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Article

Sustainable Wastewater Management: Is it Possible to Regulate Micropollution in the Future by Learning from the Past? A Policy Analysis

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Abstract: This paper applies a policy analysis approach to the question of how to effectively regulate micropollution in a sustainable manner. Micropollution is a complex policy problem characterized by a huge number and diversity of chemical substances, as well as various entry paths into the aquatic environment. It challenges traditional water quality management by calling for new technologies in wastewater treatment and behavioral changes in industry, agriculture and civil society. In light of such challenges, the question arises as to how to regulate such a complex phenomenon to ensure water quality is maintained in the future? What can we learn from past experiences in water quality regulation? To answer these questions, policy analysis strongly focuses on the design and choice of policy instruments and the mix of such measures. In this paper, we review instruments commonly used in past water quality regulation. We evaluate their ability to respond to the characteristics of a more recent water quality problem, *i.e.*, micropollution, in a sustainable way. This way, we develop a new framework that integrates both the problem dimension (*i.e.*, causes and effects of a problem) as well as the sustainability dimension (e.g., long-term, cross-sectoral and multi-level) to assess which policy instruments are best suited to regulate micropollution. We thus conclude that sustainability

criteria help to identify an appropriate instrument mix of end-of-pipe and source-directed measures to reduce aquatic micropollution.

Keywords: micropollution regulation; water quality; policy analysis; policy instruments

1. Introduction

Traditionally, water resource management has strongly relied on wastewater treatment to ensure water quality is maintained. However, the historic political approaches to managing water quality are under new pressures, such as micropollution. There are numerous micropollutants that are not vulnerable to current treatment and are therefore steadily transported into the aquatic environment. There still remains a great deal of uncertainty concerning the ability of advanced treatment technologies, such as ozonation or activated carbon, to filter micropollutants and their increased energy needs and costs.

In light of such challenges, the question arises of if such end-of-pipe solutions are a sustainable way of ensuring water quality in the future? Moreover, what can we learn from the past? To answer such questions, policy analysis provides an overview of potential policy solutions, analyzes the functioning of policy instruments and evaluates their prospects of solving the policy problem at hand. What the policy analysis literature has thus far neglected, though, is the link between policy design and sustainability criteria. The aim of this paper is therefore to examine how sustainable water quality policies for the reduction of micropollution can be designed.

The problem of micropollution has not yet been addressed in an encompassing way by either regulators on the national level, or those on the European level. With the Urban Waste Water Directive from 1991 (91/271/EEC), water quality issues have been addressed by the EU. However, its primary aim was to mitigate classical *macro*-pollution rather than *micro*-pollution. The latest EU encompassing water policy reform, the adoption of the Water Framework Directive (2000/60/EC), introduced 33 priority substances to control the chemical status of waters. The Environmental Quality Standards Directive (2008/105/EC) defined corresponding environmental quality norms and, in 2013, 12 new substances were added to the list of 33. However, there are more problematic substances than the ones defined at the EU level. For all substances not appearing on the EU lists, member states have to identify so-called water basin specific substances and define corresponding environmental quality norms. What remains fully unregulated is the question of which policy measures come into force if the quality norms are exceeded.

To demonstrate which alternatives there are to solving water quality problems, we look at policy instruments previously introduced to tackle “traditional” water quality issues (such as macro-pollution) and provide an overview of potential future policy design and solutions. In order to understand which of these policy instruments are most suited to regulating new phenomena such as micropollution, we analyze the characteristics of micropollution as a policy problem, *i.e.*, its causes and effects, as well as different sustainability dimensions (e.g., long-term, cross-sectoral and multi-level).

After an introduction to micropollution in waters, we outline a typology of policy instruments. And we present a novel theoretical framework for instrument choice, which takes into account the

characteristics of policy problems, as well as sustainability criteria. In our results we apply this framework to the case of micropollution in order to propose a sustainable instrument mix.

2. Case and Research Design

2.1. Case and Data

During the past two decades, technological progress in chemical analysis has enabled the detection of chemical substances in surface waters at very low concentration levels (ng/L to µg/L). This phenomenon is called micropollution. Micropollutants originate from different agricultural, industrial and everyday uses, such as personal care products, pharmaceuticals, or cleaning agents [1,2]. There is evidence about the negative impacts of micropollution on aquatic ecosystems, the environment and even human health [3,4]. Hence, finding a way to reduce aquatic micropollution is important and is also a political task.

Although our main argument should hold for micropollution regulation in general, for data gathering reasons, we focus our research on European and Swiss micropollution policies; and on the Rhine river basin. With 200,000 km² the Rhine catchment area is one of Europe's biggest river systems, where large-scale economic and agricultural activities, as well as population density, continue to pose great pollution threats. The Rhine basin thus provides a unique case study, not only because micropollution poses a considerable threat to its environment and humans living on its shores, but also because it has already been noted on the political agenda. This last point is relevant as it allows us to study introduced or discussed policy instruments for the reduction of aquatic micropollution. The International Commission for the Protection of the Rhine (ICPR), with its member states, Switzerland, France, Germany, Luxembourg and The Netherlands, has been addressing pollution problems since the 1960s, and is one of the first basin organizations to address the issue of micropollution.

As mentioned above, the aim here is to establish sustainable instrument designs for the regulation of micropollution. We strongly focus on micropollution as a phenomenon and identify its most relevant problem characteristics in order to conclude regarding what would be suitable and sustainable instruments to address this pollution problem. To characterize micropollution as a policy problem, we rely on an in-depth literature analysis, including environmental science literature, human- and ecotoxicological resources [5,6] (data provided by the World Health Organization). Additionally, we draw on the special reports of the International Commission for the Protection of the Rhine [7–17] and recent monitoring results for the Rhine water quality (2010 Annual Report of the International Rhine Monitoring Station in Weil am Rhein, consultation with the Department of Environmental Chemistry's (Uchem) analytical research group at the Swiss Federal Institute for Aquatic Science in 2012), which provides us with reliable information about micropollution in the Rhine catchment area [18].

2.2. Instruments for Water Quality Regulation

In environmental economics, and political and environmental sciences, there exists a panoply of different studies that address the question of policy and instrument design [19–22]. Policy design can be output oriented and defined as the selection process of policy goals and instruments to address those goals [23]. In traditional (environmental) policy analysis, there are a variety of instrument

typologies [24]. One prominent approach is to classify instruments according to the degree of state intervention or coercion [25]. Vedung [26] presents a taxonomy identifying three instrument categories: regulation, economic instruments and information. State intervention decreases from the first to the last instrument category. We acknowledge the limitation of such typologies as, in practice, some instruments can take the form of more than one category [27]. Nevertheless, this categorization is useful in order to structure the outline of instruments applied in water quality regulation.

Particularly when addressing water quality concerns, source-directed measures can be distinguished from end-of-pipe measures: while the former aim at avoiding pollution before hazardous substances enter waters, the latter focus on filtering pollution after its input into wastewater [28].

We hereafter outline policy instruments previously and commonly applied in water quality regulation and classify them into categories of source-directed *versus* end-of-pipe measures. We further attribute them to the three categories of regulation, economic instruments or information (Table 1). In the subsequent text, we then discuss in more detail those instruments that (1) were prominently applied in water quality regulation during the last decade; and (2) are difficult to clearly attribute to one instrument category or another (regulation, economic instruments and information), as they may take different forms in practice. This allows us to highlight the advantages and disadvantages of instruments, as experienced in past water quality regulation and when observing their strengths and weaknesses in implementation.

In the subsequent analysis, we will then discuss which of those instruments seem particularly suitable for micropollution regulation, taking into account the problem characteristics of micropollution (see Section 2.3), as well as the purpose of designing the instrument mix in a sustainable way (see Section 2.4).

As mentioned above, some instruments can be theoretically categorized to one instrument type, but following their design or implementation specificities, they would fit into another. Typically, best available techniques, best environmental practices and disposal requirements can take on a regulatory (command and control) character as soon as controls and sanctions are jointly introduced. However, the introduction of such control mechanisms is not adequate or feasible in all situations: in the case of requirements on the correct disposal of pharmaceuticals in households, it becomes almost impossible to set up realistic control mechanisms. Controlling every household and its respective pharmaceutical disposal habits on a regular basis would exceed administrative costs and competences.

If controls are lacking, BAT, BEP and disposal requirements are more often introduced as information measures. Information measures such as BAT can be supported by *expert advice, consulting or research*, and can take the form of *public-private partnerships* or *voluntary (negotiated) measures*. They are therefore not mandatory stand-alone instruments, but are instead of a supportive nature and are therefore indicated with italics (Table 1).

Table 1 illustrates that some instrument types and categories can only be “activated” in a source-directed, or an end-of-pipe approach. Very few instruments fit into both categories in relation to policies addressing water quality.

Table 1. Overview of regulation logics and policy instruments in water quality policy.

Logic	Instrument category	Examples of instruments	Explanation
Source-directed	Regulations		Regulations, also called “command and control” instruments, are based on strict guidelines and mandatory requirements from the state towards target groups. To ensure their effective implementation and target fulfillment, control mechanisms and sanctions have to be introduced in parallel, ensuring the prohibition or authorization of substances, procedures, and behaviors.
		Substance ban	Substance bans lead to a complete prohibition of a certain compound and thus to a cessation of pollution.
		Authorization restriction	Authorization restrictions, by contrast to substance bans, do not completely prohibit hazardous substances, but constrain their placement on the market up to a tolerated cap.
		Environmental Quality Norm (EQN), Emission limit	Emission limits and EQN define a mandatory cap on the acceptable amount of a concrete substance in waters. While limits control emissions from specific polluters, EQN regulate imissions in water. Both instruments “theoretically” follow a source-directed approach, but they are primarily introduced for their signaling effect. That is why they often take, at least in implementation, the form of information measures. When emission limits and EQN are exceeded, it is a signal to the regulator that further policy action, such as end-of-pipe measures (to remove pollution) or restrictive instruments (e.g., bans), is necessary. The Water Framework Directive, for instance, largely relies on EQN to control the chemical status of member states’ waters.
	Economic instruments		Economic instruments are based on market mechanisms. The idea is that through a change in price, target groups will adjust their behavior and emit fewer pollutants.
		Product or Substance charge	A charge is levied on substances or on final products that contain hazardous compounds in order to provide an incentive to reduce the use or consumption of a substance.
		Subsidy for behavioral change	Subsidies reward "green" action. They provide for governmental support in return for environmental commitments by the private sector. Hence, subsidies can promote environmentally friendly behavior. Farmers, for instance, could benefit from subsidies in return for applying no or less plant protection products.
	Information		Information consists of a transfer of knowledge or persuasive reasoning [26]. Their effectiveness is dependent on how the target group perceives the relevance, evidence or urgency of the communicated information.
		Best environmental practice (BEP)	BEP refers to defining codes of conduct [29] (p. 137). Most commonly, BEP are applied to the correct application of pesticides in order to reduce run-off from agricultural fields.
		Disposal requirement	Disposal requirements formulate codes of correct waste disposal. They can, for instance, be directed towards households to ensure that chemical waste, such as paint residues or pharmaceuticals, is not discharged through the toilet [8,11].
Information campaign		Information campaigns deliver insights to consumers, farmers or firms about how to avoid aquatic pollution and, thus, encourage voluntary action.	

Table 1. Cont.

Logic	Instrument category	Examples of instruments	Explanation
End-of-pipe	Regulations	Mandatory best available technique (BAT) or other form of compulsory technical standard	With a BAT the regulator defines a technical standard. A mandatory BAT obliges operators of sewage plants to adapt their technical standard to the one defined by the regulator. If a sewage plant does not comply with the BAT, operators must upgrade their plants with a further treatment step. Examples of advanced technical solutions for wastewater treatment, which can filter very small concentrations of pollutants, include ozonation, activated carbon treatment and membrane filtering [30,31].
	Economic instruments	Subsidy (for improved wastewater treatment)	Where the cost of taking remedial action is too high for individual firms or households, governmental support can help reduce aquatic pollution. Governmental support in the form of a subsidy can be allocated to sewage plants to encourage investments in advanced treatment technology. Commonly, governmental support is granted to research in order to develop innovative solutions.
		Effluent/emission charge	An effluent charge is paid by those who discharge (treated) wastewater into streams. This way, an effluent charge puts a price on using the environment as a sink [29] (p. 134).
		<i>Advice, consulting about BAT</i>	Instead of defining a mandatory BAT, the regulator often defines EQN or emission limits and leaves it to the operator of a sewage plant to decide about the filtering technology. To support operators, the regulator can provide information, advice and consultancy about BATs.
		<i>Research</i>	In the case of micropollution, research is needed to develop new wastewater technologies able to filter very small concentrations of diverse substances.
	Information	<i>Voluntary negotiated measures</i>	Voluntary measures are neither required by law nor encouraged by financial incentives [32] (p. 329). Voluntary measures include investments in treatment technology by the private sector without additional financial support from the government.
		<i>Public-private partnership (PPP)</i>	Private-public partnerships (PPP) are non-legally binding treaties negotiated on a case-by-case basis between single firms and a public authority. A PPP can follow an end-of-pipe approach when the negotiated agreement between a firm and a public authority fixes emission charges or improved wastewater treatment.

Abbreviations: EQN = Environmental Quality Norm, BEP = Best Environmental Practice, BAT = Best Available Technique Technique, PPP = Private Public Partnership.

Dark grey = regulations, medium grey = economic instruments, light grey = information.

2.3. Problem Characteristics and Policy Instrument Choice

In policy analysis, a large number of researchers and schools of thought prominently focus on so-called policy process variables (such as power distribution, coalitions among actors, stages of the policy process) to explain why a certain instrument is chosen over another in order to tackle a particular environmental or societal problem [33–35]. Peters and Hoornbeek [36] go one step back and argue that, first of all, the environmental or societal problem's characteristics should be identified as an antecedent step in order to limit the available options to a reduced number of policy instruments most suited to addressing the problem at stake (see also [37]). Alternatively: the nature of the problem itself should be the major driver of what determines the choice of suitable policy instruments. They attribute seven characteristics to policy problems, which they call complexity, scales, scope, solubility, divisibility, monetarization and interdependencies. As argued in earlier works [28], not all seven characteristics are “problem”-related, and some of them instead concern the political decision-making process rather than the problem under investigation. As Rittel and Weber have claimed in their article on wicked problems [38], “one of the most intractable problems is that of defining problems [...]”. There is thus subjectivity about the definition of problems and, clearly, problems can always be attributed to a diversity of causes. Nonetheless, these difficulties cannot lead us to ceasing to try to understand the root causes of policy problems. It can only be understood as a warning to reject any overly simplistic view and instead approach policy problems comprehensively, as is attempted here.

Our aim is to identify policy instruments that tackle the phenomenon of micropollution (rather than those which simply pass the political decision-making process). We therefore focus our analysis on the four problem characteristics presented hereafter:

- **Causation:** The idea of “causation” as a problem characteristic is that policy problems can be attributed to actors or factors causing the problem, based on scientific proof. For the choice of appropriate policy instruments, it makes a difference if a problem is due to single or multiple causes, and whether the problem is anthropogenic or naturally occurring.
- **Prevalence:** Prevalence is about analyzing the magnitude and number of factors contributing to the creation of the problem, including whether the source of the problem is seasonal, all-year-long, local or global [36] (pp. 96–98).
- **Effects:** Policy problems are diverse in terms of their effects or impacts. The idea is to analyze in detail what is being negatively impacted by a policy problem, which can be as diverse as the environment, humans, the economy, diplomatic relations between countries, and security or peace.
- **Scales:** Policy problems differ with regard to the scale at which the effects happen. They can produce effects from local, regional, and national levels to an international scale. Depending on the scale, solutions should be introduced by different jurisdictions and affect target groups of different (smaller- or bigger-scale) areas.

2.4. Sustainability Dimensions and Instrument Choice in Water Quality Regulation

Instrument design should fulfill various criteria or conditions [22]. One such condition can be that instrument choice should guarantee the sustainable management of the policy problem at stake [39].

Sustainable policy design in environmental and water quality regulation means and the dimensions taken into account will be outlined hereafter.

In the very early definitions of sustainable development [40], there are two major dimensions of sustainability that seem particularly relevant for natural resource management: first, the *integrative approach*, linking environmental protection to economic and civil societal concerns; and second, the *long-term and inter-generational* perspective, providing the same stock and quality of resources to future generations. These integrative and long-term approaches were confirmed and defined during the 2002 World Summit on Sustainable Development, and formulated specifically for the water resource. More concretely, the notion of Integrated Water Resources Management (IWRM) was introduced to ensure a sustainable and holistic approach for the regulation of this vital resource. IWRM was defined as “a process which promotes the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” [41].

How do those definitions of sustainability and integrated management apply for instrument design and choice in water quality regulation? Four sustainability dimensions can be deduced and retained for the following analysis.

- **Horizontal and cross-sectoral integration:** The integrative approach linking the environment, the economy and civil society concretely calls for coordination among different public and private sectors. This also applies to the design of appropriate instruments to regulate water quality: a sustainable instrument choice for water quality regulation should also have a horizontal character integrating political decision-making and implementation, and a variety of actors and target groups that represent different concerned sectors (such as industry, agriculture, health issues, climate change or biodiversity). Such cross-sectoral integration should therefore guarantee that instruments introduced in one domain do not harm or contradict policy goals in another domain. Ideally, synergies between different sectors could emerge through the integration of private and public actors acting in different political subsystems.
- **Vertical and multi-level integration:** Similar to horizontal integration, water quality issues also call for a vertical involvement: water problems emerge from the local and regional level to the (inter)national level. Most water bodies do not stop at pre-defined political borders. As such, sustainable instrument design should also guarantee the trans-boundary management of the water resource [42] where different actors representing various jurisdictions and decisional levels are integrated.
- **Science-policy interface:** Many uncertainties still exist about the consequences of the excessive use of natural resources and the impact of pollution on humans and the environment [43]. The sustainable management of resources thus also depends on the elaboration of the science-policy interface. By enlarging this interface, knowledge can be transferred from academia into the policy making process [44]. This not only holds true for the understanding of the phenomenon (like climate change or micropollution) at stake, but also for an appropriate instrument design. Sustainable instrument choice benefits from enhanced evidence- and expertise-based policymaking [39].
- **Long-term and inter-generational:** The long-term design of instruments to regulate water quality constitutes a challenge. Policy actors try to maximize flexibility and short-term solutions

because of their re-electoral calculus [37]. However, instrument choice should have a long-term goal and should still be adaptable to changes, in order to guarantee that future generations still benefit from intact water quality.

3. Results and Discussion

The four presented characteristics of policy problems will be discussed here—one after the other—applied to the phenomenon of micropollution, with a special focus on the Rhine catchment area (for a more detailed analysis, see [28]). In the end, we provide a sustainability assessment, thereby evaluating how the instrument designed to regulate micropollution might look, taking into account problem characteristics *and* sustainability dimensions.

3.1. Causation

Similar to the already well-studied phenomenon of climate change and global warming, micropollution can be defined as a synthetic problem *or* a naturally occurring problem. While the naturally occurring problem often happens at a scale and to an extent and frequency where harm to humans and the environment are not severe, human-induced changes (such as climate change or micropollution) exceed an acceptable frequency and extent. Anthropogenic and synthetic pollution remains in the foreground of political regulation. In Europe, there are about 100,000 synthetic substances in use. Every year 1000 new chemicals enter the market [45,46] (p. 38). The broad range of uses includes: pharmaceuticals (both human and veterinary), hormones, medical imaging contrast agents, plant protection products (pesticides, herbicides, insecticides), detergents or other cleaning agents, personal care products (cosmetics, personal hygiene), industrial chemicals (plasticizers, solvents, dyes, lubricants, *etc.*) and metabolites, many of which may be as dangerous as the parent compound.

Entry paths to the environment are via diffuse or point-source pollution. Diffuse refers to surface runoff from agricultural fields, urban areas or roads because of rain. Point-source pollution originates from wastewater treatment plants. Despite the high standards of wastewater infrastructures, numerous micropollutants cannot yet be filtered and therefore steadily enter surface water [47].

Policy instruments and multiple entry paths: Wastewater treatment as an *end-of-pipe measure* is effective in removing microcontaminants stemming from those sources discharging into wastewater collection. Since sewage treatment can be effective in remedying damage from diverse sources of wastewaters, it is the most common solution to water quality issues. However, upgrading sewage plants creates additional costs and technical challenges: first, it can increase the demand for energy in wastewater treatment. Second, some treatment technologies (*i.e.*, ozonation) could lead to by-products, which are just as toxic as the parent compound. It is thus not clear if effluent toxicity would be reduced [31]. Third, new technologies and procedures in sewage treatment increase costs and call for greater investment. To realize this aim, means of financing have yet to be found.

In the case of diffuse pollution, wastewater treatment and end-of-pipe strategies reach their limits. The geographical dispersion of diffuse pollution makes *source-directed strategies* generally more effective and preferable [29] (p. 130). To complement these strategies, it can be reasonable to define *environmental quality norms* to control concentration levels of diffuse pollution in waters.

Policy instruments and multiple pollution sources: As outlined above, depending on the pathway into the environment, end-of-pipe solutions can fail to effectively and efficiently guarantee water quality. Thus, differentiated policy responses appear to be adequate depending on the source of the pollution. So the question arises as to which policy instruments are suited to reduce micropollution stemming from *diverse origins*.

Where agriculture is the source of the pollution, source-directed and behavioral measures seem to be most suitable. Agricultural emissions can be contained at the source by *product charges* on plant protection products. Product charges have the advantage that they respect the polluter pays principle, because those who use fewer plant protection products pay fewer charges. Another policy instrument adapted to reduce the use of chemicals in agriculture is the definition of obligatory *best environmental practices*. When micropollution can be attributed to a defined agricultural management practice, *consulting* farmers about more environmentally-benign practices can be an effective instrument, as well as *subsidizing* those management practices to compensate for higher costs.

Source-directed and behavioral measures also seem to be appropriate for those micropollutants that enter the water cycle through households. Where households and their consumption of care products or detergents are the emission source, a *product charge* can reduce consumption and thus the input into wastewater of micropollutants. Additionally, *information campaigns* can be a good tool to appeal to peoples' morality and induce voluntary action, such as reducing consumption of hazardous products. Whenever the input of micropollutants can be attributed to incorrect waste disposal, it is necessary to regulate such activities with *disposal requirements*. One such example are pharmaceuticals in wastewater that seem to originate (among other origins) from households that discharge their old pharmaceuticals through the toilet [11].

As demonstrated above, there are effective and efficient source-directed measures to reduce micropollution from agriculture and households. In the case of industrial micropollution, end-of-pipe measures seem to be most suitable. More concretely, micropollutants arising from industrial manufacturing processes can be reduced by *emission charges*. When the charge is levied on effluents, firms have an incentive to invest in filtering technology or optimize their production processes to reduce the amount of emissions or chemicals used. Charges, however, do not guarantee that emissions are restricted to a defined cap. To do so, *binding emission limits* could be an appropriate solution, although one has to keep in mind that as a result of implementation problems (e.g., resource demanding controls), such regulatory instruments can also fail to reach the defined limit or cap. Since reducing discharges or optimizing production processes is often a resource-demanding task for the industry, the regulator can provide *expert advice* about reduction measures. Where industrial hazardous waste is the source of the pollution, *disposal requirements* can work well when firms are required to deliver proof of compliance. A further *end-of-pipe way* of regulating industrial emissions is the definition of *best available techniques* in order to improve wastewater treatment. The regulator can promote investments in advanced sewage treatment technology with *subsidies*. Less constraining to the industry is the reliance on *voluntary (negotiated) measures or private-public-partnerships* between a governmental body and an industrial company.

Sustainability dimension: The analysis above has outlined that micropollution is caused by a variety of actors and factors emerging in various sectors and branches of society such as industry, agriculture and households. It "activates" the horizontal and cross-sectoral sustainability dimension: only when

coordinating the introduction of the above mentioned suitable instruments across the mentioned sectors and policy fields would one be able to reduce dysfunctional interplays among measures that counteract each other's effect.

3.2. Prevalence

To reflect on the magnitude, frequency or prevalence of the factors causing micropollution, we elaborate on domestic, agricultural and industrial emission sources of micropollution in the Rhine river basin. In 2004, the European Water Framework Directive (WFD) mandated a large-scale inventory of the Rhine river basin. Results concluded that the chemical status of the Rhine was not sound in 88% of the water body, and various micropollutants were widespread and exceeded threshold values [48].

Concentrating on domestic emissions, the high consumption volumes of pharmaceuticals in very densely populated urban areas contributes to the high concentration levels of micropollutants in the Rhine catchment area. These results are not surprising: over 3000 different pharmaceuticals are legally in use in the European Union; 30,000 tons are consumed every year in Germany alone [5,11]. Swiss use of the top forty products is, on average, 100 mg per person, per day. Dutch pharmaceutical consumption is predicted to rise 20% by 2020 and, in general, trends suggest increased Rhine area consumption in the future, with more drugs being used by more people, especially given the aging of the populations. Of the four most popularly consumed drugs that are routinely monitored, bezafibrate, sulfamethoxazole, carbamazepine and diclofenac, the latter two have been detected at comparatively higher concentrations [49].

In the case of estrogens and antibiotics, intensive livestock-raising in the agricultural lands along the Rhine is another source of pharmaceutical micropollution. Dutch emissions of estrogens are an estimated 17,000 kg/year, more than ten times the total hormone contamination from human consumption [13].

Even more significant is the contribution of the Rhine agricultural industry to micropollution through its use of plant protection products. 52,100 tons of organic pesticides, equating to more than 500 different active substances, were used in France in 2009 [50]. In 2000, the nation used 5033 tons of phenylurea herbicides, including chlortoluron, one of the most popular herbicides due to its long half-life in soil (30–40 days). Unfortunately, this property also translates into a long half-life in water, more than 200 days. Herbicides remain one of the most important groups of plant protection products in the Rhine basin, used in great quantities on agricultural land and, as a result, appearing often in surface water [48].

The Rhine basin contains the greatest density of industrial plants on its shores of all the major international river basins. There are six main industrial centers distributed along the course of the Rhine from Switzerland to the Netherlands and, as such, concentrations of persistent industrial chemicals only increase as one travels down the river: Basel is famous for its medicinal chemical manufacturing sector and, along with neighboring Mulhouse and Freiburg, is host to leading corporations of agro-chemicals, the food industry, textiles, metals, nanotechnology, biotechnology, materials, construction, and personal care products. Strasbourg is known for textiles, food and metals. The Rhine-Neckar area, consisting of the cities of Karlsruhe, Heidelberg, Mannheim, and Ludwigshafen, well represents the chemical industry. Frankfurt-Rhine-Main produces chemicals,

rubber, electrical materials and metals. Cologne, Düsseldorf, and Duisburg in the Rhine-Ruhr region are famous for petrochemicals, refineries, metals and automobile production. Finally, plants in Rotterdam-Europort produce chemicals, automobiles and metals; and refineries operate there as well.

Moreover, micropollution is not only a matter of geographical spread, but also of *seasonality*. Usage in society affects pollutants' input dynamics [1]. Cleaning agents and pharmaceuticals, for example, are continuously used and produced throughout the year and wastewater treatment effluents are constantly being dumped into surface water. Plant protection products, by contrast, have time-sensitive dynamics. They are applied seasonally and are more prone to sudden run-off from changing weather patterns or due to spills and improper disposal.

Policy instruments and omnipresence of causes: The above outlined population dynamics and agricultural or industrial activities in the Rhine catchment show that causes of micropollution are omnipresent and deep-seated in the riparian societies. A complete elimination of the causes of micropollution is thus an enormous challenge. Prioritization can help us to focus on the most common and most dangerous substances or on the main sources of pollution.

One way of carrying out such a prioritization is through the use of *regulatory measures*. Regulatory measures that are jointly introduced with monitoring and control mechanisms, such as *environmental quality norms*, are an appropriate policy instrument used to gain information about concentration levels of micropollutants and, thus, to define priorities. EQNs seem to be most appropriate for indicator substances, where one compound is a proxy for pollution by a whole substance group or jointly consumed compounds. *Emission limits* can provide a suitable way of controlling the amount of emissions from agricultural or industrial point sources.

Policy instruments and seasonality: Where concentration levels of micropollution seasonally reach peak concentrations, *best environmental practices* can incorporate time-sensitive dynamics by formulating codes of conduct depending on weather patterns or the season.

Sustainability dimension: Besides the variety of factors that contribute to the emergence of micropollution, here we have learnt that there is significant variability about when and how long micropollution occurs as a problem. If its emergence can be punctual, seasonal, or even steady; its effects in waters can be persistent. This calls for a *long-term* and flexible regulation of micropollution. Sustainable instrument design should thus exceed short-term electoral periods or policy cycles and should envision water quality standards that will also be acceptable for future generations.

3.3. Effect

The label “micropollutant” already suggests that the negative effects are aquatic pollution in small concentrations. However, because of enduring uncertainties regarding the ecotoxicology and human toxicity of aquatic micropollutants, policy makers still have difficulty in deciding whether or not to take policy action.

In the 1990s, UK scientists published findings about the “feminization of fish” that had been exposed to wastewater effluents. The team was able to prove that the hormone system was affected by a synthetic estrogen typically found in contraceptive pills [51]. The alarming results of the effects on fish populations have helped to identify pharmaceuticals as one of the primary groups of emerging (micro)pollutants.

There still remains a great deal of uncertainty regarding these contaminants, and quantitative studies completed to date have found no appreciable adverse effects on human health due to trace amounts of pharmaceuticals consumed in fish or drinking water, or due to exposure in aquatic environments [4,52–54]. Exposure assessment has demonstrated that many pharmaceuticals have observed environmental concentrations significantly below their lowest observed effect concentration (LOEC) [55]. However, there are several notable exceptions for which wastewater effluent concentrations show similar levels to chronic toxicity: 17 α -ethinylestradiol, diclofenac, and carbamazepine [55]. In general, and even if a given substance is at a concentration too low to be harmful, when mixed in water with other chemicals, the combined effect can be devastating. In most of the case studies examined by Kortenkamp *et al.* [56], mixtures of pharmaceuticals contained a joint toxicity greater than individual toxicities.

Let us illustrate the negative effects of micropollutants by borrowing two examples, one from agriculture, and the other from industry: two herbicides widely applied in agriculture are isoproturon and chlortoluron. By design, herbicides are manufactured to inflict harm on living organisms. Even though there is little data on their effects on humans [57,58], it is not surprising that they negatively affect algae populations in aquatic environments by suppressing the growth of algae, which, in turn, can damage the entire ecosystem [48,59].

Diglyme is an industrial chemical solvent typically used to manufacture semiconductor chips (electronics), adhesives, paints and sealants. Occupational exposure studies of female workers in semiconductor factories show an elevated risk for spontaneous abortions and subfertility defined as requiring more than one year of intercourse to conceive [60]. From these studies it can be concluded that diglyme can have significant negative endocrine and fertility effects on humans.

Policy instruments and toxicity risks: In the face of the above illustrated knowledge gaps, political decisions are taken under uncertainty and are only justified based on the precautionary and preventive principles.

However, for those substances that pose a significant toxicity risk to humans or the aquatic ecosystem, *substance bans or authorization restrictions* may be an effective way to reduce, or even eliminate, particularly hazardous micropollutants. Prohibiting substances is an appropriate tool, when there exist substitutes less toxic than the parent compounds. In general, and where uncertainties about effects remain, enhanced *research programs and projects* would provide further knowledge to facilitate future instrument choice.

Sustainability dimension: There are still significant uncertainties about the impact of micropollution on humans or ecosystems. Benefitting from the *science-policy interface*, and therefore institutionalizing evidence-based decision-making could improve knowledge transfer and expertise from the scientific to the political sphere. In turn, this could help to steadily reduce uncertainties regarding micropollutants' impacts and effects, and thus inform effective and efficient instrument design.

3.4. Scale

Some micropollutants resist natural decomposition and therefore remain in their original form in aquatic systems for a long time, sometimes posing problems hundreds or thousands of kilometers from the contaminant source [2]. Compounds can also be of great concern to living organisms if they are

bioaccumulating—incorporated into living tissue—thus remaining in the organism and being found in progressively greater amounts further up the food chain.

Policy instruments and persistence/bioaccumulation: Where hazardous compounds are persistent throughout an entire waterway, there is the need for a basin-wide commitment to act and coordinate regulatory measures amongst the entire Rhine community. Thus, a large-scale policy solution, *i.e.*, internationally coordinated *substance bans or restrictions*, is needed for persistent substances.

Certain substances, by contrast, are only present in specific parts of the water body because of their exclusive appearance in local agriculture; because of their use in specific industrial branches; or because of particular consumer behavior in some urban areas. In these cases, targeted measures have to be adapted to the regional specificities, and *smaller-scale solutions* or *voluntary negotiated measures* (often taking the form of public-private partnerships) can be more proportional to the extent of the policy problem.

Sustainability dimension: The description of scales has shown that micropollution is a multi-level phenomenon that transcends the local and regional level, to the national and international level. Concerned parties thus represent different decisional levels or jurisdictions. Consequently, a sustainable way of regulating micropollution should respect the *dimension of vertical actors' integration*.

3.5. Synthesis and Sustainability Assessment

In Table 2, results from the presented analysis are summarized. First of all, it becomes clear that micropollution is a cross-sectoral phenomenon. It is caused by society and the economy. Hence, it not only negatively affects the environment, but also society. Consequently, instrument design and choice has to take into account sector specificities and the diversity of actors (such as polluters, target groups and those negatively affected). Or, said differently: to follow the sustainability principle of horizontal and cross-sectoral integration, cross-cutting solutions are needed that overcome fragmentation into separated policy fields. In fact, micropollution calls for a broad response integrating water policy, as well as agriculture, industry, chemical, health, consumer and work safety regulations. This means that only an instrument mix, rather than single policy measures, can take this diversity into account. Causation thus “activates” the cross-sectoral sustainability dimension the most and calls for collaboration between diverse policy fields (see Table 2).

If we disentangle this a little bit more, it seems clear that the diffuse entry paths of micropollutants ask for a source-directed, rather than an end-of-pipe, logic regarding micropollution regulation. Market-based instruments and information seem to be the suitable measures for reducing pollution at the source; whereas end-of-pipe measures, such as the upgrading of treatment plants through best available techniques or other forms of technical standards, are appropriate for managing point sources coming from urban and industrial areas.

By contrast, the persistence, omnipresence and toxicity risks call for more regulative instruments and increased state intervention. The persistence of substances in waters directly relates to the *long-term* perspective that should be adopted in instrument design when regulating micropollution; whereas uncertain effects call for a reinforcement of the *science-policy interface*.

Table 2. Instrument Design for micropollution regulation taking problem characteristics and sustainability dimensions into account.

Sustainability dimension	Problem characteristics	Characteristics of micropollution	Appropriate source-directed policy instruments	Appropriate end-of-pipe policy instruments
<i>Horizontal and cross-sectoral integration</i>	<i>Causation/ multiple entry paths</i>	Diffuse	Source-directed measures, EQN	
		Point/Wastewater treatment plants		End-of-pipe measures
	<i>Causation/ multiple sources</i>	Agricultural discharges	Product charge, BEP, Consulting, Subsidy	
		Household discharges (from cosmetics, detergents, pharmaceuticals)	Product charge, Information campaigns, Disposal requirements	
		Industrial discharges		Emission charge, Emission limit, Consulting (expert advice), Disposal requirements, BAT, Subsidy, Voluntary negotiated measures, PPP
<i>Long-term and inter-generational perspective</i>	<i>Prevalence</i>	Omnipresence of causes	EQN, Emission limits	
		Seasonality	BEP	
<i>Science-policy interface</i>	<i>Effect</i>	Toxicity risk	Substance bans, Authorization restrictions	
		Uncertainties about effects	Research	
<i>Vertical and multi-level integration</i>	<i>Scales</i>	Persistence, bioaccumulation	Internationally coordinated substance bans, Authorization restrictions; On smaller scale: voluntary negotiated measures, PPP	

Abbreviations: EQN = Environmental Quality Norm, BEP = Best Environmental Practice, BAT = Best Available Technique, PPP = Private Public Partnership.

Finally, the question of scale reflects the *multi-level* governance aspect of micropollution, where a one-size-fits-all sort of solution does not exist. Instead, policy measures can benefit from greater acceptance if they take into account the needs and constraints of actors at different spatial scales [61]. This way, policies can be designed that are proportional to the scale of the problem, which means acting on different political levels and adopting different policy instruments on different levels. Only a multi-level design of instruments can guarantee a sustainable management of micropollution.

4. Conclusions

The aim of this research was to investigate which kind of instruments would guarantee the most sustainable micropollution management. We relied on policy instruments commonly applied in water quality regulation. We then evaluated each policy instrument of the conventional canon of pollution control tools; first, in light of the specific problem characteristics of micropollution (what instrument is able to tackle problem specificities, such as causation, prevalence, effect and scales?); and second, by taking four sustainability dimensions into account (cross-sectoral, long-term, science-policy interface and multi-level). The result of this analysis is an integrative framework relating micropollution problem characteristics to the mentioned four sustainability dimensions. More concretely, we can conclude that the variety of causes and scales calls for a horizontal and vertical instrument design, where concerned actors representing various sectors and decisional levels are integrated and involved in policy decision-making and implementation. Furthermore, the omnipresence and seasonality of micropollution requires long-term and flexible planning when introducing and adapting policy instruments to regulate this water quality problem. Finally, as many uncertainties about the impacts and effects of micropollutants still exist, instrument choice should be informed by the science-policy interface, where reflexive learning mechanisms between experts and policy-makers can be institutionalized.

We further confirm that only an extensive mix of policy instruments can tackle the complexity of the micropollution phenomenon. For addressing this particular water pollution problem, we suggest going beyond wastewater treatment and end-of-pipe measures. Notably, Switzerland in its last revision of the Water Act (SR 814.20) confirmed a focus on such end-of-pipe measures in micropollution regulation via the systematic upgrading of the 100 largest treatment plants. However, this analysis has shown that there is a need to design a complementary instrument mix that includes technical solutions *and* source-directed policy instruments in order to reduce the use of micropollutants before they enter waters. However, the introduction of source-directed measures in the past has shown that they go hand in hand with behavioral changes of target-groups, which makes their introduction a challenging task. Target groups may wish to keep costs low and flexibility in actions high [37].

Breaking the problem into smaller parts would be one way of allowing targeted responses and increasing acceptability by the target group. To do so, horizontal coordination among different policy fields is needed. Furthermore, and similar to the majority of water pollution problems, micropollution does not stop at national borders. Consequently, efficient and effective instrument choices can only achieve their goals if they are designed in an international and trans-boundary context.

This study has shown that complex issues and phenomena call for complex solutions. Rather than a one-size-fits-all sort of solution, a cross-cutting policy mix addressing both the source of the problem

and the end-of-the pipe guarantees an integrated and sustainable policy response. Clearly, the more solutions and policy measures that are introduced, the more complex the coordination of their implementation, the potential set-up of control and sanction mechanisms, and the evaluation of their effects. However, former experiences with previously introduced policy instruments in water quality regulation can help to guide instrument choice to enhance the sustainable management of current and future water quality problems such as micropollution.

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Author Contributions

Florence Metz conducted the data collection and document analysis for this research. She worked out the theoretical and empirical basics to analyze policy problem characteristics. Karin Ingold wrote the first draft and developed the integrated framework presented in this manuscript relating policy problem characteristics to sustainability dimensions. Both authors discussed the structure and commented on the manuscript at all stages.

Conflicts of Interest

The authors declare no conflict of interest.

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