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Actor modelling and its contribution to the development of integrative strategies for management of pharmaceuticals in drinking water☆

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ABSTRACT

Widespread presence of human pharmaceuticals in water resources across the globe is documented. While some, but certainly not enough, research on the occurrence, fate and effect of pharmaceuticals in water resources has been carried out, a holistic risk management strategy is missing. The transdisciplinary research project "start" aimed to develop an integrative strategy by the participation of experts representing key actors in the problem field "pharmaceuticals in drinking water". In this paper, we describe a novel modelling method, actor modelling with the semi-quantitative software DANA (Dynamic Actor Network Analysis), and its application in support of identifying an integrative risk management strategy. Based on the individual perceptions of different actors, the approach allows the identification of optimal strategies. Actors' perceptions were elicited by participatory model building and interviews, and were then modelled in perception graphs. Actor modelling indicated that an integrative strategy that targets environmentally-responsible prescription, therapy, and disposal of pharmaceuticals on one hand, and the development of environmentally-friendly pharmaceuticals on the other hand, will likely be most effective for reducing the occurrence of pharmaceuticals in drinking water (at least in Germany where the study was performed). However, unlike most other actors, the pharmaceutical industry itself does not perceive that the production of environmentally-friendly pharmaceuticals is an action that helps to achieve its goals, but contends that continued development of highly active pharmaceutical ingredients will help to reduce the occurrence of pharmaceuticals in the water cycle. Investment in advanced waste or drinking water treatment is opposed by both the wastewater treatment company and the drinking water supplier, and is not mentioned as appropriate by the other actors. According to our experience, actor modelling is a useful method to suggest effective and realisable integrative risk management strategies in complex problem fields that involve many societal actors.

Introduction

Widespread presence of human pharmaceuticals and their metabolites in the water cycle and sporadic occurrence even in drinking water have been documented across the globe, resulting in increased attention in public, media and research (BLAC, 2003; Daughton & Ternes, 1999; Kümmerer, 2007a; Nikolaou, Meric, & Fatta, 2007; Robinson, Junqua, Van Coillie, & Thomas, 2007). Even though measured concentrations are often in parts per billion or parts per trillion, they can be a hazard since drugs are designed to have physiological effects in organisms at low concentrations. Approximately 38 000 tons of pharmaceuticals are used every year in Germany (UBA, 2005). Hormones, antibiotics, blood lipid regulators, analgesics, beta-blockers, antidepressants, diagnostic contrast media, and antiepileptic and cytostatic drugs have been detected in the aquatic environment (BLAC, 2003), and relate to their large prescription volumes. In 2005, drug sales grew by 5% and 7% in North America and Europe, respectively; in August 2005, more than 140 000 bioactive compounds were in the different phases of drug research and development worldwide (Daughton, 2005). European Union and the United States laws require an assessment of potential risks to the environment as part of the licence application process for new medicinal products (EMEA, 2006; FDA, 1998). In Canada, environmental assessment regulations for pharmaceuticals are currently under development (Beck, 2007). Nevertheless, when the possibility of an environmental risk

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cannot be excluded, benefits for patients obtain priority and a denial of marketing authorisation is not likely (see EMEA, 2006, and FDA, 1998 for detailed information).

Pathways of pharmaceuticals into the aquatic environment

Pharmaceuticals (drugs) usually enter the aquatic environment following normal usage (see Fig. 1): After administration, a large portion passes through patients' bodies unmodified or partly metabolised (depending on the individual, pharmaceutical agent and dosage) and are excreted with urine and faeces into waste-water (Heberer, 2002). The residue that passes through sewage treatment plants discharges into surface water. They also reach wastewater through disposal of unused or outdated drugs. Drugs disposed of to landfill may also drain into ground and surface water. In addition, drugs may enter the aquatic environment via leakage from sewer networks (Ternes, 1998, 2000). Currently, it is not possible to estimate the relative contribution of excreted and disposed drugs to environmental loadings, as precise data about the consumption of pharmaceuticals are not available and disposal routes remain highly uncertain. Chemical analysis cannot currently distinguish excreted drugs from drugs that were disposed of (Daughton, 2007). Despite this, Ruhoy and Daughton (2007) have developed a new methodology for assessing the relative impact of drug disposal versus excretion on the occurrence of pharmaceuticals in the environment at the scale of local communities using inventory data collected by coroner offices in the United States. In Germany, 16% of the population dispose of tablets via domestic sewage at least occasionally and as many as 44% do this with liquid drugs according to a survey by Götz and Keil (2007).

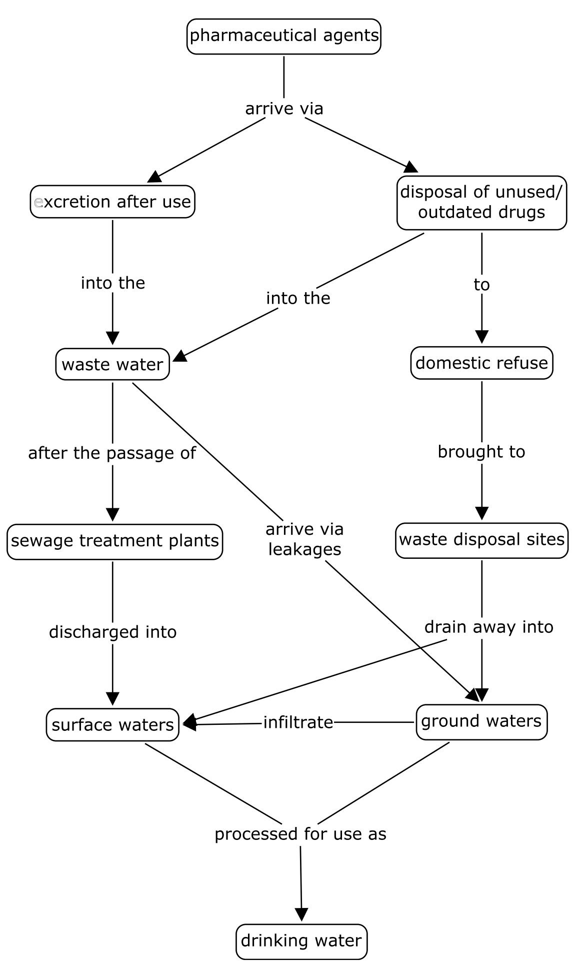


Fig. 1. Most important entry paths of human pharmaceuticals into the water cycle (modified after Ternes, 2000).

Evidence of adverse effects of pharmaceuticals in the environment

Adverse effects on aquatic organisms have been detected for a large number of pharmaceutical agents at environmental concentrations (Khetan & Collins, 2007; Robinson, Junqua, Van Coillie, & Thomas, 2007). In case of a mixture of numerous endocrine pharmaceuticals that bind to the alpha human oestrogen receptor, and for a number of beta-blockers, the toxicological effects of the pharmaceuticals are additive (Khetan & Collins, 2007). With respect to adverse health effects of pharmaceutical agents in drinking water, there is only very scant information. Although environmental concentrations are low compared to therapeutic doses so that most scientists assume that they do not pose an appreciable risk to human health, it was acknowledged that there are exceptions, e.g. oestrogens, genotoxic antineoplastics or compounds with high potential for bioaccumulation like diclofenac (Khetan & Collins, 2007). Pregnant women and their babies, as well as children, are at particular risk. During pregnancy, women would ingest 13% of a clinical dose of the synthetic oestrogen ethynyl estradiol via drinking water, a hormone that is absolutely contraindicated during pregnancy (Collier, 2007). Children are at risk by pharmaceutical agents in drinking water that are contraindicated for children.

EPA (2008) provides a compilation of literature references on pharmaceuticals (and personal care products) in the environment. Occurrence, fate and toxicological effects of pharmaceuticals in the environment have been covered by many publications (Heberer, 2002; Khetan & Collins, 2007; Kümmerer, 2007a; Robinson et al., 2007).

Table 1
Actions and actors of the three main strategic approaches that were designed in the research project "start" for reducing the occurrence of pharmaceuticals in the water cycle.

Action [Actor]
Technical approach
Implement advanced drinking water treatment (e.g. granular activated carbon filtration) [Drinking water supplier]
Install advanced wastewater treatment [Sewage treatment company]
Install separate treatment of wastewater from hospitals and nursing homes [Owner of facilities]
Install sewage separation [Municipality]
Behavioural approach
Avoid over-prescription [Physician]
Avoid prescription of pharmaceuticals with unsound environmental behaviour [Physician]
Develop an environmental classification list for pharmaceuticals [Scientific institute]
Establish increased co-payments for pharmaceuticals [Ministry of Health]
Include topic in retraining of physicians and pharmacists [Professional association]
Initiate a discourse with medical professionals [PR-Agency]
Introduce electronic health card [Ministry of Health]
Legislate binding standard disposal for pharmaceuticals [Legislator]
Offer varying packaging sizes/starter packs [Pharmaceutical industry]
Operate a communication campaign for proper disposal of unused/outdated pharmaceuticals [Government/Health insurance]
Prescribe drug-free therapies [Physician]
Print advice for proper disposal on packaging and instruction leaflet [Pharmaceutical industry]
Pharmaceutical agent approach
Couple marketing authorisation and environmental risk assessment more strongly [Authorisation Agency]
Establish thematic programmes on pharmaceutical and organic chemistry at universities [German Research Foundation]
Extend patent terms for sustainable pharmaceuticals [Legislator]
Initiate specific research programmes for the development of sustainable pharmaceuticals [National Research Programmes]
Offer awards and competitions in sustainable pharmacy [Federal Environment Agency]

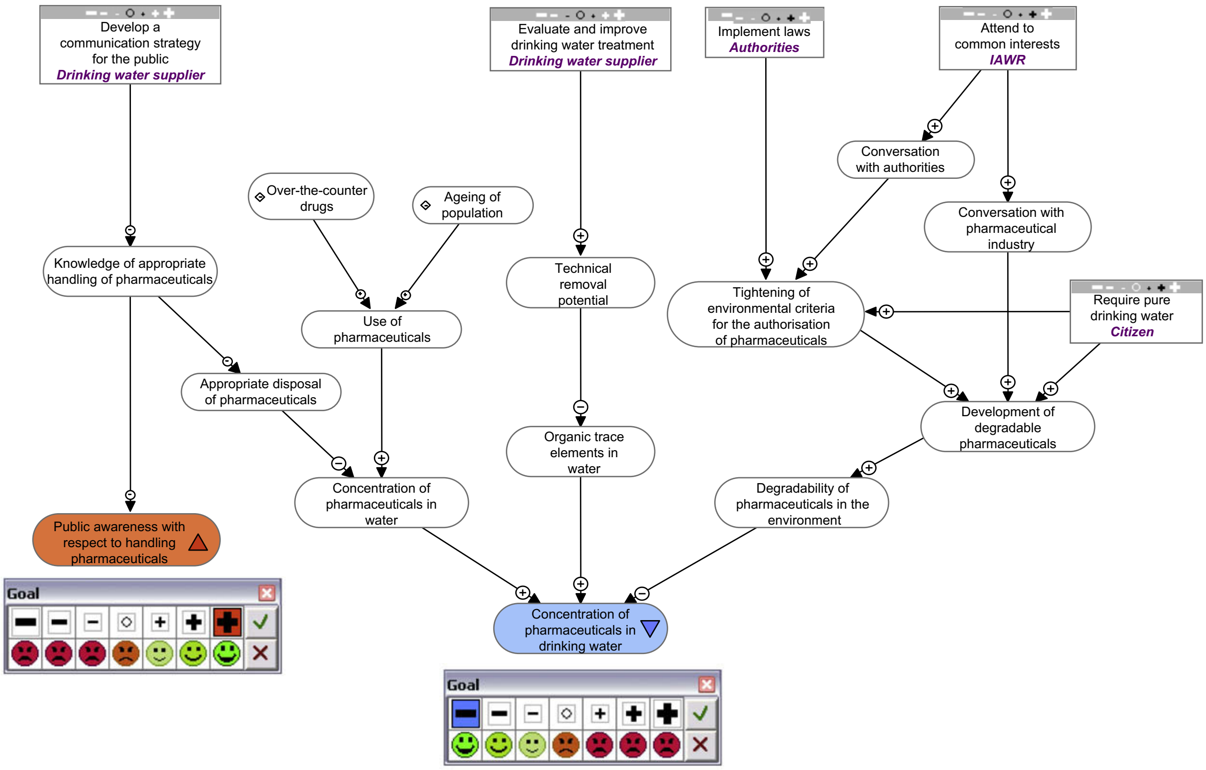


Fig. 2. Exemplary perception graph of the actor “Drinking water supplier”.

Risk management

Due to the large number of pharmaceutical agents, their metabolites, diversity of target organisms of concern, and general difficulty in determining chronic effects, research results to date do not suffice to derive well-founded and comprehensive dose–effect relationships, thus preventing reliable risk assessments. Even further research is unlikely to reduce the uncertainty in the short term. In such a situation where risks remain unquantifiable due to limited scientific knowledge, it is reasonable to invoke the precautionary principle (Von Schomberg, 2006). Assessing risk assessments of pharmaceuticals in the environment, Enick and Moore (2007) conclude that the precautionary principle provides a direction for future research and policy development, not only on the inherent uncertainties but also on the impact of human values on the assessments. Clearly, the precautionary principle requires a reduced occurrence of pharmaceuticals in the environment, and Doerr-MacEwen and Haight (2006) suggest that scientific uncertainty must not be allowed to delay actions that help to achieve such a goal.

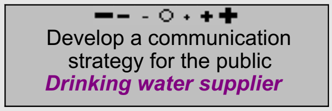
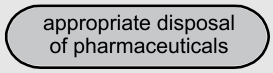
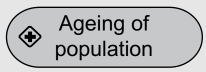
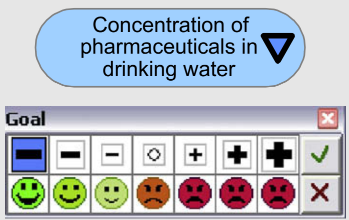
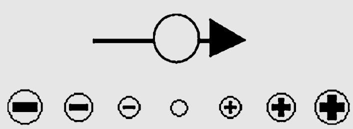
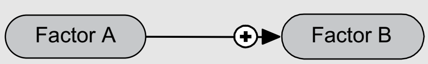
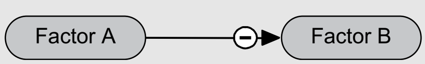
Promoting life-cycle stewardship of pharmaceuticals, Daughton (2003a, 2003b, 2007) delineates major actions to minimize emissions of pharmaceuticals into the water cycle. An effective strategy would require a holistic integration of actions addressing drug design (e.g. see Kümmerer, 2007b), packaging and dispensing, prescription, patient compliance and drug disposal (Daughton, 2003a, 2003b, 2007). Technologies for the removal of pharmaceuticals from wastewater and drinking water are presented and discussed, for example, by Barceló and Petrović (2007), Drewes (2007), Drewes, Heberer, and Reddersen (2002), Heberer (2007), and Petrović, Gonzales, and Barceló (2003). In Sweden, Stockholm City Council has used manufacturer supplied data to classify pharmaceuticals according to their potential impact on the aquatic environment. This enables physicians and patients to select the least water polluting drug when therapeutic equivalent alternatives are available, and the pharmaceutical industry becomes motivated to develop environmentally-friendly pharmaceuticals (Stockholm läns landsting, 2008; Wennmalm & Gunnarsson, 2005).

In general, human health and environmental health are societal aims that support each other. In the case of pharmaceuticals, however, it might be argued that there is a conflict between the goals of curing sick people by pharmaceuticals and providing uncontaminated drinking water. As Daughton (2003a, 2007) points out, however, high quality health care and ecologic health need not to be competing goals, as actions for minimizing the occurrence of pharmaceuticals in the environment hold the potential for improvements in therapeutic outcomes, patient health, and reducing health care costs.

Modelling of societal actors

An integrative strategy for reducing the occurrence of pharmaceuticals in the water cycle and thus in drinking water has not yet been developed. To facilitate the development of such a strategy for Germany, the transdisciplinary research project “start” (“Management Strategies for Pharmaceuticals in Drinking Water”, http://www.start-project.de) was established. Our hypothesis was that such a strategy must be integrative with respect to actors and actions, i.e. involve a large number of societal actors and combine a number of technical and behavioural measures, as well as, measures to promote development of environmentally-friendly pharmaceutical agents. Table 1 summarizes the three strategic approaches of our research project. For identifying an implementable and sustainable risk management strategy, we considered it to be useful to analyse problem perceptions and goals of the actors in a participatory approach. By involving experts who represent key actors such as pharmaceutical industry, physicians’ and pharmacists’ associations, sewage treatment companies, drinking water suppliers, health insurance providers, consumer councils, and public authorities in the project, we hoped to identify strategies

Table 2
Elements of a DANA perception graph.

Action		Actions describe the capacity of an actor to cause changes. Changes are defined on a seven-part scale that varies from strong decrease through “no change” to strong increase (displayed by minuses and pluses).
Factor		A factor is a system variable that can be influenced by actions and other factors.
Prospect		A prospect represents an expected change in a factor. Changes are displayed by minuses and pluses on a seven-point scale. Prospects cannot be influenced by actions or factors. Example: Actor expects the factor “Ageing of population” to increase.
Goal		A goal represents a desired change in a factor. Each of the seven possible changes is linked to a certain “utility value” (emotional levels, displayed by face icons). Example: a strong decrease in the “Concentration of pharmaceuticals in drinking water” is desired.
Causal link		A causal link represents the relationship between factors, where a change in factor A causes a change in factor B. The effects range from a strong negative effect through “no effect” to a strong positive effect.
		Positive correlation – if factor A increases, factor B will also increase
		Negative correlation – if factor A increases, factor B will decrease

that reflect multiple perspectives and objectives and are thus more likely to be sustainable than strategies derived by scientists alone. According to Assmuth, Lyytimäki, Hildén, Lindholm, and Münier (2007: 3), “novel methods for integrated assessment and management of risks from stressors to ecosystem and human health are much needed. […] In this connection, it is important to clarify the opinions and views of the key actors about risk, risk assessment and risk management […].”

Computer-based modelling has become a dominant scientific assessment method in the field of ill-structured and complex issues and the transition towards sustainability, and it is necessary to include not only natural and technical systems but also human systems in such assessments (Pahl-Wostl, 2002). Inclusion of the knowledge of stakeholders in an assessment process is often achieved using models that differ considerably from models used in the natural sciences. In this context, Bots, Van Twist, and Van Duin (2000) argue that analysts should stay away from “hard” solution oriented models. Instead, the analyst should acquire knowledge by using a range of “soft” perception oriented models, to improve her understanding of how actors think. The so-called “soft-systems” approach, developed by social scientists and practitioners from industry and management sciences (e.g. Checkland, 1993), allows for application of systems thinking to non-systematic issues where hard systems approaches fail to deal with complex issues that have a considerable social dimension. Actor modelling fits into this tradition and is a novel method for exploring feasible changes and strategies to improve a problematic issue. For example, Döll and Döll (2008) applied actor modelling to issues related to mobile organic xenobiotics in surface waters.

Consideration of the actors' perspectives and goals was not only achieved by the experts' participation in workshops and written comments on research results, but in particular, by modelling of societal actors. In actor modelling, the problem perceptions of all relevant societal actors are represented in perception graphs and thus modelled in a highly-structured, semi-quantitative way. In this paper, we present actor modelling with the software DANA (“Dynamic Actor Network Analysis”, Bots, 2007) as well as actual actor perspectives on the problem of pharmaceuticals in drinking water. We discuss the method of actor modelling and offer suggestions for an integrative risk management strategy that could contribute to minimizing the occurrence of pharmaceuticals in the water cycle and thus in drinking water.

Methods

The software DANA (version 1.2.0, http://dana.actoranalysis.com/) was applied to model and analyse the problem perceptions of the key actors in a semi-quantitative manner. DANA has been developed to help policy analysts to reflect actors' views on a policy issue and to investigate possibilities of conflict resolution (Bots, Van

Table 3
Optimal strategies (optimal change levels of set of actions) from each actor's perspective.

Actor	Action [Actor]	Optimal strategy	Goal(s)
Drinking water supplier	Develop communication campaign [Drinking water supplier]	+	Increase sensitivity of the public with respect to handling pharmaceuticals, Decrease concentration of active compounds in drinking water
	Implement advanced drinking water treatment [Drinking water supplier]	○	
	Attend to common interests [Association of drinking water suppliers]	+	
	Implement laws [Authorities]	+	
	Require pure drinking water [Citizens]	+	
Sewage treatment company	Couple marketing authorisation and environmental risk assessment more strongly [Authorisation Agency]	−	Increase (improve) environmental conditions of water bodies
	Inform consumer [Physician]	+	
	Inform consumer [Pharmacist]	+	
	Inform consumer [Consumer council]	+	
	Call for advanced wastewater treatment [Government]	−	Increase cost effectiveness
	Inventory taking [Environment Agency]	○	
Pharmacist	Legislate a threshold for pharmaceuticals in wastewater from hospitals [Legislator]	+	No increase of pharmaceuticals in wastewater from hospitals
	Avoid over-prescription [Physician]	+	Decrease occurrence of pharmaceuticals in the water cycle
Physician	Prescribe drug-free therapies [Physician]	○	Decrease occurrence of pharmaceuticals in the water cycle
	Avoid over-prescription [Physician]	+	
	Avoid prescription of pharmaceuticals with unsound environmental behaviour [Physician]	+	
	Establish increased co-payments for pharmaceuticals [Ministry of Health]	+	
	Legislate a binding standard disposal for pharmaceuticals [Legislator]	+	
	Support disease prevention as a political mandate [Politics]	+	
Health insurance	Introduce electronic health card [Ministry of Health]	+	Increase health, decrease illness
	Provide evidence of a risk for human health [Science]	+	
	Provide funds [Government]	○	
Pharmaceutical industry	Develop highly active substances [Pharmaceutical industry]	+	Increase therapeutic benefit, innovative drugs, and profit
	Advance diagnostics [Pharmaceutical industry]	+	
	Assess production wastewater [Pharmaceutical industry]	−	No increase in the occurrence of pharmaceuticals in the water cycle
Ministry of health and subordinated agencies	Introduce electronic health card [Ministry of Health]	○	Decrease occurrence of pharmaceuticals in the water cycle
	Continue research [Federal Environment Agency]	○	
	Couple marketing authorisation and environmental risk assessment more strongly [Authorisation Agency]	+	
	Install separate wastewater treatment in hospitals [Municipality]	+	Decrease drinking water contamination
	Legislate a binding standard disposal for pharmaceuticals [Legislator]	+	

Twist, & Van Duin, 1999; Bots et al., 2000). The underlying principle is that various actors perceive a problem in different ways and act based on how they perceive a problem rather than based on facts.

Perception graphs

Problem perception of each societal actor is modelled in a perception graph. A perception graph is a directed acyclic graph and is structured like a causal map. As an example, Fig. 2 shows the perception graph of the actor "Drinking water supplier". The actor's goal(s), possible actions by the actor himself and by other actors, prospects, and relevant factors are interconnected by causal links (influence arrows), showing causal relationships between elements in a consistent and transparent form. Thus, perception graphs not only show actions and factors to which the actors attach importance but also parts of the issue they are oblivious of. The elements of a DANA perception graph are explained in Table 2. Changes in factors, i.e. actions, goals, prospects, as well as causal links, are attached to symbols providing a seven-point scale.

With regard to actions (e.g. "Implement laws" in Fig. 2), the minuses and pluses in the headers of boxes refer to seven possible "change levels" which range from a strong decrease of the action (a big minus) through "no change" to a strong increase (a big plus), as compared to the current course of action. While minuses and/or pluses shown in black colour represent change levels that the actor considers to be possible to occur, change levels displayed in white colour are considered to be impossible. For example, the actor Drinking water supplier regards a constant degree of implementation of laws by the authorities as possible, as well as a slightly improved or an improved implementation (Fig. 2). A goal represents a desired change in a factor. Each of the seven possible changes, from a strong decrease (a big minus) through "no change" to a strong increase (a big plus), is associated with an emotional level ("utility level", displayed by face icons). The utility levels specify how the actor values a certain change and range from strong disapproval through "neutral" to strong appreciation. The actor represented in Fig. 2, for example, desires a strong decrease in the factor "Concentration of pharmaceuticals in drinking water" and would be somewhat unhappy even if the concentration remains constant. Prospects (e.g. "Ageing of population" in Fig. 2) represent independent changes in a factor (i.e. not caused by some action in the perception graph) the actor expects to occur. Causal links from one factor to another are defined by positive and negative correlations and can be described by seven different "change multipliers" (for a detailed explanation see Table 2). Both causal links and prospects can be expressed probabilistically, but this option was not used here.

Eliciting actors' perceptions and generating perception graphs

As a first step in the actor modelling process, perceptions of the relevant actors were systematically elicited by participatory model building and guided interviews with one to three representatives of the key actors listed in Table 3. The actor representatives were recruited upon recommendation of the experts involved in the research project. In participatory model building, the representatives of each actor together constructed their actor's perception graph by putting it down on a paper sheet. The process of model building was assisted by the researcher, and complementary information was gained through guided interviews. The most important cause–effect relationships were then discussed (and modified if required) with the actor representatives, and finally the model was checked with regard to consistency. Participatory (group) model building using system dynamics approaches "can be helpful to elicit and integrate mental models in a more holistic view of the problem" (Vennix, 1996: 3) than with interviews only. The perception graphs were then transformed into DANA perception graphs by the analyst, who slightly modified (mostly simplified) the graphs. The perception graphs were then verified in a second meeting with the actor representatives.

Analysis of actor perceptions

DANA allows computation of the impact of actions on goal achievement by assigning numerical values to change levels, change multipliers, and utility levels (see Fig. 3). Taking Fig. 2 as an example, the numerical value assigned to the change level of an action (e.g. 2 for a medium increase of the action "Implement laws") is multiplied with the numerical value of the change multiplier of the influence arrow (1 for a medium plus) to compute the change level of the factor "Tightening of environmental criteria […]", i.e. 2. After multiplication with the numerical values of subsequent change multipliers (twice by 1 and finally by −1), a change level of the action "Implement laws"

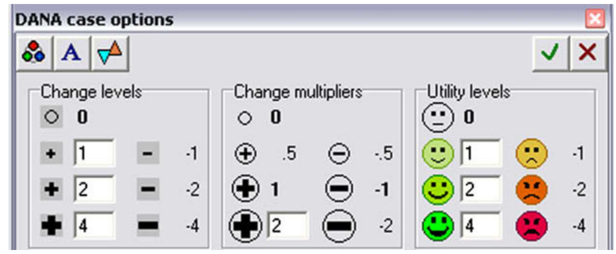


Fig. 3. Quantification of change levels, change multipliers, and utility levels by assigning numerical values to the symbols.

of 2 (medium increase) will result in a change level of −2 for the goal "Concentration of pharmaceuticals in drinking water" (medium minus according to Fig. 3), which corresponds to a medium positive face icon (Fig. 2) and thus a utility level of 2 (Fig. 3). In this way, the impacts of all possible change levels of actions on the goal(s) in a perception graph are computed. If more than one influence arrow reaches a factor, the impacts on the change level of the factor are additive. As every change in a goal factor is related to a specific utility (goal achievement), the utilities of all combinations of (change levels of) actions can be determined. This allows identification of a combination of change levels that will lead to the optimal goal achievement and therefore to the highest possible utility, i.e. an optimal strategy from the actor's point of view. As there are often large numbers of strategies that lead to the highest utility, only the strategies that require a minimum change in all actions (and therefore a minimum effort) are considered to be optimal.

Furthermore, an analyst's view of the problem "pharmaceuticals in drinking water" (see Fig. 4) was constructed in a semi-automatic manner. First, DANA automatically merged all perception graphs, and then this new graph was modified by the analyst. With this graph, the analyst integrated her knowledge about the system of actors and factors that she gained from the actors' perceptions and other sources in such a way that a strategy (i.e. the optimal combination of change levels of actions) for decreasing the occurrence of pharmaceuticals in the water cycle could by computed by DANA.

Results

Optimal strategies from the actors' perspectives

The optimal strategies from each actor's point of view as well as the goals of the different actors are listed in Table 3. The pharmacist, the physician as well as the Ministry of Health and subordinated agencies (MOH) share the goal of reducing the occurrence of pharmaceuticals in the water cycle. In contrast, the pharmaceutical industry only wants no increase of pharmaceuticals in the water cycle. Some actors do not explicitly aim at reducing the occurrence of pharmaceuticals in the water cycle, but aim at decreasing the concentration of active compounds in drinking water only (drinking water supplier) or at generally improving the environmental conditions of water bodies (sewage treatment company). The health insurance provider does not formulate a goal related specifically to pharmaceuticals but to human health in general. Concurrent goals are related to increased sensitivity of the public with respect to handling pharmaceuticals (drinking water supplier), and financial costs (sewage treatment company).

The actors perceive multifaceted actions that are supposed to decrease the occurrence of pharmaceuticals in the water cycle and to support further individual goals as well. The drinking water supplier, the physician, the pharmaceutical industry and the MOH consider themselves to be autonomous actors who can contribute to achieving their goals by their own actions (in their perception

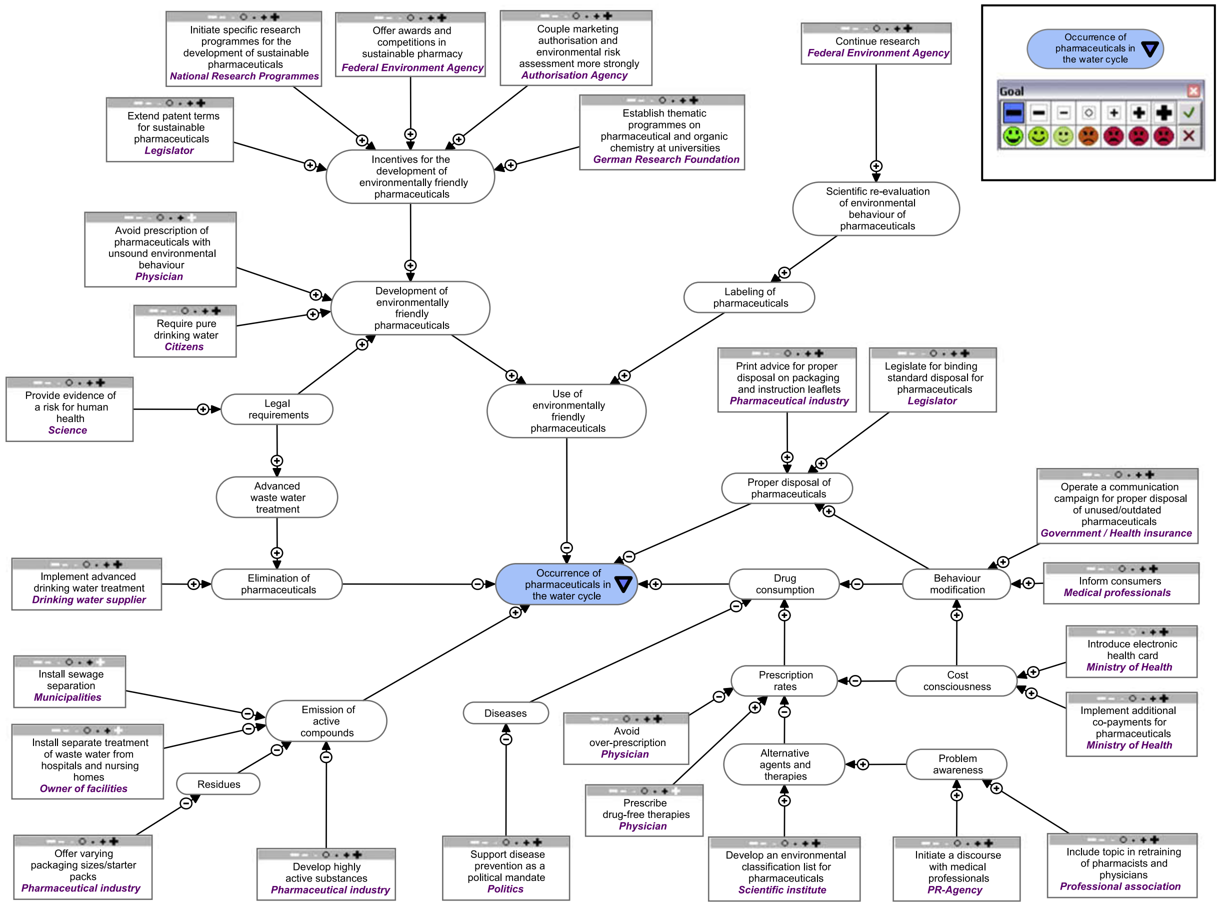


Fig. 4. Perception graph of the issue "Pharmaceuticals in drinking water" representing the perception of the analyst.

graphs, they include own actions, compare Table 3). In contrast, the pharmacist, the wastewater treatment company and the health insurance provider consider themselves as actors who at least currently do not feel that it is feasible to take action at this time (see Table 3). They think that any own actions need to be triggered by actions of other actors, e.g. by legislators or scientists. For instance, the health insurance provider argued that they do not feel it necessary to take action as long as there is no scientific evidence that the occurrence of pharmaceuticals in the water cycle poses a threat to human health.

With respect to optimal changes in technical strategies, the sewage treatment company and the drinking water supplier consider advanced wastewater and drinking water treatment technologies not to be beneficial for achieving their goals. Installation of separate treatment for sewage from hospitals and nursing homes, however, is considered to be an effective strategy by the MOH (Table 3). The other actors did not include technical measures as actions at all, partly because they felt that these technical approaches are not appropriate to deal with the problem. Increased investments in scientific risk assessments appear not to be desired by the actors. Most of the actors think that 1) changing the use of pharmaceuticals and 2) developing environmentally-friendly pharmaceutical agents are appropriate approaches to achieve their goals. According to the physician's optimal strategy, the prescription of drug-free therapies should not be increased since this is not yet facilitated by health insurance providers. Instead, this actor favours additional co-payments for pharmaceuticals. From both the pharmacists and the physician's viewpoint, changing prescription behaviour in order to minimize unnecessary drug consumption would decrease the occurrence of pharmaceuticals in the water cycle. Both the physician and MOH favour a binding standard disposal for pharmaceuticals. An electronic health card should be introduced as planned, according to the MOH, while an accelerated introduction of the card would be preferable from the health insurance provider's perspective (Table 3; an electronic health card will be implemented in Germany in the near future. It will allow storing personal data as well as personal health data, e.g. a documentation of medication taken to inform medicinal professionals treating the patient).

Many actors think that it is important to develop environmentally-friendly pharmaceuticals (not shown in Table 3, as this action does not appear as autonomous action in the perception graphs but as a factor that is influenced by e.g. legislation). In order to foster the development of environmentally-friendly pharmaceuticals, coupling marketing authorisation and environmental risk assessment of pharmaceuticals more strongly is seen as an optimal strategy by the MOH, while it should not be done according to the perspective of the sewage treatment company. However, the pharmaceutical industry does not think that it is necessary to develop environmentally-friendly pharmaceuticals. Instead, strongly increasing the development of highly active substances, developing diagnostics and assessing wastewater from pharmaceutical manufacturing could contribute sufficiently to avoid increasing amounts of pharmaceuticals in the water cycle (according to their perspective, see Table 3).

Optimal strategy from the analyst's perspective

Fig. 4 shows the analyst's perception graph. In support of identifying an integrative risk management strategy for pharmaceuticals

Table 4
Optimal strategy (optimal change levels of set of actions) for decreasing the occurrence of pharmaceuticals in the water cycle as determined from the analyst's perspective.

Action [actor]	Optimal strategy 1	Optimal strategy 2
Technical approach		
Install sewage separation [Municipality]	✚	○
Implement advanced drinking water treatment [Drinking water supplier]	○	○
Install separate treatment of wastewater from hospitals and nursing homes [Municipality]	○	○
Behavioural approach		
Print advice for proper disposal on packaging and instruction leaflet [Pharmaceutical industry]	✚	○
Support disease prevention as a political mandate [Politics]	✚	✚
Develop an environmental classification list for pharmaceuticals [Scientific institute]	+	○
Implement additional co-payments for pharmaceuticals [Ministry of Health]	+	○
Include topic in retraining of physicians and pharmacists [Professional association]	+	○
Introduce electronic health card [Ministry of Health]	+	+
Operate a communication campaign for proper disposal of unused/outdated pharmaceuticals [Government/ Health insurance]	+	+
Prescribe drug-free therapies [Physician]	+	✚
Avoid over-prescription [Physician]	○	○
Avoid prescription of pharmaceuticals with unsound environmental behaviour [Physician]	○	○
Inform consumers [Medical professionals]	○	○
Initiate a discourse with medical professionals [PR-Agency]	○	+
Legislate binding standard disposal for pharmaceuticals [Legislator]	○	+
Offer varying packaging sizes/starter packs [Pharmaceutical industry]	○	✚
Pharmaceutical agent approach		
Establish thematic programmes on pharmaceutical and organic chemistry at universities [German Research Foundation]	✚	✚
Continue research [Federal Environment Agency]	+	○
Initiate specific research programmes for the development of sustainable pharmaceuticals [National Research Programmes]	+	○
Couple marketing authorisation and environmental risk assessment more strongly [Authorisation Agency]	○	○
Develop highly active substances [Pharmaceutical industry]	○	○
Extend patent terms for sustainable pharmaceuticals [Legislator]	○	+
Offer awards and competitions in sustainable pharmacy [Federal Environment Agency]	○	○
Provide evidence of a risk for human health [Science]	○	+
Require pure drinking water [Citizen]	○	+

in the water cycle, only one goal is featured: the analyst desires a strong decrease in the occurrence of pharmaceuticals in the water cycle. The 26 actions include both actions from the actors' perception graphs that according to the actors' perceptions contribute to decrease the occurrence of pharmaceuticals in the water cycle as well as feasible actions of the three strategy approaches (Table 1) that were not mentioned by the actors. Change levels of actions that the analyst considers to be possible (shown in black in the header of the action boxes) are, for most actions, restricted to "no change" and increases in actions mainly because these actions are formulated as new measures. The 26 actions influence factors which the analyst regards as important for goal achievement: the development and use of environmentally-friendly pharmaceuticals, proper disposal of pharmaceuticals, drug consumption, emission of active compounds, and elimination of pharmaceuticals in the water cycle (see centre of Fig. 4). These factors are seen as starting points for an integrative risk management strategy for pharmaceuticals in the water cycle.

Computing the optimal strategy of the analyst's perception graph comprises an investigation of all possible combinations of change levels of all actions, here 4.5×10^{15} strategies. Due to computational constraints DANA samples the strategy space instead of evaluating all possible strategies. In our case, we could evaluate a sample of 50 000 strategies and identified a total of two optimal strategies that result in maximum goal achievement and require a minimum change in all actions (Table 4). If all strategies could have been evaluated, a much larger number of optimal strategies would have been identified due to the strong equifinality, i.e. the fact that a goal may be achieved by many different combinations of change levels of actions (i.e. by many different strategies), in the case of the perception graph. Therefore, both strategies listed in Table 4 should be regarded only as two suggestions for a good risk management strategy. In both strategies, only 11 of the 26 possible actions have to be performed (strengthened) to achieve a strong decrease in the occurrence of pharmaceuticals in the water cycle: 7–8 actions among the 14 potential actions from the behavioural approach, 2–3 out of the 7 possible actions of the pharmaceutical agent approach and only 0–1 of the 3 actions of the technical approach (Table 4).

According to optimal strategy 1, to which we restrict discussion of Table 4, drinking water treatment technology should remain at the present level, which is in agreement with the perception of the drinking water supplier. Separate treatment of sewage from hospitals and nursing homes should also remain at the present level. However, domestic sewage should be treated separately in order to achieve the analyst's goal. Within the behavioural approach, the optimal strategy would include a slight intensification of a number of actions that target behaviour and awareness of medical professionals and consumers (see actions with small plus icons in Table 4). In addition, advising proper disposal on packaging and instruction leaflets of pharmaceuticals would have to be moderately extended. In the same way, the importance of preventing diseases should be strengthened through policies. With regard to actions targeting the development of sustainable pharmaceuticals, the optimal strategy from the analyst's perspective would require actions that promote research and development (Table 4). Thematic programmes with respect to pharmaceutical and organic chemistry should be implemented at universities, and specific research programmes for the development of sustainable pharmaceuticals are part of the analyst's optimal strategy. Then other actions should remain at their current level. For example, it would not be necessary to "Couple marketing authorisation and environmental risk assessment more strongly" (even though some actors favour this strategy; see Table 4).

The optimal strategies from the analyst's point of view indicate that a decrease in the occurrence of pharmaceuticals in the water cycle cannot be achieved by measures in one field of action and by single actors only. An integrative risk management strategy which combines manifold measures and addresses a large number of societal actors appears to be preferable. The optimal strategy from the analyst's view would require less effort from each actor (i.e. small changes in actions) compared to the actors' optimal strategies (compare Tables 3 and 4).

Discussion

Making the perceptions of the relevant actors more transparent to both the actors themselves and other actors, actor modelling may contribute to enhance the understanding and knowledge of actors and scientists about dynamics and cause–effect relationships in the system to be managed. Having her own perception of the problem under investigation, the analyst may increase her knowledge and change her underlying assumptions as well. The involvement of actors in the model construction fosters a participatory process and reflection on the issues. Recording actor perceptions in visual illustrations, the perception graphs may serve as basis for discussions among the actors. There are certain limitations that should be considered when using this modelling approach. It is not possible to represent stock flows, feed-back loops or "if–then" relationships (causal links that are conditional on the value of a factor) in the perception graphs. The perception graphs and thus the computed optimal strategies represent the current perceptions of the actors, which may well change in the future. These possible changes are not taken into account in the present analysis.

Eliciting the actors' perceptions by performing participatory model building with actor representatives means that no statistically representative information can be obtained. In actor modelling it is assumed that organizations and institutions (i.e. aggregated actors, e.g. collectives of individuals and not single individuals) are of particular importance, and that actors are homogeneous. For example, the pharmaceutical industry is assumed to have a uniform problem perception, while in reality, different pharmaceutical companies may have different world-views and consider different actions to be feasible, as was shown by Doerr-MacEwen and Haight (2006). However, actor representatives who were selected for the interviews were well acquainted with the prevalent problem perception of their occupational group, corporation, organisation or institution with regard to the considered issue. Indeed, the perception graphs as derived from model building and the interviews were compared with published policy documents by the actors groups and found to be consistent. Due to the explorative nature of actor modelling with DANA, the modelling results are uncertain. In order to validate the results of actor modelling, they were discussed with the experts in a workshop and the written findings were later sent to them for perusal. We found it difficult to communicate the complex results of the analysis to our experts. This is also due to the fact that DANA has been developed as a tool for policy analysts, and not as a tool for participatory processes. With respect to the analyst's perception graph in particular, it was not easy to find a balance between complexity and triviality. With respect to identifying optimal strategies, due to the equifinality among strategies, it is not possible to identify one optimal strategy for perception graphs with many actions and only one goal (like the analyst's perception graph). Besides, a high number of possible strategies and the resulting computational constraints prevented the identification of all optimal strategies from the analyst's perspective.

Doerr-MacEwen and Haight (2006) conducted a survey on the opinions of expert stakeholders from governments, academia, and the pharmaceutical and consulting industries, from Canada, the United States and Europe on possible risk management strategies for pharmaceuticals in the environment. However, in contrast to our research project, the interviewees were asked to respond to a list of strategies, whereas our participants were not acquainted with the strategy approaches developed by our project team. Yet another distinction is that no actor modelling was conducted by Doerr-MacEwen and Haight (2006). Above all, we considered a wider range of actors, including additional actors who influence the release of pharmaceuticals to the water cycle, e.g. physicians, pharmacists, wastewater treatment companies, and drinking water suppliers. According to Doerr-MacEwen and Haight (2006), advanced wastewater treatment technology, education of medical professionals to reduce over-prescription, pharmaceutical return programmes coupled with public education, and requirements for all municipalities to have a minimum of secondary wastewater treatment were seen most effective management strategies by expert stakeholders. Pharmaceutical return programmes and secondary municipal treatment were regarded as the most feasible strategies. In contrast, our actor representatives were opposed to implementing advanced technology-based strategies since all sewage receives secondary (or mostly even tertiary) treatment in Germany. The integrative strategy we suggest takes into account specific German conditions and cannot be simply transferred to other countries.

Conclusions

Our analysis shows that a successful risk management must be integrative with respect to societal actors and measures. A combination of various strategies that 1) encourage environmentally-responsible and cost-conscious behaviour of medical professionals and consumers, and 2) foster the development of environmentally-friendly pharmaceuticals will likely be most effective and realisable in reducing the occurrence of pharmaceuticals in the water cycle. Advanced drinking water and wastewater treatment (beyond tertiary treatment in the case of wastewater) is supported neither by water suppliers and sewage treatment companies nor by any other actors. Besides, we deduce from our analysis that legislation will be required to encourage actions of some actors, in particular to motivate the pharmaceutical industry to develop environmentally-friendly pharmaceuticals.

With respect to the method of actor modelling, we conclude that actor modelling is a useful method to identify effective and realisable integrative risk management strategies in complex problem fields that involve many societal actors. The construction of perception graphs by actor representatives leads to a well-structured, logical and transparent representation of the actor's problem perception that is rather unbiased by the analyst's problem perception. The perception graphs as well as the analysis results of actor modelling help to communicate the different problem perceptions among the actors and thus may support the joint identification of integrative sustainable strategies. In addition, the perception graphs provide transdisciplinary information to the analyst who then can construct her comprehensive perception graph from which an integrative strategy can also be derived. Currently, however, important influences such as power relationships among actors and changing problem perceptions are not taken into account by actor modelling.

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