with respect to for example parameters recorded or metrics applied for the same endpoint. The WFD distinguishes three different types, in a tiered and cost-effective basic design: surveillance, operational and investigative monitoring. The surveillance monitoring shall be carried out at a sufficient number of sites to provide an assessment of the overall surface water status and aims to monitor the actual status and to assess long-term changes resulting from widespread anthropogenic activity. The operational monitoring should establish the status of those water bodies identified as being at risk of failing to meet the environmental objectives, and to assess any changes in the status of such water bodies that result from the programmes of measures. Investigative monitoring again shall be carried out where the causes of a water body failing to achieve the environmental objectives are unknown. MODELKEY developed innovative environmental assessment tools to support all three monitoring programmes to unravel unknown chemicals that might be responsible for the observed degradation.

Current monitoring programmes are less comprehensive than previous national or regional monitoring programmes with respect to frequency, number of stations, matrices and parameters, as a result of the Common Implementation Strategy. That favours the success of intercalibration of assessment tools, but reduces the overall ambition. Within MODELKEY, new assessment tools were tested and applied on existing monitoring data from the case study river basins (Elbe, Llobregat and Scheldt) and from Danube basin (Fig. 6). The experiences gained during the project resulted in suggestions to improve the monitoring programmes applied in function of the WFD. The main strengths of the existing programmes have been the long-time series of standardised methods and the occasional high frequencies, providing a high temporal and spatial resolution of water quality changes. In some monitoring programmes, chemical and biological assessment in all environmental compartments (water (suspended) and sediment biota) supplemented with eco-toxicological assessments provided extra tools for early warning. This is certainly not the case in the WFD monitoring strategy applying three different types, where warning only starts when ecosystem effects already occur. Moreover, the example of persistent, lipophilic contaminants (e.g. PCBs, DDT, BFRs, PFOS) highlights that it is not sufficient to monitor these substances in the water phase alone, as required by the WFD.

A weak point of the historic monitoring programmes was often a lack of harmonisation of methods, which resulted in the phenomenon that water quality earmarks could change when water simply crossed a border. Moreover, water quality monitoring often focused on compliance with environmental criteria of a limited number of chemical parameters as well as on the macroinvertebrate community and was not

Fig. 6 Time series of number of measured chemicals in the four investigated case studies



designed to establish cause–effect relationships. Minimising monitoring effort was even rewarded by facing fewer problems under the WFD.

The WFD investigative monitoring offers opportunities to determine the causal link between pressures, stressors and the impact causing an insufficient ecological status. The main aim of MODELKEY was to address just these cause–effect links. By combining tools working at different eco-system levels (e. g. from chemical toxicity, via food web bioaccumulation to biological reproduction), possible causes of impaired ecological status could be detected. The major finding from these case study assessments is that minimising the monitoring ambition in any of the three WFD monitoring types creates the risk of leaving the real ecosystem problems to the next generation. This is not the basis for sustainable development, as also recognised by the European community.

Suggestions for improving the monitoring strategy under the WFD include:

- the use of bioassays as early warning indicators in surveillance monitoring. Bioassays cover a wide range of known and unknown chemicals (> hazardous substances),
- to measure biological communities and chemical stressors at the same site and at the same time to allow for cause–effect relationships,
- to harmonise biological and chemical codes on a European level to facilitate the application of European assessment tools,
- to discriminate between the optimal matrices for hazardous substances analysis: water for hydrophilic and suspended matter, sediment, biotic tissues for hydrophobic compounds,
- to explore the use of biomimetic monitoring techniques which are concentrating and time-integrating, and can be used both for chemical and bioassay analysis,
- to discriminate the ecological targets (organisms), e. g. by food web studies (birds and fish have completely different stressors).

8 MODELKEY provides new integrated tools for risk assessment and decision-making on a basin scale

European water managers find the ecological status of the water bodies in their river basins threatened by different pressures (“multiple stresses”; among them the possible toxic effects of a wide range of chemicals.

MODELKEY investigated and applied different methods to predict toxic stress on the basis of measured concentrations in the field. The TU method offers the possibility to differentiate the predicted toxic stress between phytoplankton, macroinvertebrates and fish (von der Ohe et al. 2009). The “multi-species potentially affected fraction of species” (msPAF) directly quantifies the expected loss of species, taking into account mixture toxicity. Both methods use estimated bioavailable concentrations (de Zwart et al. 2009).

Despite the fact that these methods quantify only “known” toxicity connected to chemicals which are measured, and do not account for unmonitored emerging pollutants, the predicted effects can indeed be observed in the field. The SPEAR (SPecies At Risk) indicator expresses the share of invertebrate species sensitive to toxic stress within the total spectrum of species (Liess and von der Ohe 2005). Any significant reduction of this indicator, compared to a reference value of 50 %, indicates possible effects from toxic stress.

By state-of-the-art effect modelling, MODELKEY research demonstrated in different case studies (Scheldt River, Danube River) that the msPAF predicted loss of species is significantly related to the actually observed loss of species, even in complex multi-stress conditions (Fig. 7). Furthermore, the msPAF predicted loss of species correlated well with the results from bioassays.

The tools mentioned above have been implemented in the MODELKEY DSS (see Sect. 9) which supports the analysis of field data for evidence of various stressors on the ecosystem and the prioritisation between different polluted sites, in support of cost-effective programmes of measures.

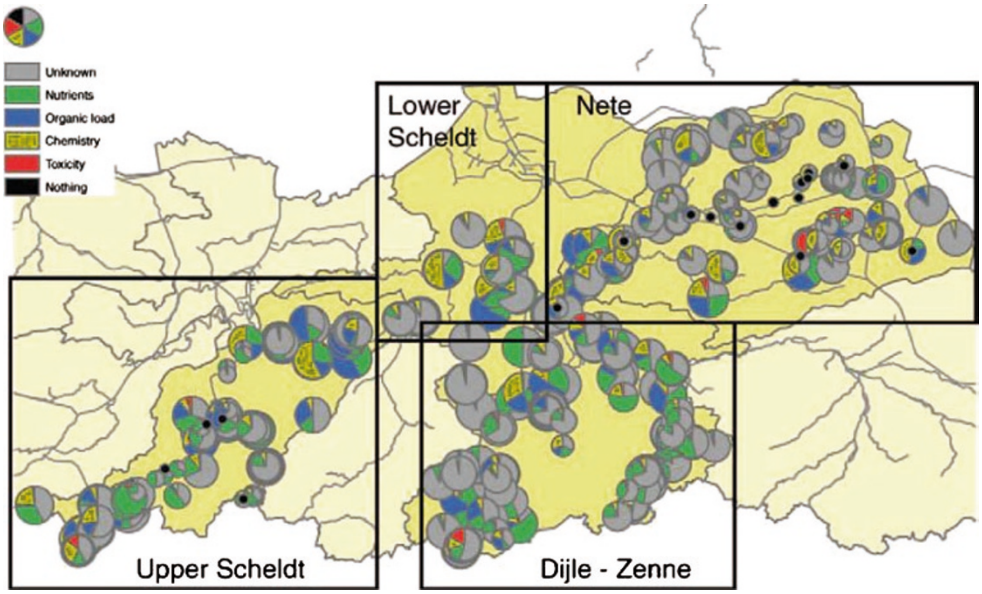


Fig. 7 Observed loss of species (pie size) and identified causes (stressors), among them the msPAF predicted loss of species ("toxicity" pie slices). From de Zwart et al. 2009, with permission

With respect to prioritisation between different polluted sites, MODELKEY research also resulted in the EXPOBASIN model (van Gils et al. 2009). This model establishes spatial relations between causes (pollution sources) and downstream impacts (ecological risk, expressed as TU) to allow a spatial, quantitative and objective ranking of chemicals and/or pollution sources. The model can easily be applied to all European river basins. Within MODELKEY it has been applied to the Rhine, Elbe, Scheldt, Llobregat and Danube Rivers. Figure 8 demonstrates a comparative assessment of two pollution sources in the Czech part of the Elbe Basin. The EXPOBASIN model includes the latest insights in bioavailability modelling and also addresses bioaccumulation, so that the impacts up to the level of top predators (secondary poisoning) can be included in the assessment (Fig. 9).

MODELKEY research resulted in clear insights into future research needs. To further facilitate the drafting of cost-effective programmes of measures in Europe, the MODELKEY effect-oriented approach should be connected to a source-oriented approach (as e. g. applied in the project SOCOPSE), including the compilation of suitable inventories of diffuse sources of pollution. For some chemicals this may necessitate the integration of the environmental compartments water, air, ground water and soils in a spatially distributed fashion.

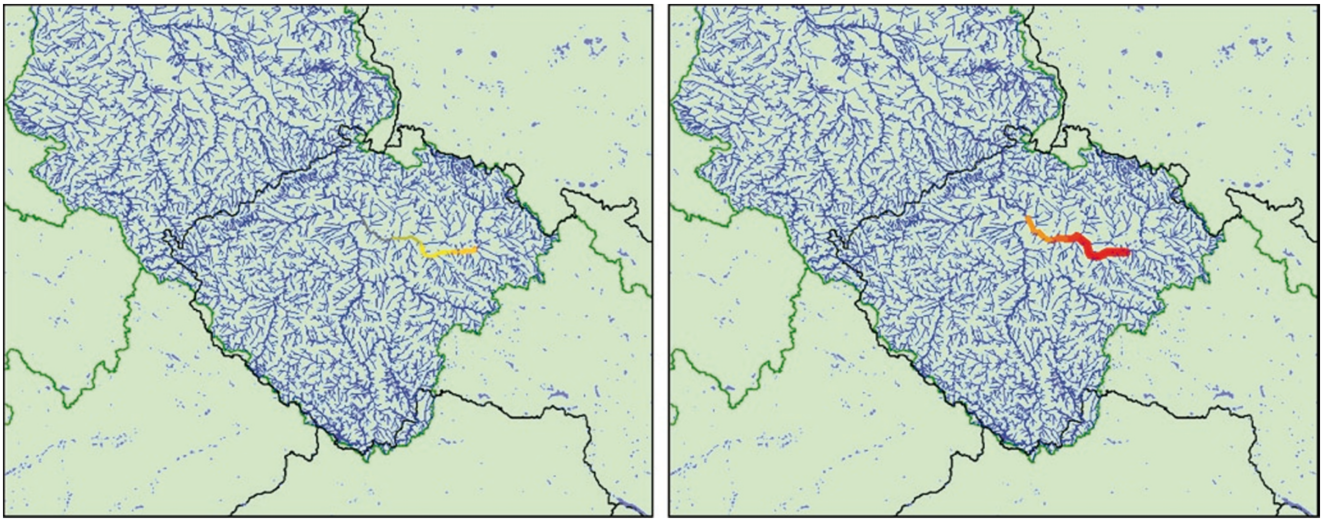


Fig. 8 Sample results from EXPOBASIN: the colours indicate the maximum relative risk to the phytoplankton community (expressed as TU) as a result of two pollution sources, showing a clearly different downstream impact of both sources

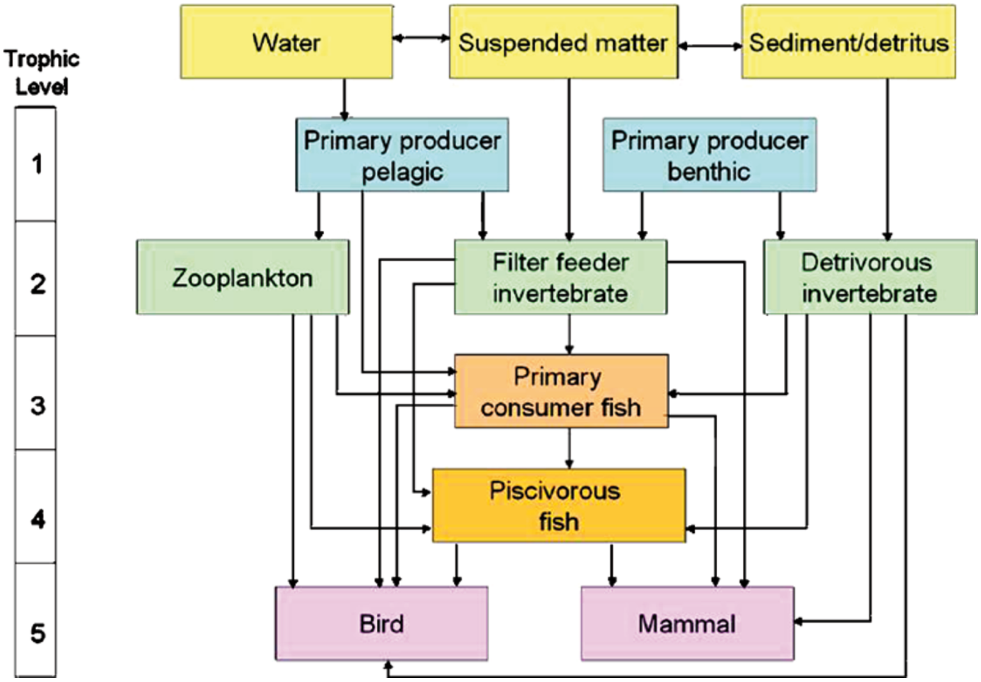
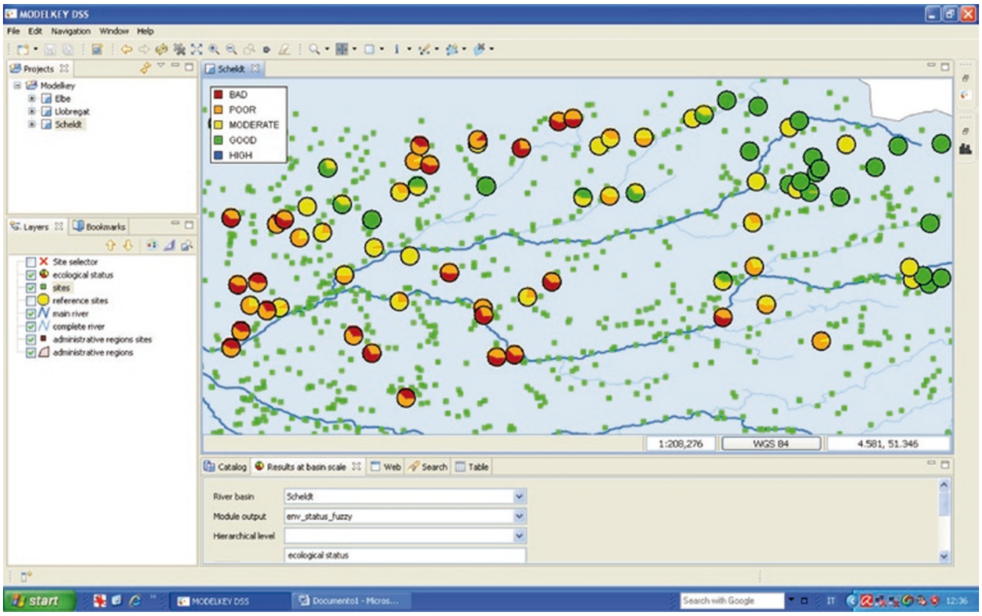


Fig. 9 Simplified generic food web included in EXPOBASIN model

9 The MODELKEY Decision Support System supports river basin managers

Within MODELKEY, a decision support system (DSS) supporting the overall assessment process of river basins according to WFD requirements is implemented (Gottardo et al. 2009).

The MODELKEY DSS is an innovative software system that combines several risk-based assessment tools supporting river basin management. It allows classifying the ecological and chemical status of individual water bodies or (monitoring) locations. It prioritises hot spots by integrating environmental and socio-economic information. By identifying relevant causes of impairment (key stressors and key toxicants) and the most impaired biological communities (key ecological endpoints at risk) the DSS supports the set up of additional (investigative) monitoring and consecutive measures.



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☑ ecological status
☑ sites
☐ reference sites
☑ main river
☑ complete river
☑ administrative regions sites
☑ administrative regions

River basin: Scheldt
Module output: env_status_fuzzy
Hierarchical level:
ecological status

Fig. 10 Example of IRI results: pie charts expressing the probability distribution of ecological status classes for each sampling site

All these features are available in a simple-to-use, geographically resolved, GIS-based software system structured in three modules: environmental, socio-economic and prioritisation. It offers adaptability to various rivers and local conditions, perfect coherence with the language and the reporting requirements of the WFD, technical simplicity and preferential flexibility, transparency and traceability of results, enhanced by strong graphical interface visualisation.

In Fig. 10, an example of the results provided by the DSS is reported.

The MODELKEY DSS is user friendly and freely downloadable from the MODELKEY project website (www.modelkey.org) after registration.

After the end of the MODELKEY project the main objective of the DSS developers team is to promote the application of the software system both within Europe (e. g. to support the preparation of the future River Basin Management Plans according to WFD cycles) and outside Europe through training courses and presentations at international conferences.

The present DSS offers the possibility to develop further modules and/or adapt existing ones to support new applications, for instance to address groundwater, or water quantity issues due to climate change impacts. Also a management module supporting the selection of more appropriate interventions for identified hot spots may be developed.

10 Do projected management measures improve the ecological status? Combining MODELKEY diagnostic tools with recent ecological methods opens up new opportunities for success prognosis

MODELKEY has clearly shown that toxic compound mixtures may cause deviations from the good ecological status (GES). These effects often remained hidden because of a Europe-wide tendency to focus on a limited set of chemicals and because of the intrinsic complexity of the problem: At any specific site many compounds and mixtures play a role within a complex multi-stress context. Thus, a suite of approaches and techniques was developed and applied in MODELKEY locally and on large geographical scales to diagnose and unveil those GES-relevant mixture impacts hidden so far. This will help to design River Basin Management Plans to counteract mixture impacts and to limit the risk that management successfully acts on one or two *apparently* major drivers for poor ecological conditions, but fails to reach GES because of chemical mixtures being the next “weakest link”.

MODELKEY but also the Integrated Project NoMiracle, confirmed by recent US (National Research Council US 2008) or EU (Council of the European Union 2010) concerns on joint impacts, suggest an increasing focus on the net impact on the protection endpoints rather than on separate causes. Supporting this, the EU recently stated in a flyer on Ecosystem Services that “*policy makers are changing their perspective and are integrating ecosystem health into some sectoral policies*” (European Commission 2009). Thus, we suggest taking a receptor in its surface water or sediment setting, and studying the complex stresses operating on the receptor via a stepwise “peeling-off probable causes” approach, to result in the identification of major stressors. With a focus on chemical stressors MODELKEY demonstrated the strength of this approach in EDA. Likewise, given major (bio)monitoring databases (as collected under the WFD), MODELKEY has proposed various methodologies for site-specific diagnosis of impact magnitudes and probable causes.

While MODELKEY results provide a crucial step towards a holistic, receptor-based approach, we argue that these findings can be further expanded and deepened by combining them with recently developed, other promising eco(toxico)logical approaches and data. This will help to further improve site-specific diagnosis and prognosis of management effectiveness. We could show that ecological methods, adding data on species traits (functional proxies for their ecological “opportunities”; and data on “who eats whom?” (mathematical proxies for species‘ positions in food webs), are potentially of great help in the diagnosis of local ecosystem impairments and quantification of stability and resilience. Additional costs are quite limited, since the (bio)monitoring data are already available.

The same approach may provide the basis for prognoses, whether “Good Ecological Status” will be reached when River Basin Management Plans (potentially designed for GES) are implemented further. Even without being fully able yet to predict the consequences of human impacts on structures and functions of aquatic systems, we have to develop prognostic tools to provide informed guesses on the dimensions of change and improvements expected from management and to alert on the most relevant remaining threats.

Within MODELKEY the *proof of the pudding* for our argument has already been given. Considering ecotoxicological methods, combination of existing (bio)monitoring data with species sensitivity data for toxicants and mixture modelling approaches yielded a novel proxy parameter (the multi-substance potentially affected fraction, msPAF), which is a measure for a net local toxic pressure (de Zwart et al. 2009). This novel proxy helped to unravel local multistress impacts, including the unravelling of the role of mixtures and separate compounds therein.

As shown here, scientific additions to existing (bio)monitoring data sets may enrich databases to such an extent, that they signal and rank local stressor relevance – which is then the basis for (cost-)effective river basin management – more clearly than before. Linking the landscape-scale diagnostic techniques (based on monitoring data) with the site-specific tools results in a versatile toolbox for effective river basin management.

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