Understanding the Co-Evolution of Research and Water Protection Policies: From Single Technologies to Systemic Integrated Approaches for the Sustainable Use of Water

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Abstract Over the last 50 years, water research has been strongly driven by the poor condition of water bodies underpinned by growing environmental awareness in society. This was characterised by interactions between the state of the environment, policy making and water research. Three phases can be distinguished: In the first phase (1970s and 1980s), the focus of activities in the establishment of environmental policy was on improving the precarious state of the environment in the water sector (first phase "establishment"). From 1990s to around 2010, further environmental pressures and new findings on the causes and changed framework conditions led to a need for further action. The interactions with other issues and a systemic perspective gained in importance (second phase "expansion"). In the years since 2010, the pressure to act has increased once again, particularly due to climate change. The need for systemic change is becoming increasingly clear (third phase "transformation"). The development is also characterised by an internal dynamic that is constantly increasing the scope and complexity of water research. The focus has shifted from individual technologies to systemic solutions. The need for transformation in the water sector is reflected, for example, in the national water strategy.

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1 Background/Objective

The field of water research is very broad. It encompasses many areas, which show no obvious relation to innovation research, such as basic natural-science related research on the fundamentals of the natural water system. However, our chapter focuses on water research which is clearly linked to innovation issues, in particular research which deals with the specific segments of water systems as part of the built environment. This segment is key for determining the interaction between the socio-economic system and the natural water system. From the perspective of the socio-economic system, water resources provide input for production and consumption in form of water supply. But water bodies also have the function of absorbing output from the socio-economic system in the form of wastewater and inflows from agricultural land and soil surfaces. A sustainable use of water requires that there is no overuse of both functions, which would lead to a deterioration of the natural system. The last 50 years, however, have been characterised by the fact that these functions were being increasingly challenged. For the water systems there are three dimensions to the challenges in particular: (a) water quality problems due to emissions from the socio-economic system into the water bodies; (b) overuse of water resources; (c) problems in management of storm water caused by the increased sealing of soil surfaces and changing precipitation patterns.

The water sector is peculiar in that it is subject to a triple regulatory challenge for innovation: The first challenge relates to the external benefits of R&D and requires regulation to deal with the protection of intellectual property rights and the incentives for research. This challenge is the same in all other innovation domains. The second challenge arises from the external nature of environmental pollution, which is key to the challenges arising for water systems. It follows from this second challenge that the demand for water innovations crucially depends on regulation and environmental policy (Rennings 2000). The third regulatory challenge arises from the economic nature of (public) water supply and wastewater treatment systems as monopolistic bottlenecks, which require economic regulation. These economic regulations also have specific effects on the demand for innovation in regulated areas (Walz 2007). Demand, however, is an important factor for innovation activities, which is interacting with the supply side of innovations (Edler 2016). Thus, our chapter is also of particular interest as a case study on the interaction of pressure to act, research and regulation in an innovation system which is subject to this triple regulatory challenge.

Our chapter deals with two research questions. First, we want to analyse how the pressure to act interacts with innovation-related water research and regulation or policies. Second, we want to find out more about the logic of the long-term development of research and innovation in the water sector. The underlying analysis focuses on the national development in Germany. Cross-connections, especially with developments at the EU level, are taken into account. For both research questions, we start with the following hypotheses.

Our first hypothesis states that the interplay between the pressure to act, which is triggered by the state of the environment, the knowledge gained through research work and the identification and implementation of regulation and policies, contributed in Germany to the emergence of three different phases. These three phases can be summarised as follows:

- Particularly in the 1970s, but also to some extent in the 1980s, the focus of activities in the context of establishing environmental policy was on improving the precarious state of the environment in the water sector. Major causes of a large proportion of environmental pollution were obvious, so that measures could be directly derived and implemented (First Phase "establishment").
- In the subsequent phase (1990s to approx. 2010) further environmental pressures, new findings on the causes and the strongly changing framework conditions led to an additional need for action. The measures resulting from this pressure highlighted the need for a systemic perspective that took into account the intensive interactions with other thematic fields and areas of action (Second Phase "expansion").
- In the years since 2010, the pressure to act has intensified once again, also, and especially against the backdrop of the climate change impacts that are now becoming increasingly clear. The need for comprehensive, systemic changes in the water sector is now becoming widely accepted (Third Phase "transformation").

The hypothesis for the second research question states that starting from the approaches which addressed the need to act in the 1970s with the initial strong problem-oriented focus on technologies and regulations, water policy has evolved into more integrated approaches. This is consistently increasing the complexity of the underlying innovation system by integrating more actors and more perspectives. Initially, the approach was very much motivated by the precarious state of the aquatic environment and the search for technical solutions. However, with increasing insights into the complexity of water management, the role of water research and a systemic approach based on it increased as a basis for the formulation and implementation of environmental policy measures.

In order to tackle the research questions, the connections between the development of the environmental states in the area of water, water policy and water research are shown and explained in more detail for each of these three phases. Due to the complexity of the water sector, it is not possible to provide a fully comprehensive view. Instead, specific lines of development are selected as examples that are of particular importance and representative of the water sector in terms of the changes that have taken place.

The chapter is structured chronologically through the decades. The three phases are analysed in three sections. The individual sections are subdivided according to the following aspects: (a) pressure to act; (b) concrete important changes in research activities, which are related to the change in the phase; (c) important implemented measures and regulations. The chapter concludes with a discussion and an outlook, with regard to our two research questions: (a) logic of interaction between pressure

to act, innovation-related water research, and policies; (b) logic of change in research over time. In order to support our line of argument with empirical data on development of research, we analysed databanks which show information of the projects funded in Germany. To back up our arguments, we also looked at the development of innovation indicators such as publications and patents in order to figure out, how our specific research topics linked to sustainable use of water developed within the overall broad topic of water research.

2 Phase 1: Establishing Water as Key Issue in Environmental Policy

2.1 Pressure to Act

In 1971, the first environmental programme of the federal government was adopted. It included fundamental aspects such as the "polluter pays" and the precautionary principle as well as the topic of water as seen from various facets. The catastrophic condition of the water bodies was reflected in very high levels of organic matter and nutrient concentrations in the water bodies. Improving water quality by reducing these loads was seen as a key imperative (Sachverständigenrat für Umweltfragen (SRU) 1974), and the pressure to act increased quite substantially in terms of the need for wastewater treatment. The first environmental programme therefore called for a cleaning up of the German water bodies by 1985 (BMI 1971). Various activities started in subsequent years—both in the field of research and with regard to the establishment of the legal and institutional framework, such as the founding of the German Environment Agency in 1974.

2.2 Important Research Activities

In the 1970s, research activities in the field of water were greatly intensified. This was reflected in the increase in research projects and funding in the early 1970s. Various funding institutions were active (Eberle 1978) with different focuses (cf. Merkel and Reiff 1983; Bauer 1977; Eberle 1978):

- the federal government, primarily through the then BMFT as well as the BMI, which was responsible for environmental affairs prior to establishment of the BMU;
- the federal states, which are responsible for supporting the construction of sewage treatment plants, with funding of very specific application-oriented research,
- more academic-oriented research funded by the DFG and institutional university funds,
- projects and institutes supported by the water supply companies themselves.

The diversity of institutions active in the field of water research, which developed in Germany in the first phase, has remained a special characteristic in this country until the present day (see Fig. 1). The most important funding agency over time has been the BMBF, which funded larger research projects in particular compared to the numerous research projects of the Bundesländer, which typically have been rather small.

The research projects in this first phase focused primarily on technical approaches to water treatment and wastewater purification. This reflected the pressure to act quickly: The primary focus was on the development and optimisation of single technologies. The analysis of water research projects included in the BMBF funding catalogue clearly shows that research in this phase was organised primarily as individual projects. Furthermore, most research was performed in a disciplinary manner, with a move towards more interdisciplinary research occurring only slowly (Sachverständigenrat für Umweltfragen (SRU) 1974). As the importance was recognised at the beginning of the 1980s of embedding research into the practical implementation context, the involvement of practical partners and the technical implementation of the findings from the research projects were a requirement for some of the funding measures. This also resulted in the number of collaborative projects increasing steadily, a trend which can be seen also in the BMBF funding catalogue.

Important developments during the first phase were, for example, the improvement of biological purification or treatment processes and the use of new processes (activated carbon, ion exchangers, membrane technology, ozone, etc.) for drinking water and wastewater purification, the elimination of nitrogen/nitrate and phosphorus, or the improved treatment of industrial wastewater. At the end of the 1970s and in the 1980s, the increased procedural and process engineering effort due to the increased requirements also led to research efforts in the areas of process stability with the necessary accompanying measurement, control and regulation technology. In addition, improved wastewater treatment led to an increase in the amount of sewage sludge and the resulting often anaerobic sludge treatment with sewage gas production. In-plant generation of electricity, combined heat and power generation and improving the energy efficiency of the facilities became important R&D topics. Furthermore, first research and demonstration projects were performed that fulfilled the requirements of the integration of practical partners, so that practice-oriented guidelines for action were developed as a result (e.g., Kunz and Müller 1986; Hillenbrand and Kunz 1989).

Another important research focus during this time was the improvement of the analysis and monitoring of environmental pollutants in bodies of water, in drinking water or wastewater, as well as the ecological assessment of the effects of pollutants. It was here that the foundations were laid for more far-reaching requirements in terms of protecting health and water. Thus, from the perspective of a policy cycle of environmental policy (Böcher and Töller 2012), water research did not only support the design and implementation of policy strategy, but it also contributed towards identification and agenda setting.

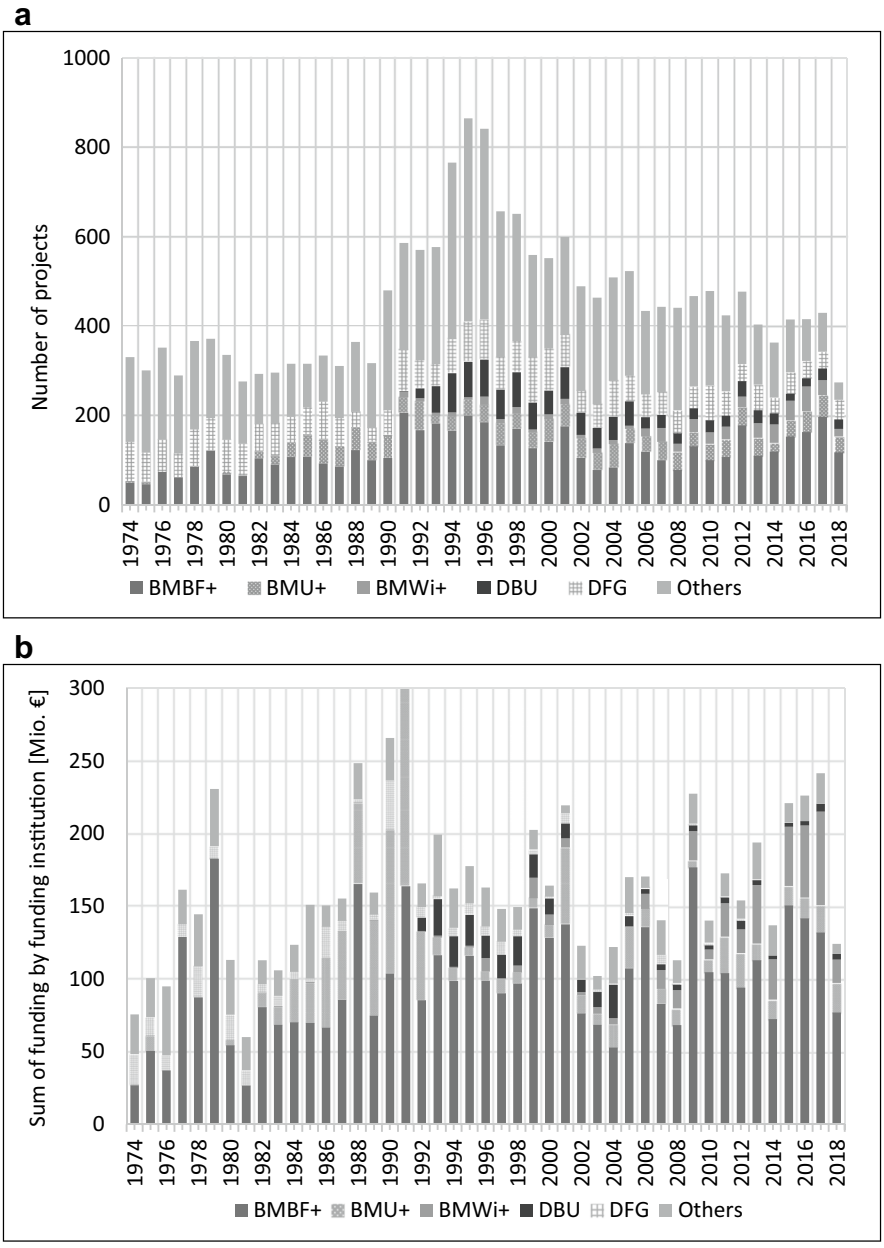

Fig. 1 Representation of (**a**) number of research projects and (**b**) funding volumes in the water sector, subdivided by funding institutions. Explanations: Evaluations of UFORDAT, without EU projects; BMBF+, BMU+, BMWi+: each with predecessor institutions in the period under consideration; others: federal states, foundations, companies, other ministries, etc.; funding totals adjusted for inflation with reference year 2020. Data for 2018 incomplete. Source: Fraunhofer ISI

Due to the favourable climatic conditions with its ample supply of water resources in Germany, no urgent need for research to improve water efficiency or reduce water demand was seen in the 1970s, and studies on the future development of water consumption were carried out only to a limited extent. The forecasts of the population's water consumption and the associated wastewater generation were extrapolated from the history of water consumption in a highly simplified manner and assumed a significant increase in per capita water consumption. For example, in the early 1970s, household water consumption was predicted to reach 200 litres per capita per day (lpcd) by the year 2000 (Battelle-Institut e.V. 1972), while it actually dropped to less than 130 lpcd. These forecasts served as a basis for the design of water infrastructure systems (especially water supply and sewerage networks) in settlement areas. Only a few studies (e.g., Merkel and Reiff 1983), motivated primarily by possible cost savings, started at the beginning of the 1980s to study the multiple use of water and the reduction of water losses.

2.3 Measures and Regulations

The high political pressure to act caused by the poor water quality led to regulatory measures at the national as well as the international level. In Germany, parallel to the further expansion of drinking water and sewer networks, a total of more than 8000 municipal wastewater treatment plants with mechanical-biological stages were built or expanded with the primary objective of reducing the input of oxygen-consuming organic and easily degradable wastewater constituents into bodies of water. Minimum requirements for wastewater treatment were formulated through the amendment of the Federal Water Act (Wasserhaushaltsgesetz) in 1976 with the introduction of the state of the art through §7a as a requirement for wastewater treatment and the concretisation through the first Wastewater Management Regulation (Schmutzwasser-Verwaltungsvorschrift) of 1979. Based on research results, the necessity of limiting nutrient inputs became increasingly clear for reasons of water and ocean protection and additional restrictions on nitrogen and phosphorus were imposed in 1989 as part of the so-called "10-point programme" from 1986 (Töpfer et al. 1988).

On the basis of the emission principle, industrial wastewater discharges in particular were more strongly regulated with the help of sector-specific wastewater management regulations. In addition, restrictions began to be imposed on individual areas of application through a chemicals policy (Detergents and Cleaning Agents Act (Wasch- and Reinigungsmittelgesetz) in 1975, a Fertilisers Act (Düngemittelgesetz) in 1977, a Chemicals Act (Chemikaliengesetz) in 1980, and aEU Directive 76/464/EEC on the discharge of certain dangerous substances into the aquatic environment (Sachverständigenrat für Umweltfragen (SRU) 1987). The stricter requirements were supported by economic incentives within the framework of the Wastewater Discharge Act (Abwasserabgabengesetz) passed in 1976 with levies for the discharge of various pollutants.

The success of the measures could be verified, for example, by the water quality map published for the first time in 1975: The quality classes I (unpolluted to very slightly polluted) to IV (excessively polluted) show the results of biological-ecological inventories of watercourse sections based on the saprobic system, with the help of which the biological water quality can be assessed using the organisms found in the water as bioindicators. Water quality maps illustrated the improvements achieved in the late 1970s and in the 1980s and also were quickly used in the new federal states after reunification, illustrating short-term improvements as a result of the investments in water infrastructure made there (cf. Kautt 1996).

3 Phase 2: Expanding Existing Approaches

3.1 Pressure to Act

Phase 1 had led to initial regulations and measures being taken for major sources of nutrient and pollutant inputs (wastewater management regulations, ChemG, WRMG, nitrate guidelines, etc.). Despite the resulting improvement achieved in the quality of surface waters, there was still a clear need for further action in order to achieve a good hygienic, ecological and chemical state in which the aquatic ecosystems deviate only slightly from their natural condition. This would allow for water to be used without restriction, for example, for bathing water, fishing water or for the production of drinking water (Sachverständigenrat für Umweltfragen (SRU) 1987; UBA 2006). Furthermore, various chemical accidents (Seveso in 1976; Bhopal in 1984; Sandoz in 1986) demonstrated the need to look beyond organic matter and nutrients as the only sources of pollution.

In the second phase, it also became increasingly clear that trade-offs between different goals existed. Traditionally, the sewage sludge from wastewater treatment had been used as agricultural fertiliser, and phosphorus was kept within the nutrient cycle. However, the conflict of goals between the nutrient character of the phosphorus contained in sewage sludge and the pollutants also contained in sewage sludge led to a decrease in direct agricultural utilisation. Thus, the question arose whether the phosphorus could be technically recovered and used as fertiliser (Sachverständigenrat für Umweltfragen (SRU) 2002).

In addition to these remaining challenges, the focus changed in phase 2, both in water research and in the political objectives and implementation measures. Changes in important framework conditions played a very important role (cf. Hillenbrand and Hiessl 2007):

- The original forecasts of drinking water consumption (cf. Battelle-Institut e.V. 1972) forecast an increase in the specific water demand of households up to 200 lpcd, on which the planning of the water infrastructure had been largely based until then. But instead of a steady increase, there was a stagnation or even a decline in water demand. In the industrial sector, the reasons for this decline

were cost reduction measures, changed production processes, and stricter environmental requirements. In the private sector (decline to below 130 lpcd), the use of more efficient household appliances also played an important part. These efficiency improvements were often motivated by the associated energy and cost savings. However, reduced water use could also lead to problems in the operation of the water and wastewater networks, e.g. the deposition of solids from the wastewater in the sewer network.

- These problems were exacerbated by demographic change, which had very different regional effects in Germany, especially after reunification. The decline in population figures which was in part sharp, partially coupled with a decline in industrial activities, led to an under-utilisation of the water infrastructure and thus to technical operating problems. It also resulted in a deterioration of the economic framework conditions which was in part drastic, due to the decline in revenues to cover a fixed cost structure of infrastructure assets with long lifespans and depreciation periods (Hillenbrand et al. 2011). This led to debates about increasing water and sewage fees.
- Due to the global intensification of the water issue, the importance of the export relevance of water technologies also increased against the background of the globally recognised excellent state of the art of German technology. This resulted in additional incentives for research activities in cooperation with German technology providers, in order to further strengthen the advantage of German exporters (cf. Kluge and Schramm 2016).
- In addition, the in part poor condition of the existing water infrastructure in the settlement areas, including the associated hazard potential and the need for rehabilitation to be derived from it, became clear from the mid-1980s onwards. For example, on the one hand, the risk to groundwater from exfiltration of wastewater increased. Leaky sewage systems, on the other hand, cause extraneous water quantities that put a strain on the sewage treatment plants both in terms of the purification processes and the amount of wastewater produced.
- The threat to water infrastructure from possible attacks and the link to security issues came into particular focus against the backdrop of perceived threats from terrorist organisations in the early 2000s. Thus, even though not debated in public a lot, innovations for protecting water infrastructure systems against terrorist attack were seen as necessary.

To sum up, the pressure to act in Phase 2 is shown, on the one hand, as a continuation of existing challenges and on the other hand, as challenges related to the water infrastructure itself. Thus, expanding existing approaches and increasing the scope of solutions became central for the pressure to act in Phase 2.

3.2 Important Research Activities

Water Protection

With reduced emissions from key point sources, induced by the initial regulations and measures such as wastewater management regulations, ChemG, WRMG, nitrate guidelines, more precise statements on the sources of inputs, input pathways and effects became necessary. Thus the development of corresponding methods and findings became important research tasks. The various chemical accidents (Seveso 1976; Bhopal 1984; Sandoz 1986) also resulted in calls for more information on substances used in industry, their quantities and their emissions into the environment. In addition, the effects of accidents and shock or continuous loads on bodies of water, and thus also on water uses (e.g., after bank filtration and treatment as drinking water), were increasingly investigated scientifically. In corresponding research projects on forecasting and assessing water quality or quantifying the effect of measures, a more comprehensive view of water bodies and their environment had become necessary. This was stimulated in particular by international activities, such as the Toxic Release Inventory (TRI) in the USA (1986) as the first national emission inventory, and by Chap. 19 of Agenda 21 on Establishment of pollutant emission registers ("Pollutant Release and Transfer Register—PRTR"). Thus, research began in Germany on the inventorying of pollutant inputs. The results showed the clearly increased importance of diffuse sources of pollution and input pathways, e.g. heavy metal inputs via urban areas or nitrogen inputs from agriculture (Böhm and Hillenbrand 2000; Fuchs et al. 2002; Hillenbrand et al. 2005).

The various inventories also supported the comprehensive view of the body of water, taking into account its entire catchment area: at such a river basin management level, the influence of the important global change processes can be identified and cost-efficient measures can be developed. Such inventories also supported the new institutional approach of the European Water Framework Directive to manage emissions with a look at the entire catchment area instead of looking at single processes only (see below). This resulted in various projects which were devoted to how to institutionalise such integrated water management (Richter et al. 2013; Helmholtz-Zentrum für Umweltforschung—UFZ 2015). The resulting projects also led to even higher degrees of bringing together different research institutions in large research projects. The BMBF's GLOWA research focus,[1] for example, consisted of research consortia which linked different systems modellers with technical expertise. In the GLOWA project for the river Elbe catchment area, this led, on the one hand, to an integration of modelling the diffusion of technical innovations in the municipal and industrial wastewater sector with modelling of the socio-economic framework conditions. On the other hand, the modelling of the effects of the innovations was embedded within natural-science based models, which show the

[1] BMBF-Forschungsschwerpunkt GLOWA https://www.fona.de/en/measures/funding-measures/archive/global-change.php.

effects of resulting emission reductions on water quality (Wechsung et al. 2013; Sartorius et al. 2011; Hillenbrand and Böhm 2008). Furthermore, research started to look at systemic issues of water basin management, such as setting up water management plans and cost-effectiveness analysis (Böhm et al. 1999; Böhm et al. 2002).

In conjunction with improved analysis and assessment methods, research results simultaneously clarified the multitude of relevant pollutants and the effects they trigger. While pollution with heavy metals had already been focussed on at the end of the 1970s, organic microcontaminants (sometimes also referred to as micropollutants or later also trace substances) only moved into the spotlight of research efforts in phase 2. This can also be seen by looking at the development of topics of publications or focus of funded research projects (Figs. 2 and 3). Studies were conducted on the whereabouts of pharmaceuticals in the environment, among other things, which demonstrated their occurrence in groundwater and drinking water for some representatives of this group of substances (Bergmann et al. 2011).

After the simple landfilling of sewage sludge as well as its agricultural utilisation had been increasingly restricted, the importance of sewage sludge incineration grew significantly. In order to counteract the associated loss of phosphorus contained in sewage sludge, processes were developed from the beginning of the 2000s on, with

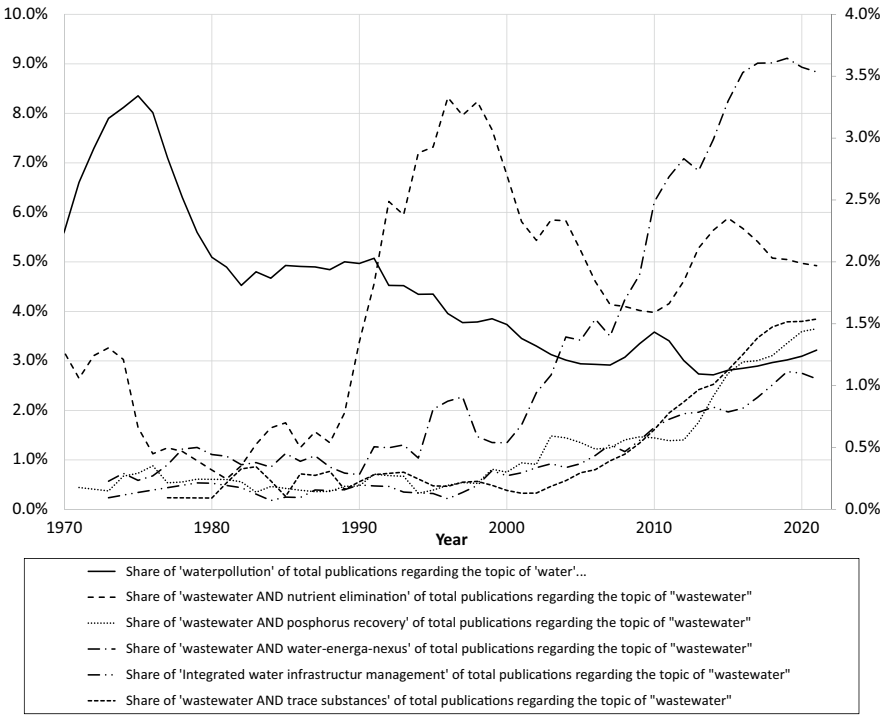

Fig. 2 Shares of publications on different topics in the field of water/wastewater to document thematic priorities in the period since 1970 (moving average over 3 years). Source: Fraunhofer ISI

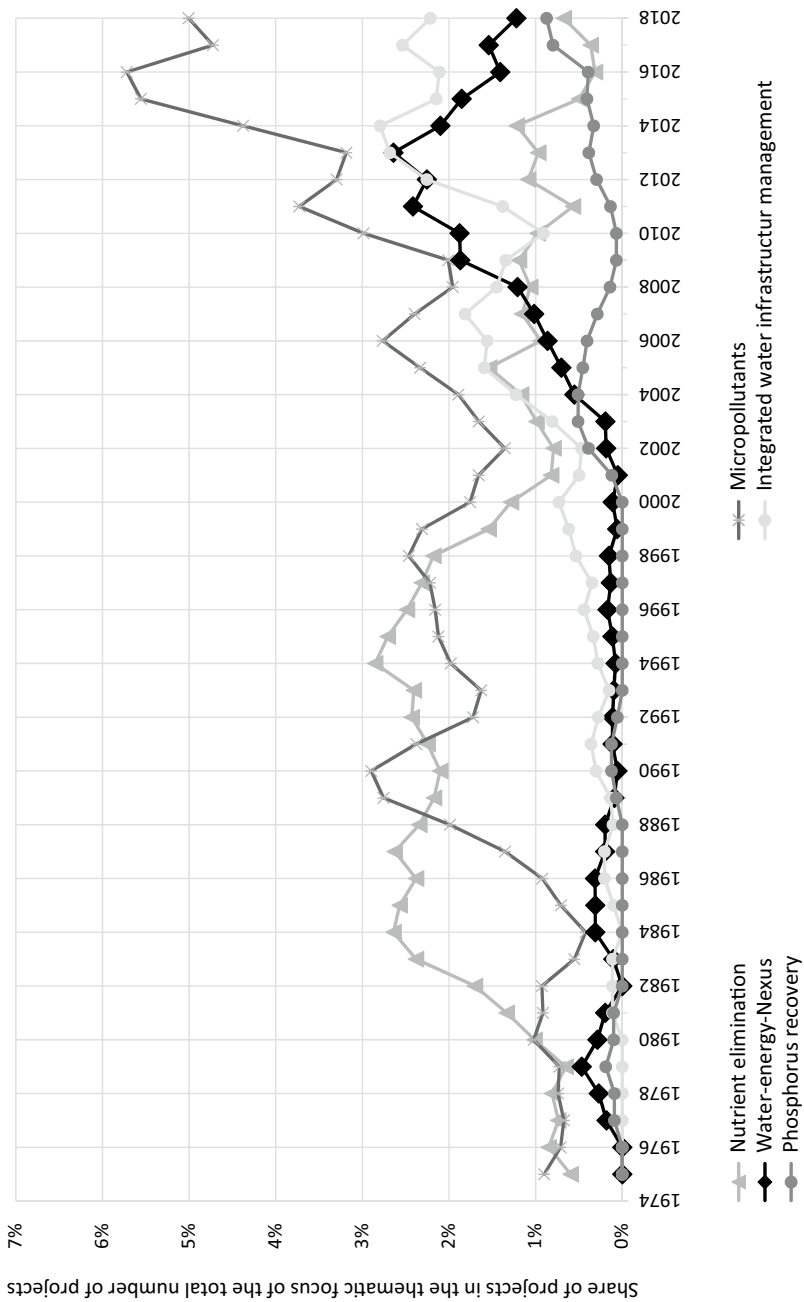

Fig. 3 Shares of research projects on selected topics of the total amount of projects in the field of water/wastewater since 1974 (data basis: UFORDAT; moving average over 3 years). Source: Fraunhofer ISI

which phosphorus can be recovered from wastewater, sewage sludge or sewage sludge ash (cf. BMBF funding call in 2004). Investigations showed that recovery from ash is more effective than recovery from sewage sludge or wastewater. At the same time, a conflict of objectives between cost efficiency and environmental effectiveness became apparent: the higher quality of the p-products was usually accompanied by relatively high costs, whereas more cost-effective processes produced p-products with a limited fertilising effect only and higher pollutant contents. This conflict of objectives was ultimately responsible for the fact that under the conditions prevailing in the early 2010s, research results concluded that phosphorus recovery could not be implemented in an economically viable matter (Sartorius et al. 2012).

The remaining pressure to reduce emissions also led to further development of existing approaches. In the case of drinking water treatment, for example, an important task was to develop treatment processes, even for smaller facilities, in cases where nitrate and pesticide concentrations were too high. In the industrial and commercial sector, comprehensive, integrated approaches were developed, that aimed at avoiding the transfer of harmful substances across all media, at closing the cycle or reusing treated wastewater, and also at recovering valuable substances from wastewater. As early as 2003, studies were carried out analysing industries which used persistent, toxic chemicals. The aim of these studies was to enable companies to identify environmentally hazardous substances in products and processes and replace them with lower-risk, technically efficient solutions (Ahrens et al. 2003).

The large number of problematic substances and different sources of input also showed the limits of end-of-pipe technologies. Investigations on the basis of successive substance flow and substance input modelling highlighted the need for a combined approach of emission and immission principles and the need for more source-related efforts to prevent environmental pollution (Hillenbrand et al. 2014). This resulted in calls for implementing improved agricultural practices with regard to the input of nutrients and pesticides, reducing the atmospheric deposition of pollutants or developing substitution options for emission-relevant uses of substances.

Water Infrastructure for Water Supply and Sanitation

The significantly increased pressure in the area of (urban) water infrastructure systems for water supply and wastewater disposal led to an intensive search for improved procedures for the assessment and restoration of pipeline and sewer networks. The involvement of practical partners in collaborative research projects was a prerequisite for the rapid implementation of research results. With regard to wastewater discharge, the subject of sustainable rainwater management (decoupling, percolation, treatment, charging structures, etc.) was also increasingly addressed. In particular, in the second half of phase 2, this also resulted in a substantial increase in collaborative projects dealing with integrated water infrastructure management (see Fig. 3).

At the same time, research into improving energy efficiency within the water infrastructure was intensified in different directions. Work on anaerobic sludge stabilisation was advanced quite significantly in the 1990s. The approaches were expanded in the early 2000s to include the goal of hydrogen production at sewage treatment plants and the energetic use of sewage gases in fuel cells (cf. significant increase in the importance of the topic of energy in Fig. 3).

The changing framework conditions also led to more fundamental reflections and scenario considerations for the future development of water infrastructure. The framework concept "Urban Ecology" (Stadtökologie) developed by the BMBF in 1990 focused on recommendations for action in the design and use of water and bodies of water in cities and urban regions, which included the objective of near-natural rainwater management in settlement areas. At the same time, long-term sustainable decentralised or semi-centralised system concepts as well as novel or resource-oriented sanitation concepts (NASS) were developed and tested (Hiessl et al. 2005; Deutsche Vereinigung für Wasserwirtschaft, Abwasser and Abfall e. V. (DWA) 2008; Hiessl et al. 2012; Londong et al. 2011). Possibilities for sector coupling with the energy or waste sector were also developed. In addition to the energy technologies described above that can be used at the wastewater treatment plant, the use of the waste heat contained in the wastewater from the sewer network also plays an important role. After initial research had been carried out as early as the 1980s, broader implementation-oriented projects started in the 2000s. Wastewater heat from grey water, the lightly contaminated domestic wastewater partial flow, e.g. from the shower, can be recovered closer to where the heat is generated and therefore with a higher degree of efficiency. More intensive research activities on this began at the end of the second phase. The prerequisite for this is the separate discharge of black and grey water, as favoured in the concept of resource-efficient infrastructures (Vetter et al. 2011; Menger-Krug et al. 2012).

The increasing prices for water supply and discharge of wastewater also induced research activities. One string of research looked into ways of improving the efficiency of the water utilities by investigating the role of technical standards or various forms of benchmarking tools (Böhm et al. 1998; Zschille et al. 2010; Hoffjan et al. 2011; Holländer 2011). Another string debated the role of privatisation and competition in the water sector (Mankel and Schwarze 2000; Michaelis 2001; Sachverständigenrat für Umweltfragen (SRU) 2002; Koch 2003; Brunner and Riechmann 2004; Wackerbauer 2009). This research concluded, by and large, that a modernisation of the industry is necessary, though not a general restructuring (Gawel and Bedtke 2015). The threat to water infrastructure from possible attacks and the link to security issues also influenced research. Against the background of the more comprehensive requirements, water management systems and measures were assessed in terms of their vulnerability as critical infrastructure and their sustainability (van Leuven 2011; Petermann et al. 2011; Schneidmadl et al. 2000; Deutsche Vereinigung für Wasserwirtschaft, Abwasser and Abfall e. V. (DWA) 2008; Hillenbrand et al. 2009).

The expansion of existing approaches and a stronger focus on the infrastructure systems led not only to interdisciplinary collaborative projects but also required the

involvement of important stakeholder groups, including those outside the water sector. Furthermore, socio-economic issues, e.g. regarding the acceptance of innovative approaches and their effectiveness, were increasingly included in the projects (Hiessl et al. 2005; Hiessl et al. 2012; Kluge and Libbe 2010).

3.3 Measures and Regulations

In conjunction with the research efforts aimed at improved wastewater treatment processes which can (also) be applied in the industrial and commercial sector, additional sector-specific minimum requirements were imposed via annexes to the Wastewater Management Ordinance (Abwasserverwaltungsvorschrift) (or, from 1997, as annexes to the Wastewater Ordinance (Abwasserverordnung)) and its amendment (Sachverständigenrat für Umweltfragen (SRU) 2004). The technological advancement in treatment technologies achieved in research projects contributed to the introduction of more stringent regulations by showing that technical solutions exist which enable the standards to be fulfilled. Increased emphasis was also placed on the purification of wastewater partial flows and, if necessary, their pre-treatment. The European IPPC Directive (96/62/EC—Directive on Integrated Pollution Prevention and Control) introduced an integrated, cross-media approach for the first time for selected, particularly environmentally relevant industrial sectors. The aim was to achieve the highest possible level of protection for the environment on the basis of the best available techniques (BAT). According to Article 15 (3) of this Directive, the main pollutant emissions should be recorded and published every 3 years. The first inventory was published in 2003 for the reference year 2001; 90% of the emissions from IPPC installations were to be recorded within.[2] From 2007 on, the EPER was replaced by the E-PRTR (Regulation (EC) 166/2006), which significantly extended the obligation to provide information.

To implement the research results with regard to the relevance and entry pathways of chemicals into the environment, the requirements were also extended via chemicals policy—both at the international and European as well as at the national level (EU Directive on the placing of plant protection products on the market ((91/414/EEC); EU Biocide Directive (98/8/EC) on the placing of biocidal products on the market; Chemicals Prohibition Ordinance (Chemikalienverbotsverordnung) for implementing the Chemicals Act (Chemikaliengesetz), etc.). In addition, information tools were developed to inform consumers about environmentally hazardous substances (e.g., in 1993 the first Blue Angel award for detergents with the criteria complete biodegradability and limited toxicity to aquatic organisms was established).

In contrast, the establishment of immission-related limit values (quality targets) for hazardous substances in bodies of water, which was already envisaged in EU Directive 76/464/EEC, was delayed considerably. Quality objectives became legally

[2] cf. https://cwm.unitar.org/publications/publications/cbl/prtr/pdf/cat3/eper_de.pdf.

binding for the first time in Germany with the Quality Objectives Ordinance (Qualitätszielverordnung) being used to implement the EC Water Protection Directive 76/464/EEC in 2001.

Shortly before that, in 2000, the EC Water Framework Directive came into force (Directive 2000/60/EC). This changed the implementation of German water management fundamentally. The Water Framework Directive requires water management in river basins, an integrated management of ground and surface water, and the definition of ecological, chemical and quantitative environmental targets with the involvement of the public in planning processes (cf. Leinweber 2008). The goal was and is to align all uses that have an impact on ground and surface waters with the management objectives. This conceptually reoriented, integrated approach took place in parallel to changes in research activities in the area of water protection and water management described. Nevertheless, before its implementation the Water Framework Directive had been already debated intensively. Thus, even though the Water framework Directive was implemented in 2000, it can be assumed that its influence on the direction of research already started much earlier towards the beginning of Phase 2.

Over time, it became increasingly clear what an important role agriculture played in the condition of bodies of water. After this could be scientifically proven by corresponding inventories of the pollution situation, the pressure to act in this area increased. The influence of the 1977 Fertiliser Act (Düngemittelgesetz) was minor. However with the Nitrate Directive at the European level (91/676/EEC: Combating water pollution caused by nitrates from agriculture (Nitrate Directive) and the resulting Fertiliser Ordinance of 1996, improvements were achieved, even though the overall balance for Germany still shows high N and P surpluses (see UBA 2006, p. 88).

With regard to nutrient management, the majority of scientific experts agreed as early as at the end of the 2000s that the recycling of sewage sludge in agriculture had no future and that phosphorus recovery would instead represent the state of the art by 2030 (Sartorius et al. 2012). At this stage, however, the political will for widespread implementation was lacking, due to the fact that this would most likely have resulted in an increase in sewage fees.

The discussions, especially in eastern Germany, on the sharply increased water and wastewater charges led not only to research, but also to some changes. Based on the results of Böhm et al. (1998), changes were initiated in the standard-setting associations, which were intended to strengthen the innovation-promoting influence of technical regulations. Furthermore, water utilities were introducing some measures to increase efficiency whilst still remaining within the existing regulatory framework (Gawel and Bedtke 2015).

4 Phase 3: The Current Status—The Need for Transformation in the Water Sector

4.1 Pressure to Act

The pressure to act on the water sector increased significantly in the 2010s, especially with regard to the impact of climate change, which also affects the water system (Sachverständigenrat für Umweltfragen (SRU) 2020). Increasing heavy precipitation leads to more frequent overloading of the sewer networks, which were not designed for such precipitation events. As both heavy precipitation and the duration of dry periods increased and, at the same time, the actual water consumption of households decreased significantly in comparison with assumptions on which their design was based, the sewer networks' ability to function was no longer ensured to the extent required.

The greatly increased pressure to act, also at the political level, is likewise closely linked to the extreme weather events that are widely perceived and discussed in the public domain as an indicator of the anticipated future impacts of climate change on the water cycle. The extreme periods of drought and heat in the summers from 2018 to 2020, as well as the increase in heavy precipitation events, and extreme flash floods, flooding or high water events such as in the summer of 2021, have made the need for action clear to the wider public.

At the same time, the effects of change processes from other areas (e.g., energy transition, circular economy) were and are to be integrated. As well as the continuing poor state of the water infrastructure in some areas, demographic changes, which depend on the region show either significant population growth or decline combined with the perspective of an increasingly ageing population (associated with a significant increase in the consumption of medicines and increased inputs of pharmaceutical residues into the bodies of water), all continue to play an important role. The increased environmental awareness among the population also makes greater participation of the public or the relevant groups of actors necessary. The PFT scandal, the heavy contamination of groundwater with nitrates and the widespread, to some extent increasing, contamination of water bodies with micropollutants or trace substances from the most diverse sources (pharmaceuticals, pesticides, biocides, etc.) are important additional drivers towards comprehensive change in water management—changes which now increasingly involve the relevant stakeholders.

4.2 Important Research Activities

Water and Resource Protection

The ability to better analyse the effect of pollutants in the environment has been increasing over time. It is now possible not only to analyse those pollutants that show effects in the aquatic environment even in very low concentrations, but also those that are so mobile that they can be detected in boundaries ground and drinking water. This is due to the improved analytical and assessment methods that have been developed in research projects. With the use of more advanced, very specific analytical methods (non-target analytics), detection of additional, potentially environmentally relevant substances was possible. However, there is still a need for research concerning the exact classification and evaluation of the characteristics. In order to identify input sources and to make estimates of elimination measures and their costs, new or improved methods were also used to better quantify the input pathways in conjunction with input modelling.

As a result of the findings regarding the need for action to reduce water pollution through trace substances and pathogens, the shares of research and demonstration projects and publications in this field increased (Figs. 2 and 3). On the one hand, the project's focus was on the development of reduction technologies, e.g. the so-called fourth purification stage for improved wastewater treatment in the municipal sector. On the other hand, research increasingly targeted also comprehensive strategies which included communication measures and raising awareness of the target groups (cf. Löwe et al. 2012, BMBF funding measures RiSKWa: http://riskwa.de resp. DECHEMA 2016).

Extensive work regarding selected micropollutants showed that sufficient emission reductions following the polluter pays and precautionary principle are only possible through a combination of source- and application-oriented as well as downstream measures (Hillenbrand et al. 2016; cf. Figure 4). These results formed the basis for the subsequently launched stakeholder dialogue on the federal government's trace substance strategy. It aimed at developing comprehensive approaches to solutions involving all relevant stakeholders. This development also signifies a transformational shift in paradigm in the reduction of emissions. The challenge is no longer solely assigned to the water sector. New actor constellations together with new forms of producer and user responsibilities are emerging.

Expanded requirements also affect research efforts in the area of resource and energy efficiency. The data on innovation indicators clearly show a substantial increase in the field of energy-water nexus in Phase 3 (see Figs. 2 and 3). In terms of energy and resource efficiency, efforts are being made in line with the energy transition and changes on the energy market. Corresponding research projects aim at energy self-sufficient sewage treatment plants, or sewage treatment plants as resource centres (Deutsche Vereinigung für Wasserwirtschaft, Abwasser and Abfall e. V. (DWA) 2018; Ministerium für Umwelt, Landwirtschaft, Natur- and Verbraucherschutz des Landes Nordrhein-Westfalen (MULNV) 2018).

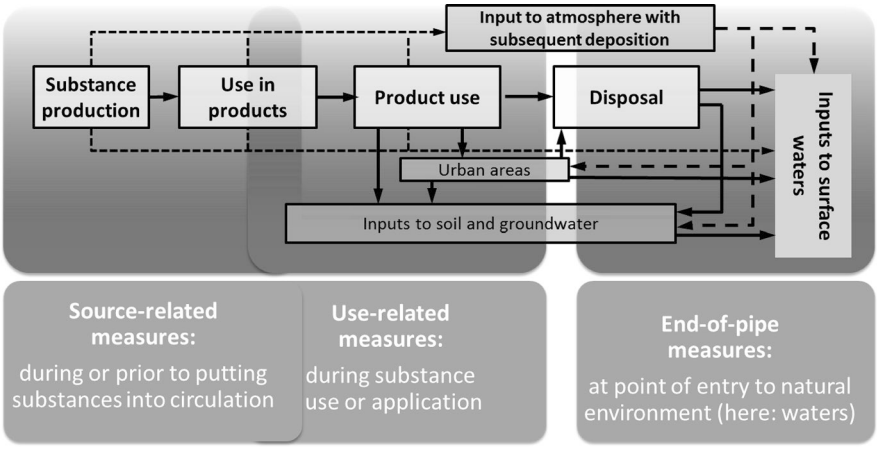

Fig. 4 Starting points for emission reduction measures. Source: Hillenbrand et al. 2017

Niederste-Hollenberg et al. (2021) show the potential of the wastewater industry to achieve climate protection goals and also discuss integrating the wastewater industry into the energy system in order to contribute to regional balancing energy at the same time as using innovative technologies, such as hydrogen production. These scenarios are part of a systemic transition that includes a consistent sector coupling for the synergetic utilisation of all potentials. These developments signify a transformational change on two levels: First, on a technical level, it enlarges the system boundaries and links water and energy technologies together. Second, it shows the overriding impact of climate change as a cross-cutting influence for different innovation domains. In addition to climate adaptation, which greatly influences the challenges of water systems to handle changing precipitation patterns, climate mitigation is now also increasingly shaping solutions in wastewater treatment.

Water Infrastructure for Water Supply and Sewage Disposal

With regard to the recycling of phosphorus contained in wastewater, comprehensive concepts for its practical application are being developed on the basis of other separate technologies that have been developed in the meantime and are now available (see BMBF funding measure Regional Phosphorus Recycling "RePhoR"[3]).

Changes in water and the water infrastructure are an essential element of the climate adaptation measures in the urban environment. Improving the urban climate has become a key issue as a result of the overall changes in climate conditions. This gives rise to the paradigm of blue-green infrastructures or the concept of "water-sensitive urban design", in which the integration of water issues into urban

[3] https://www.bmbf-rephor.de.

planning, in traffic and green space planning, and even in the housing industry are core components. New concepts also include resource-oriented sanitation systems (NASS), which include, for example, small-scale water cycles and heat recovery at a neighbourhood level (von Horn et al. 2013; Niederste-Hollenberg and Hillenbrand 2020), or decentralised system concepts, in which the traditional disadvantages of decentralised approaches can be overcome through the use of innovative technologies and operator concepts (Eggimann et al. 2015; Niederste-Hollenberg et al. 2017).

The new system concepts essentially enable new options for the further development of existing water infrastructure systems. In scenario processes, corresponding development options were concretised and assessed in terms of their sustainability and vulnerability (Hiessl et al. 2005; Hiessl et al. 2012; Hillenbrand et al. 2016). However, the associated changes were so extensive, both in terms of the actors involved, as well as the necessary technologies and the organisational and legal framework conditions, that comprehensive transition processes were required, which various research projects have started to investigate (Hillenbrand et al. 2019; Hillenbrand et al. 2018; Schramm and Winker 2023; Winker et al. 2017; Winker 2017).

4.3 Measures and Regulations

New forms of governance to reduce the emissions of micropollutants have been triggered by the need to act in this field and by research results indicating that reduction potentials also involve other groups of actors outside the water sector. Based on the research results which showed a necessity for a very broad approach to solving the trace substance problem, a stakeholder dialogue "Federal Trace Substance Strategy" was launched by the Federal Ministry for the Environment in 2016. The results produced show that new instruments involving the relevant stakeholders are needed both in assessing the relevance of substances and in developing comprehensive emission reduction concepts (Hillenbrand et al. 2017, 2019b). The results also led to the establishment of the Federal Centre for Trace Substances at the German Environment Agency in 2021.

The implementation of the cross-sectoral, resource-oriented and integrated approach to water infrastructure, which was developed through research projects, among other things, requires extensive changes to the framework conditions. In the WHG (Wasserhaushaltsgesetz—water resources act), for example, the 2010 amendment prioritised the local management of precipitation. In 2014, an amendment to Annex 1 of the Wastewater Ordinance (Abwasserverordnung) stipulated that wastewater facilities were to be operated in an energy-efficient manner and that the energy potential arising from wastewater disposal was to be used, as far as technically possible and economically justifiable. At the same time, the DWA (German Association for Water, Wastewater and Waste) developed the first set of rules for new sanitation systems (NASS, DWA-A 272: Principles for the planning and implementation of

new sanitation systems (neuartige Sanitätssysteme; NASS)) with the aim of implementing resource-oriented concepts.

With regard to phosphorus recovery, in the 2010s more and more federal states completely withdrew from the use of agricultural sewage sludge due to the problem of pollutants. Against the background of the classification of phosphorus as a resource in need of protection in the German Resource Efficiency Programme (ProgRess) in 2011 by the BMU, the question increasingly arose as to the whereabouts of the phosphorus contained in the ash. A clear answer to this question was provided by the amendment to the Sewage Sludge Ordinance (Klärschlammverordnung) in late 2017, which stipulates phosphorus recovery for large sewage treatment plants (>100,000 inhabitant equivalents.) by 2029 and by 2032 for somewhat smaller ones (>50,000 inhabitants equivalents). Implementation requires inter- and transdisciplinary work involving plant operators, potential users of the products emerging in the future, public administration staff, politicians and other members of society. Ultimately, there must be a restructuring and substantive changes in essential parts of all areas involved, which also justifies the term transformation process in this case.

In 2023, the BMU's water strategy included the goal of adapting water infrastructure to climate change (BMU 2023). To this end, further development of water infrastructures is envisaged, with the implementation of a water-sensitive city (e.g., sponge city, multifunctional land use during heavy rainfall) and the use of resources-oriented sanitation systems as well as the connection of water, energy and material cycles. Corresponding objectives are now also being embedded at the level of the federal states. For example, the future plan water ("Zukunftsplan Wasser") of the state of Hesse was developed with a variety of different measures aiming to ensure the long-term protection of water resources and supply, including the support of groundwater formation through retention and seepage; or the protection of bodies of water from pollutant inputs (Hessisches Ministerium für Umwelt, Klimaschutz, Landwirtschaft and Verbraucherschutz (HMUKLV) 2022). The DWA position paper "Water-conscious development of our cities (Wasserbewusste Entwicklung unserer Städte)" published in 2021 also contains the demand for a water-conscious design of cities in which blue-green infrastructures are strengthened, resources are used efficiently and land is used multifunctionally (Deutsche Vereinigung für Wasserwirtschaft, Abwasser and Abfall e. V. (DWA) 2021). These developments demonstrate the need for comprehensive change and transformation in water management in Germany, which is meanwhile widely recognised.

5 Discussion and Conclusion

The development in water management since the 1970s has shown three phases in which pressure to act, research and regulation and policies all interacted with each other. Figure 5 shows the main developments over time. In the first phase, especially in the 1970s, specific individual measures were required as a direct response to the

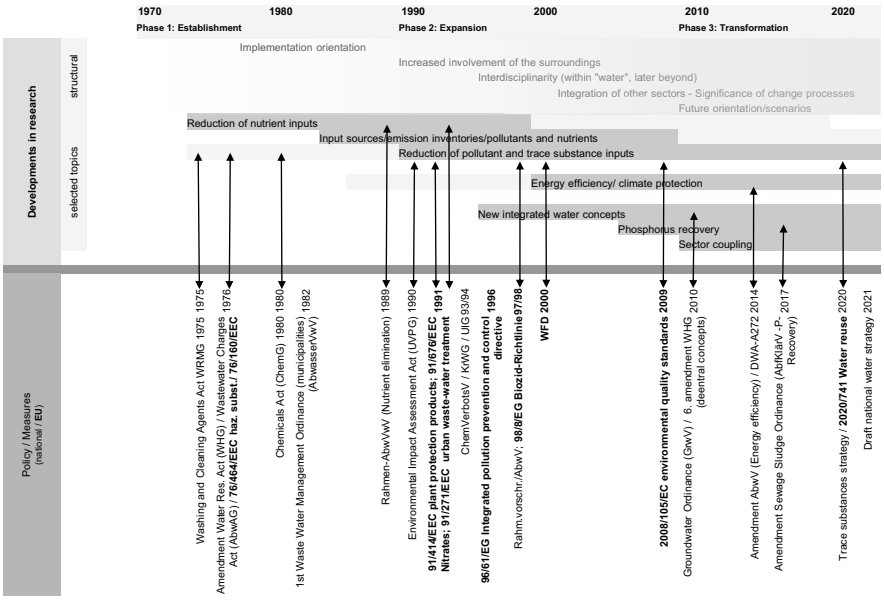

Fig. 5 Priorities and developments in research in comparison with policy measures in the water sector since 1970. Source: Fraunhofer ISI

critical environmental situation of water bodies. The essential cause–effect relationships were largely known, and the necessary measures could therefore be derived directly from them. Accordingly, the focus of research activities lay on the development of the necessary technologies, e.g. for improved wastewater treatment. Due to the implementation requirements, it was of great importance to ensure the practical relevance of the work already while the research activities were taking place. For this reason, an increasing number of projects were funded that could guarantee this practical relevance by involving practical partners. Regulation played a central role in the broad implementation of the measures.

In the subsequent second phase, which spanned the 1990s and 2000s until around 2010, the focus of research expanded significantly: the investigations to remedy the persisting deficits in water protection revealed significantly more complex interrelationships and a comprehensive need for action, which required interdisciplinary, cross-media and integrated solution approaches. The contents and structures in research changed accordingly: the importance of collaborative projects increased significantly, not only to involve practical partners to implement the results as directly as possible, but also to ensure interdisciplinary and integrated processing of the (new) questions. Research results showed the great importance of environmental factors and change processes. Work with scenario processes was started in order to identify development possibilities owing to the uncertainties associated with the development of the above factors and against the backdrop of the long duration of use and substantial sunk costs in the area of grid-based infrastructure systems and

the associated high technological (and organisational) path dependencies. The comprehensive need for action was also evident at the level of measures. Particularly outstanding examples are the European IPPC Directive with its parallel consideration of the various environmental media and the EU Water Framework Directive with its overarching objective of "good status" for all bodies of water and the demand for comprehensive river basin management that also takes the water body's environment into account.

From 2010 onwards, one can speak of a third phase in which the pressure to act, which had already been identified in the work performed and in the scenario considerations in the second phase, intensified significantly. The increase in severe precipitation events or the very hot and dry summers also showed the effects of climate change on water management in Germany. The requirements with regard to resource and energy efficiency are increasing as is the need for action with regard to water pollution with nutrients and trace substances. The questions derived from this were taken up in research and as a result showed a comprehensive need for change in water management and the necessity for integrated concepts at different levels: the interaction of bodies of water and their surrounding environment have to be coupled with source-oriented and downstream measures to reduce trace substance pollution of bodies of water. Furthermore, the water infrastructure systems have to be integrated into the urban environment much stronger. Against this background, additional instruments were used with regard to measures being implemented (participatory approaches, stakeholder processes and education and awareness campaigns). The pressure on the entire water sector to adapt, as evidenced by research findings and reinforced by changes in key framework conditions, has led to a gradual recognition of the need for transformation in the water sector. This necessity is now reflected in various regulations and political objectives such as the national water strategy (BMU 2023).

The diverse challenges suggest that a holistic approach in combination with cross-sectoral coupling with areas that also face challenges (energy transition, resource efficiency, urban development, etc.) will determine the next phase. Sustainable solutions will only be possible through cross-system concepts.

The analysis for the three phases also revealed the following pattern of interrelation: The pressure to act influences not only regulation and policy, but also research. Thus, water-related research is a field where contributing to societal challenges is not new, but has been practised for a long time. The impact of policies and regulations influences the pressure to act in accordance with their impact on the state of the environment. Research, on the other hand, also influences the pressure to act through its influence on identifying new problems and agenda setting (Fig. 6).

The interactions between research, on the one hand, and regulation and policy responses, on the other, take place in both directions and through different channels. Regulatory agencies influence research in the first instance through the funding of research projects. In particular, the research projects of the Federal Ministry for the Environment and the projects funded by the federal states are driven directly by supporting future regulation and implementing policies. Sufficient leeway is important in the design of the regulations, for example, with regard to the use of different

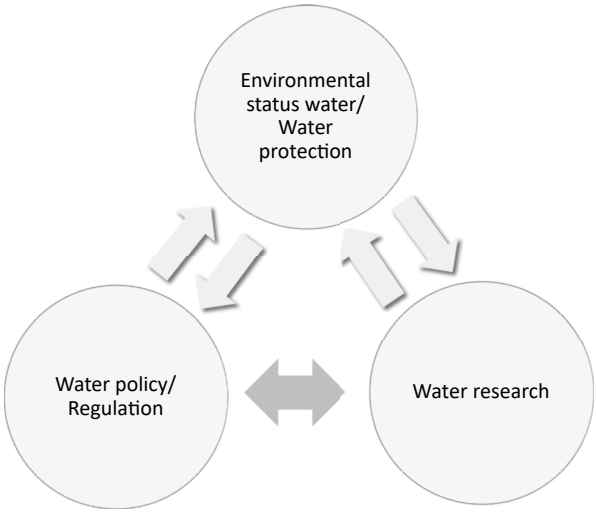

Fig. 6 Interplay between environmental status, policy and research in the water sector. Source: Fraunhofer ISI

technical solution concepts. Thus, research projects are designed in such a way that planned new regulations can be met technically. Other research topics, which have increased from phase one to three are the evaluation of policies and issues such as planning procedures and acceptance, which are also of increasing importance for policymakers. Furthermore, regulation also influences research by establishing new institutional rules. In particular, the EU Water Framework Directive has driven an approach of looking into the integrated management of water bodies and strongly influenced the topics and organisation of research projects. However, as it takes time for regulations and policies to be adopted and implemented, the influence of regulation and policies on research usually begins with the debates on the regulation.

If the influence of regulation on research leads to successful results, then research establishes an influence on regulation. There are several links to achieve this impact path: First, the traditional paradigm of the implementation of regulation follows a best available technology approach: New technical solutions, which allow for reduced emissions limits to be reached, can be implemented quickly during implementation even without the formal modification of existing laws and ordinances. Second, research can also influence regulation and policies in the medium and long-term if it identifies shortcomings and new forms of policy solutions. The need for solutions to tackle micropollutants during phase 3 outside the water sector is one of the key success stories, where research also triggered a new policy approach. However, there is no guarantee that this sort of interplay always takes place. The institutional move towards integrated water basin management in phase 2 also improves the institutional setting for making use of new policy instruments such as emissions trading. During Phase 2, this policy instrument was implemented in parallel in the field of climate mitigation. However, despite these developments, emissions trading has hardly been recognised in German water research and policy at all.

If we look at the development of water research over the course of all three phases, we can see certain developments which also indicate a development of the underlying research and innovation system. Several changes have contributed to research getting more systemic and more interdisciplinary:

- technical systems are becoming more integrated, e.g., across different infrastructure areas,
- policy strategies are increasingly looking beyond technical solution concepts and their feasibility,
- climate change and approaches such as the water and energy nexus are linking problems and sectors and require integration with other local domains such as urban development,
- new approaches require sectorial expertise within a water basin, but also require to move beyond the water sector by integrating producer and user perspectives,
- technical perspectives have to be integrated with social science perspectives, not only because acceptance and communication issues gain in importance, but also because technical solutions are supplemented with social innovations.

Even though the challenge of transformation calls also for questioning the organisational and institutional setting of the water sector, there is currently neither a debate about changing the innovation culture within the water sector nor one about its restructuring. Although the need to move beyond incremental innovations is called for, e.g., by the national water strategy, the discussion about the general need to increase innovation dynamics in the water industry and on ways to achieve this still seems to be rather hesitant. There is also only limited debate about the need to create successful transition strategies for socio-technical regime change within the water sector. Indeed, there are some developments in innovation strategies and transformation needs which are similar in the innovation domain of renewable energy and in water systems. In the case of renewable energy, such a need has led to an intensive debate about policy instruments and analysis, and the heuristics of the innovation system and multi-level-perspectives are important components of research (see Panny et al. 2024 in this anthology). In the water domain, however, there are only a few exceptions in this direction, (e.g., Hillenbrand et al. 2013; Heiberg and Truffer 2022; Kiparsky et al. 2013; Hohmann and Truffer 2022), and approaches such as technological innovation system analysis or multi-level perspectives have not been shaping research in the water sector. It remains to be seen to what extent the need for action to transform the water system will also lead to these key heuristics of innovation research being included in the water research portfolio.

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