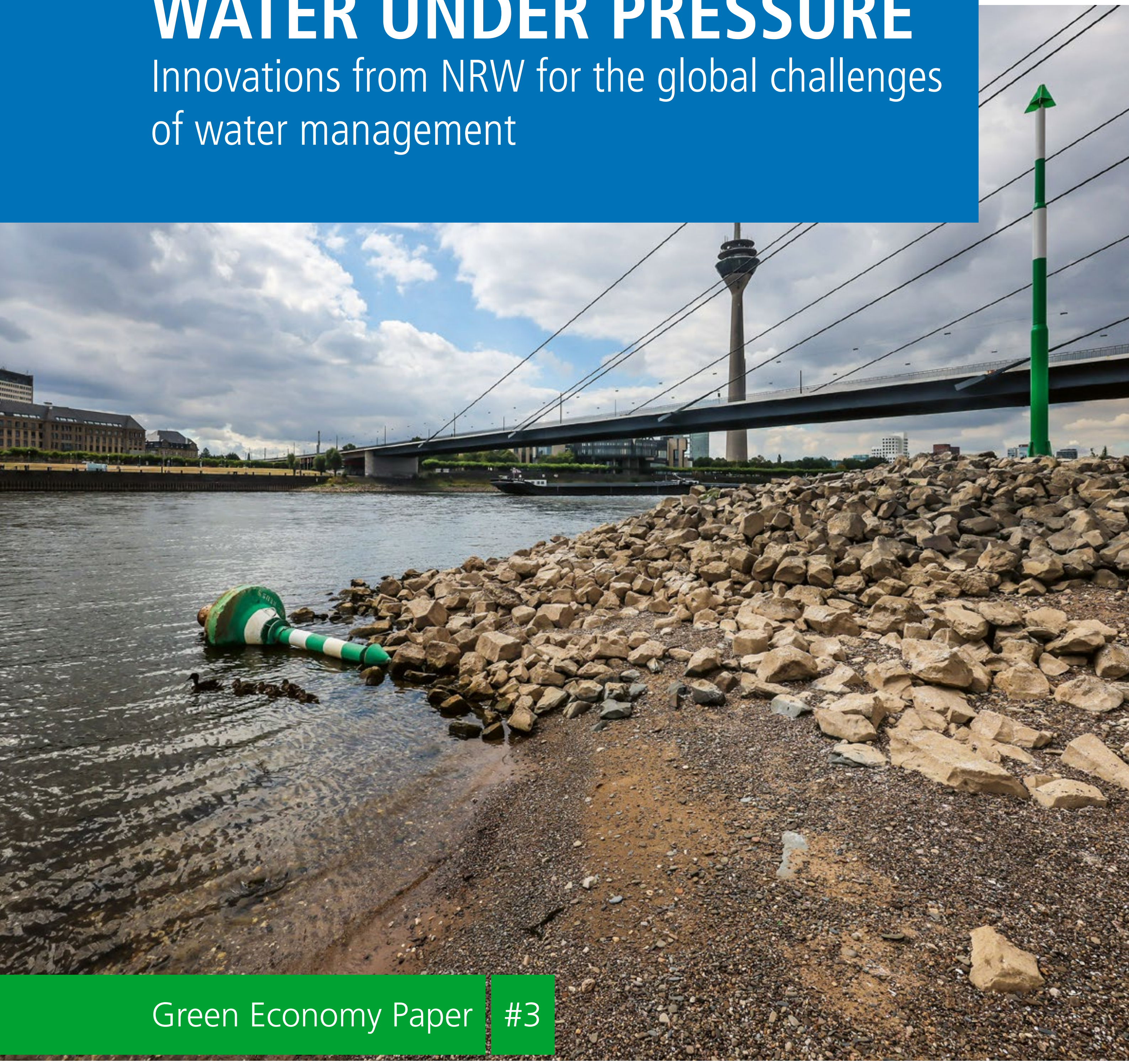
Green Economy
Network.NRW

WATER UNDER PRESSURE

Innovations from NRW for the global challenges of water management



Green Economy Paper #3

A Measure of the Green Economy Strategy
green economy
Leading in North Rhine-Westphalia

On behalf of
Ministry of the Environment,
Nature and Transport
of the State of North Rhine-Westphalia

Title Page: Low water levels on the Rhine – a growing challenge for inland shipping and local authorities

Foreword of Minister Oliver Krischer

Dear reader,

At a time when environmental, nature and climate protection are increasingly being questioned – even by some global political leaders – it's more important than ever to speak up: our lives and economic well-being are directly dependent on a healthy environment, a stable climate and rich biodiversity. Nowhere is this clearer than when it comes to water. As a vital resource, water plays a central role in our society: it is essential for human health, agriculture, industry, energy, and transport. Yet across all these areas, water is facing growing pressures, turning our reliance on it into a potential risk for future development.

The causes are many: microplastics, persistent chemicals and pharmaceutical residues are placing new demands on wastewater treatment. Increasing urban development raises flood risks. Overuse of fertilisers is contaminating groundwater with nitrates. And the effects of climate change are making the situation worse – longer dry periods and heavier rainfall events are becoming more common, threatening communities and entire economies.

North Rhine-Westphalia (NRW) is actively preparing for these changes through initiatives such as its upcoming "Water Strategy for the Future". At the same time, many businesses in the environmental sector are stepping up. Their technologies help conserve water, improve wastewater treatment, expand blue-green urban infrastructure, and support more sustainable irrigation practices in agriculture. The water industry is therefore crucial to securing our long-term water supply and plays a vital role in public services.

To remain at the forefront, water sector businesses are investing heavily in research and development. This third edition of the Green Economy Paper identifies key international technology trends in water management and highlights research priorities in NRW. It shows how innovation is helping address major challenges and how these solutions can support policy goals and existing structures.

The findings demonstrate that NRW is already making significant contributions to global water solutions – thanks to its strong research landscape and a dynamic water industry. By working with international partners and learning from others, NRW is building the foundations for collaborative progress on our most critical resource.

I hope this paper sparks new ideas and encourages further dialogue – within NRW and far beyond.

Oliver Krischer
Minister for Environment, Nature and Transport
of the German state of North Rhine-Westphalia

Artificial Intelligence (AI) transparency statement

This Green Economy Paper #3 makes use of an AI tool developed by Prognos AG. The tool systematically collected and analysed millions of data points using various AI-based methods, including clustering algorithms, machine learning techniques and large language models.

Through this approach, over 200,000 scientific publications related to water management – published between 2020 and 2024 – were identified and analysed. This formed a robust data foundation for exploring current trends and technological developments in the field and helped shape the questions addressed in this paper.

The use of AI made it possible to process a large volume of information while also allowing a more detailed examination of individual topics when needed. Any potential inaccuracies or imprecision in individual findings were offset by the large dataset and by expert review carried out by the Green Economy Network.NRW team.

This review included independent relevance checks by five experts and a discussion of preliminary results with specialists at the 8th SUMMIT Green Economy.NRW in November 2024.

It is important to note that AI was used solely to generate the data basis. All analysis, written content, conclusions and visual materials were produced by humans.

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1 Introduction

The Bigge Dam in the Sauerland region – one of the largest reservoirs in Germany.

Water is one of our most valuable and versatile natural resources. It is essential not only for meeting basic human needs but also for economic growth and social development. According to estimates, about 78 % of global jobs rely on water – half of them heavily so.[1]

This applies not just to water-focused sectors like drinking water supply and wastewater treatment, but also to areas such as agriculture, fisheries, energy, transport, industry, and even services. Furthermore, around 60 % of the world's GDP depends on processes that require water.[2] In North Rhine-Westphalia (NRW), with its strong economy, high population density and significant industrial base, the importance of water is especially clear – particularly in water-intensive industries like chemicals and metal production.

Globally, everyday issues raise critical questions about water as a resource. In Germany, the average person uses nearly 130 litres of drinking water each day for hygiene, cooking and cleaning.[3] By global standards, that's a luxury. Many countries in the Global South face severe water shortages, and unless urgent action is taken, the World Economic Forum predicts that 1.6 billion people could lack reliable access to drinking water by 2030.[4] Even Europe is beginning to feel the strain – Italy and Spain already impose water restrictions during summer.[5]

This third Green Economy Paper from the Green Economy Network.NRW explores innovation trends in international water research and highlights regional research priorities in NRW.* These insights were gathered through a unique AI-assisted process, combined with qualitative analysis. The paper categorises how identified technology trends address key challenges, including: (1) Water scarcity and global resource protection, (2) Protection of aquatic ecosystems, (3) Pollution and harmful substance inputs, (4) Climate adaptation of water infrastructure, (5) Water-smart, climate-resilient land use in both urban and rural areas. These challenges were selected based on a careful review of strategic documents from NRW, the German federal government, and international bodies. In addition to offering solutions to these five issues, the AI-supported analysis also revealed broader, cross-cutting themes – referred to as global "megatrends" in water research. These include: (1) digitalisation technologies, (2) water treatment technologies, (3) water efficiency technologies (4) sustainability technologies. All four trends are presented in detail in Chapter 4.

Finally, the paper links its findings to political and institutional structures in NRW. In four thematic sections – (1) water management functions in times of climate change, (2) wastewater treatment and water infrastructures, (3) cooperation in NRW and with international partners and (4) digital excellence in water management – practical starting points are identified for locating scientific innovations in practical contexts and thus realising political goals.

In order to identify innovation trends in the water sector, the Green Economy Network.NRW used an innovative, AI-supported tool to systematically analyse over 200,000 scientific publications and identify overarching innovation topics that have the potential to shape research and development in the water sector in the coming years. A key indicator of how important a topic may become in the future is the "future score" awarded by the tool, which can be used to quantify the development potential of a topic. The global results were also analysed in relation to research activities in NRW. This made it possible to determine how institutes in NRW are involved in global research activities, which subject areas are present in NRW and which topics are not being pursued. As a result, the field of membrane technology for water purification and extreme weather forecasting based on AI, in which NRW plays a pioneering role, are particularly worthy of mention.

The joint consideration of North Rhine-Westphalian and international challenges and solutions is particularly relevant in the field of water management. It is true that the world differs considerably in terms of how acutely regions are affected by the challenges. Nevertheless, the water industry is confronted with similar future tasks worldwide. The question of how and by whom water as a resource is managed – i.e. who fulfils the tasks that water management takes on in Germany – also answered differently. NRW is one of the most water-rich regions in the EU and is also very well positioned internationally in terms of infrastructure. The fact is, however, that people, economic systems and ecosystems are connected worldwide via the global water cycle. Accordingly, scientists around the world are researching innovative approaches**, that make

* The water industry in North Rhine-Westphalia and Germany ensures that the economy and society are supplied with sufficient high-quality water. This includes water supply, wastewater disposal, flood protection and the protection of aquatic ecosystems.

** In the context of this paper, innovative approaches are those that a) improve an existing product or facilitate its manufacture or b) develop new products, processes or (scientific) principles to address water management challenges.

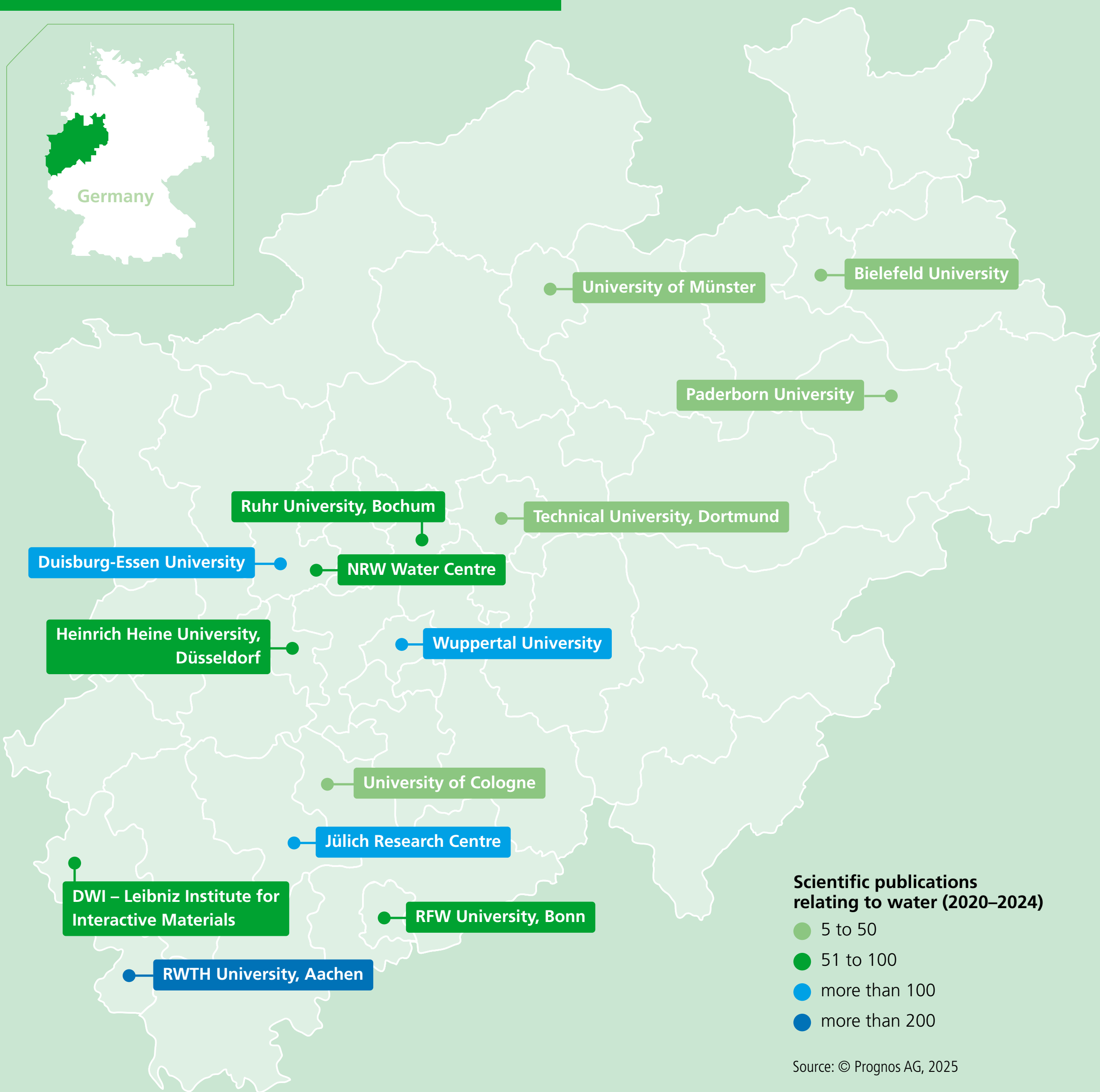
The City of Bochum monitors the quality of its blue-green infrastructure's waterways using sensor technology.

a decisive contribution to solving these challenges. This paper helps categorise which of these approaches have a high development potential for relevant international challenges.

The water management research landscape in North Rhine-Westphalia

NRW benefits from a dynamic research landscape. In the period 2020 – 2024, scientists from NRW published more than 1,500 scientific publications in 386 subject areas of water management. 121 of these subject areas have a high future score and could therefore become even more relevant in the coming years. This is clear to see: NRW is helping to shape the global research landscape and is active in subject areas that are of international importance. A look at the water science publications from NRW in subject areas with a high future score reveals a concentration of research in certain key institutions. These include RWTH Aachen University, the University of Wuppertal, the Jülich Research Centre and the University of Duisburg-Essen. In addition, there are numerous examples of collaboration and co-operation between several universities, indicating a strong culture of interdisciplinary and cross-institutional cooperation, which is crucial for tackling complex water-related challenges. The key institutions in particular also demonstrate a wide range of water-related topics, from membrane technology and bio-based solutions to electrocatalysis, which emphasises the broad and diverse research capacity in NRW.

Figure 1: Location of key research institutions in the water sector



Source: © Prognos AG, 2025

2 Methodology: How AI supports the identification of research and development trends in the water industry

The University of Duisburg-Essen (UDE), a beacon of water management research in North Rhine-Westphalia, is advancing the field of artificial intelligence with its high-performance computer "AmplitUDE". On stream since December 2024, it ranks among the 500 fastest supercomputers in the world.

The areas of tension in which the water industry operates, as described in the introduction, show that there is still a lot to do: There is still a lot to do. In addition to political decisions and responsible behaviour on the part of all individuals, companies and institutions, innovations from research and industry are needed to help solve the various challenges and support the future-oriented positioning of the water sector. Against this backdrop, this Green Economy Paper identifies key contributions to innovation and takes a closer look at them.

To obtain the most comprehensive overview possible of innovations in the water industry, an AI analysis was carried out that systematically analysed over 200,000 scientific publications from the period 2020 – 2024. Compared to traditional desk research, this enabled significantly more information to be collected on current innovation in the water industry. Before the specific results of this AI analysis are presented (see Part 3), this part describes the methodological approach in more detail. It also describes how the frame of reference for the results of the AI evaluation was set. To ensure that the innovations do not exist in a vacuum, they were placed in the context of the water management challenges to which they contribute. These challenges were derived qualitatively.

2.1 AI as a tool for identifying innovations in the water industry

A quantitative methodology was used to obtain information on current scientific developments in the field of water management. Specifically, the InSciT tool from Prognos AG was used for this paper. This tool is equipped with comprehensive access to the global publication databases OpenAlex and Semantic Scholar as well as the patent database PATSTAT. By systematically analysing the underlying databases, the InSciT tool, which is based on artificial intelligence, can identify innovation topics that have the potential to shape research and development in the water industry in the coming years. The InSciT tool also had access to registered patents and other statistics and information sources to supplement the results. It should be noted that the data used in the analysis was obtained from publicly accessible databases, which in some cases may contain inaccuracies. However, due to the size of the data set, it can be assumed that these potential deviations do not have a significant impact on the general trends of the results. The results as a whole therefore indicate a reliable development, even if variations and incompleteness cannot be completely ruled out. It should also be noted that the identified innovation trends in the water industry were determined quantitatively. The analysis was also enriched by a selection of publications that were analysed qualitatively in detail.

A multi-step process was carried out to determine the current trends in water management:

1. **Definition of the water industry:** The water industry was first defined as the basis for the database search using the InSciT tool. As water management is a submarket of the environmental economy, the definition of water management from the NRW Environmental Economy Report was used. This definition reads as follows: *"Water management encompasses all measures and activities concerned with the sustainable use and protection of water resources. This includes water supply, wastewater disposal, flood protection and the protection of aquatic ecosystems. The aim of water management is to ensure an adequate and high-quality water supply while protecting and preserving natural water resources and ecosystems."*[6]

2. **Application of a classification procedure:** Based on the definition, the InSciT tool was used to identify topic areas with a direct or indirect connection to water management. Such a topic area should either have a clear or at least recognisable connection to water management. The search for thematic fields was deliberately broad in order to include research fields that at first glance appear to have nothing to do with water management issues, but are relevant at second glance. As part of this first run through the classification process, a list of several thousand subject areas was compiled that have a recognisable connection to water management for AI.

3. **Prioritisation of the topic areas:** As the classification procedure with the InSciT tool deliberately undertook a very broad categorisation in the second step in order to cover all potentially relevant topics, the topic areas were narrowed down in the third step. In order to narrow down the topics to suit the subject of the study water management, the topics were checked for their actual relevance and prioritised. The review was carried

out both by an AI within the InSciT tool and by experts from Prognos AG. The results of both processes were then combined. This targeted thematic prioritisation, which is based on the definition of water management as a submarket of the environmental economy, ensured that no erroneously assigned marginal topics distorted the quantitative analysis of the data. For example, topics related to hydrogen were removed from the analysis. Although hydrogen plays an important role in the context of the energy transition and is linked to the water industry, it is not considered part of the water industry according to the common definition and is therefore not the focus of this study.

4. **Detailed analysis of the topic areas:** In the final step, the consolidated list of more than 1,200 topic areas relevant to water management was analysed in detail. The following indicators were analysed:
   - Number and timeliness of scientific publications (global and by authors from NRW, before 2020 and after 2020)
   - Sum and average of citations of scientific publications (global and by authors from NRW)
   - Organisational affiliation and thus the geographical location of publications and citations
   - Future score in the form of the cumulative estimated impact of the topics over the next few years

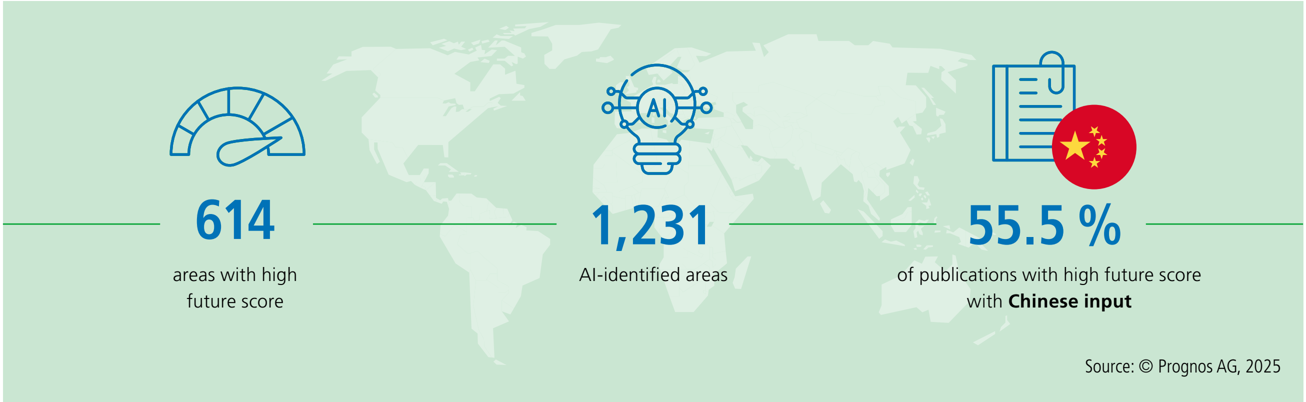
With the aim of mapping key innovation trends for the water industry as comprehensively as possible, the analysis was carried out on three levels using the InSciT tool. Firstly, general and global scientific topics were analysed. This means that publications from all countries in the world were collected and categorised into thematic focus areas. Secondly, in the course of the detailed analysis of the subject areas (see step four of the method description), the global results were analysed with reference to research activities in NRW. This made it possible to determine how institutes in NRW are thematically integrated into global research on water management topics and in which subject areas with a high future score NRW has a high share of global research. Finally, thirdly, the thematic fields were analysed in terms of their relationship to previously defined challenges. Where possible, all subject areas were assigned to a suitable challenge. The next section deals with the derivation of the challenges. The charts 2 and 3 provide an initial insight into the results of the analysis. They show in figures how many topic areas in the water sector for NRW and the world were identified by the AI analysis. They also provide an overview of how many publications were published on these topics between 2020 and 2024 and how many topics have a high future score. When looking at the global figures, it is striking that 614 of the 1,231 topic areas identified with the help of AI have a high future score. Of all publications

In-depth analysis: Future score

In order to identify global trend topics in the water industry, the topic areas that were assessed by the InSciT tool as particularly relevant for the water industry were systematically analysed according to their development potential. A key indicator of how important a topic may become in the future is the future score assigned by the tool. The future score can be used to quantify the development potential of a topic. This allows the dynamics of the various topics to be compared and categorised. The dynamics describe the estimated relative change over the next three years.

The future score and thus also the estimate of the dynamics of a topic is arrived at as follows: Based on historical data, an AI model from Prognos AG was trained using a machine learning process. The model learns to predict interdependencies and relationships between features of publications on the basis of predefined criteria, each of which has contributed to the success of a scientific publication. The (success) characteristics on which the AI model is based citations and their progression, subject areas, organisations involved, their geographical location and the composition of authors. Based on these criteria and their combination, the AI model predicts future interdependencies and relationships between topics and publications. The model categorises the future relevance of a topic according to the extent to which it may appear in the coming years as a result of these calculations. In the context of this paper, this means that an individual future score is available for each of the 1,200 topics relevant to the water industry, which categorises the relevance of the topic. In addition, the topic areas with a high or rather high future score can be localised globally. This shows whether research activities can also be found in NRW in the respective topic area.

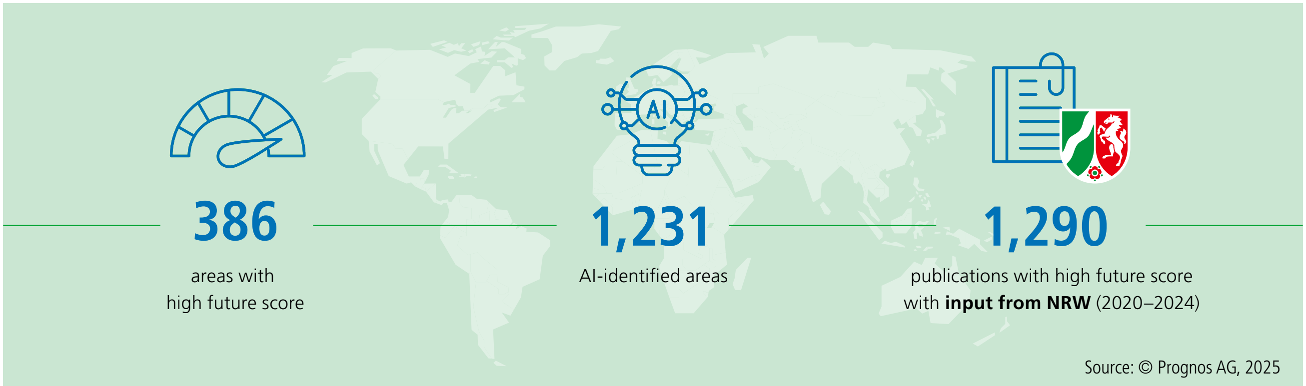
Figure 2: Overview of general figures and data from the AI analysis – global perspective



in this field, over 55 % originate from China, which indicates an extremely dominant research position of the People's Republic.

NRW is also strongly represented in research on water management topics. Research is conducted in NRW in almost a quarter (386 of 1,231) of the subject areas, which was reflected in 1,290 scientific publications between 2020 and 2024 – a high figure, especially for a single state.

Figure 3: Overview of general figures and data from the AI analysis – North Rhine-Westphalia perspective



2.2 Derivation of challenges for water management

Water management in NRW faces current and future challenges. These are presented in detail in Chapter 3. The aim here is to identify these challenges. To this end, relevant political strategies relating to water at international, national and NRW level were first researched and analysed with regard to the problems described therein. At global level, these include the Sustainable Development Goals (SDG) of the United Nations. In particular, SDG 6 – *Clean water and sanitation* sets the framework for improving the water supply for all people. Key components for achieving the sustainability goal are technologies for drinking water utilisation (SDG 6.1), water treatment (SDG 6.3) and efficient water use (SDG 6.4). The UN Water Strategy 2030 was adopted in 2020 to accelerate progress towards achieving SDG 6. At the same time, it also aims to promote cooperation between UN member states on global water issues. At EU level, the Water Framework Directive (2000) is an important political instrument with the aim of achieving "good status" for all rivers, lakes, groundwater and coastal waters by 2027. At a national level in Germany, the Federal Government's National Water Strategy of 2023 provides a framework for action for modern water management. It takes into account the challenges of water management up to 2050 and is divided into ten strategic topics that set the direction for the next 30 years and describe concrete goals and measures. At NRW level, the key issues paper on North Rhine-Westphalia's future water strategy published in 2024 outlines 17 key issues for safe and resilient water management.

The following criteria were used to identify the challenges:

1. The challenge is directly related to water management.
2. The challenge is important both for NRW and for the global level.
3. The challenge is not a purely political one, but encompasses a research topic and can be solved (at least in part) through innovation.*
4. The challenge is addressed in several relevant strategies.

This resulted in the five thematic challenges that are presented in the following chapter and linked to the innovations and thematic trends from the AI analysis.

* This Green Economy Paper focuses on the role of innovation in water management and its potential to solve key water management challenges. Against this background, political and structural challenges are not discussed in detail here.

3 Challenges of water management and solutions from research

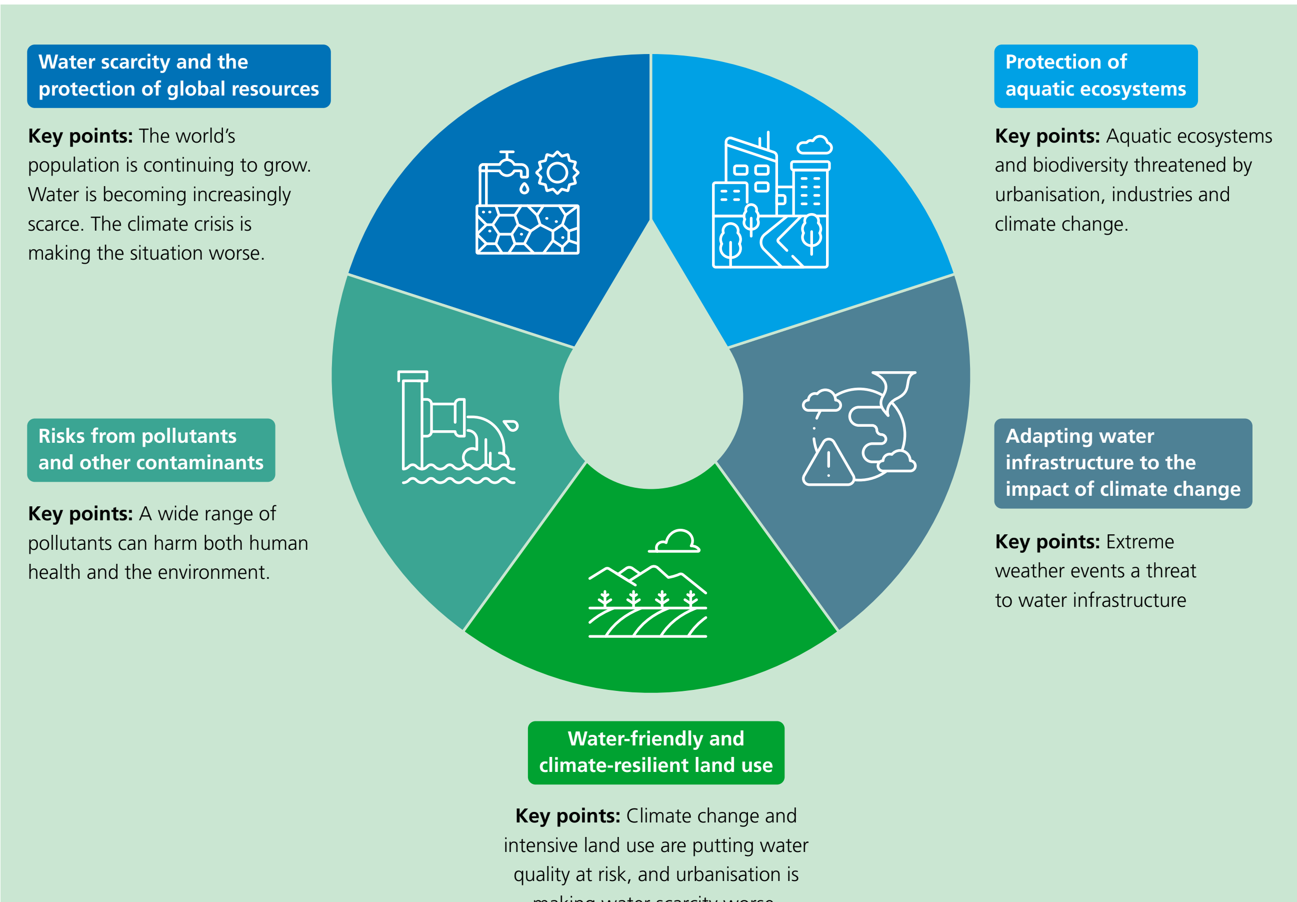
Remote sensing is playing an increasingly important role in water management – from flood monitoring and water quality surveillance to the application of AI. The satellite image shows the water management infrastructure of Amsterdam and Flevoland in the Netherlands, a key partner of North Rhine-Westphalia in managing the Rur, Meuse, and Rhine river basins.

The qualitative analysis of key strategies in the area of water management (see Chapter 2) has revealed five central challenges that need to be solved in the coming years

- *First* and foremost is the increasing water shortage in a growing number of regions of the world, which is currently extremely significant in regions threatened by drought, but could also make itself felt in the near future in formerly "water secure" regions such as NRW.
- *Secondly*, the condition of water ecosystems is deteriorating worldwide, and the waters in NRW are still a long way from achieving "good status".
- *Thirdly*, a problematic cocktail of different, sometimes harmful substances continues to be detected in our water. Preventing the entry of chemicals into water bodies and filtering out harmful substances is one of the biggest challenges.
- *Fourthly*, climate change is leading to an increase in extreme weather events such as heavy rainfall and flooding. The water infrastructure must be prepared for this in the coming years.
- And finally, *fifthly*, water-compatible and climate-resilient land use in urban and rural areas is needed to ensure both the irrigation of arable land and the drinking water supply for people in an increasingly urbanised world in the future.

Figure 4 offers an overview of the key challenges currently facing the water sector. Each challenge is explained in greater detail below, along with the solutions and innovations identified through AI analysis. For a more detailed categorisation, the results were enriched with additional information through desk research. Furthermore, the participation of the research landscape in NRW is also highlighted and the research fields in which institutions

Figure 4: Key challenges in water management



Source: © Prognos AG, 2025

from NRW are involved to a large extent in important research fields are described.

- Research fields with high participation from NRW are all those in which the share of publications by research institutions from NRW in all (global) publications since 2020 is over 5 %.
- The research fields in which NRW is not active, but for which a high future relevance is nevertheless forecast, are identified as follows: Within all subject areas assigned to a challenge, those with the most publications and a high future score are selected. Accordingly, there is no specific threshold value in this case and the number of publications in the globally relevant topic areas differs depending on the challenge.

3.1 Water scarcity and protection of global resources

The challenge – what's it all about?

It is estimated that 9.7 billion people will be living on Earth by 2050. By 2100, it could even be 10.2 billion.[7] At the same time, the lifestyles of many people are changing, leading to increased utilisation of water resources. Around 2 billion people already live in regions with high water scarcity.[8] And even though water supply and disposal has improved considerably in many regions of the world in recent decades, at least 3 billion people, mainly in the Global South, still do not have adequate access to water of sufficient quality. And almost half of the world's population is unable to make use of adequate sanitation.[9] The ongoing climate crisis will further exacerbate these trends in the future and make water resources scarcer elsewhere too. and regional precipitation and evaporation patterns are also changing as a result of global warming. This increases the water content in the atmosphere, which leads to more frequent extreme events such as floods and droughts.[10] In addition, freshwater resources close to the sea are increasingly threatened by salinisation, which further exacerbates water scarcity.[11]

A look at the national level shows that although the basic supply is largely secured in Germany, the water industry is also coming under increasing pressure in this country. The water industry covers two essential supply areas that are part of the critical infrastructure (KRITIS) – a reliable supply of water and wastewater disposal. Both areas are increasingly confronted with challenges that could jeopardise a secure supply of clean water in the future. Falling groundwater levels, uncertain water availability and an increased demand for water during hot spells could jeopardise the water supply in parts of Germany in the long term. Solutions must therefore be developed to ensure a sustainable supply of drinking water, even in countries such as Germany that are fundamentally rich in water. The effects of climate change also play a decisive role here. Although average annual amount of precipitation is increasing, precipitation is concentrated in just a few months. While excessive amounts of precipitation are to be expected in the colder months in particular, too little rain falls in the summer months. This is exacerbated by the fact that the draining of moors, sealing of surfaces and deforestation mean that soils can store less water, meaning that dry phases lead to water shortages more quickly. Overall, Germany has lost an average of 2.5 km^3 of water per year since 2000 due to more intensive dry periods and lower storage capacities.[12]

Regional geological, hydrochemical and hydrological conditions result in differences in the availability of groundwater. In Germany, for example, there are areas that have sufficient or even too much groundwater available, as well as urbanised regions in particular, whose groundwater supplies are dwindling. This is due on the one hand to the higher population density and the resulting higher consumption, and on the other hand to the lack of near-natural options for collecting and storing rainwater in cities. It is equally true for all regions that water requirements in agriculture and industry will increase in the future due to the increasing frequency of hot days and high consumer behaviour. If water resources are not reorganised and used sustainably in the affected regions, this can lead to shortages.

Possible solutions: Save water and protect global resources!

Overall, it should be noted that relatively few research fields could be assigned to the challenge under consideration as part of the AI analysis. The political framework conditions and measures to reduce global warming play a particularly important role in the protection of global resources. Nevertheless, 88 research topics related to the challenge of "water scarcity and protection of global resources" can be found in the data analysed. Of these, 34 topics have a high or rather high future score. NRW does not have a general research focus in this topic area. However, NRW does stand out in one subject area – desalination and solvent-based water treatment. Here, the re-

Between the two Palm Islands lies the world's largest seawater desalination plant, Jebel Ali – powered by fossil fuels.

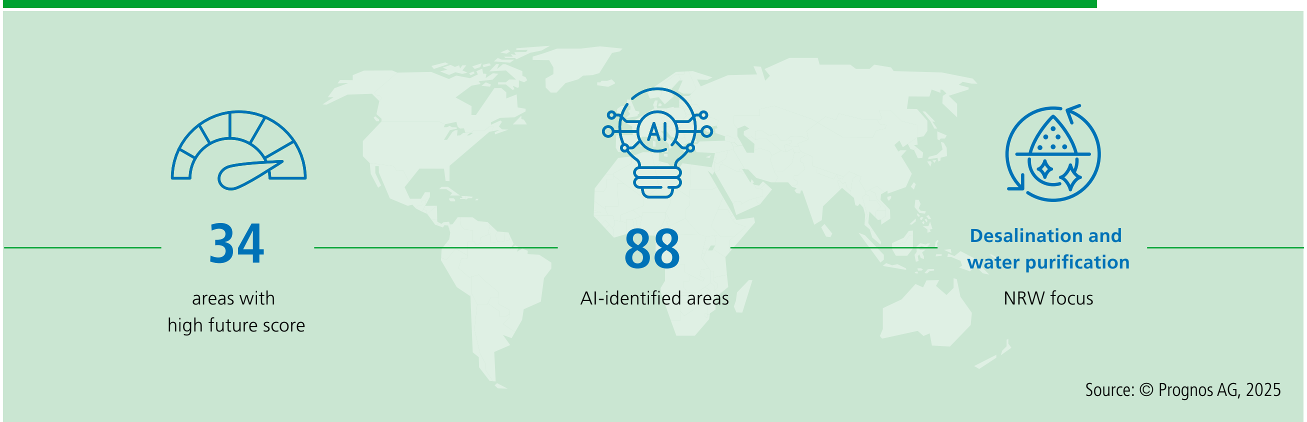
search institutes in NRW have a high proportion of global publications. This is pleasing, as the research field is attributed a rather high future score, i.e. increased publication activity is to be expected in the coming years. This also offers the opportunity for practical applications to be improved even further through innovative processes.[13]

Solvent-based desalination and water treatment:
This process uses organic solvents to extract clean water from saline sources. The approach offers advantages over conventional desalination techniques, as less energy is required and the process is more efficient and environmentally friendly.[14] This method could play a particularly important role for economically strong regions with water shortages such as California and the Gulf States. There is therefore an opportunity here for research institutes from NRW to become more involved in order to contribute to further progress in the process in the future.

In principle, desalination processes can be used in various areas, such as the treatment of aqueous industrial waste, municipal wastewater and in brackish and seawater desalination. What all desalination processes have in common is that they recycle water and thus reduce fresh water consumption. Seawater desalination plants can help to supply urban centres with drinking water . However, it should be noted that the conventional desalination process is controversial due to the high energy consumption and the environmental impact of the toxic brine that remains.[15] However, the evaluation of the InSciT tool analysis shows that there has been a high level of activity in the related areas of water management in recent years.

The international research trends that contribute to solving the global water shortage are concentrated in the area of water treatment, among others. Southern Europe stands out here, with research focussing on Greece and Spain. On the other hand, research institutes from China also record a high proportion of innovative publications. The purpose of water treatment is to recirculate water once it has been used in processes or to utilise it for other purposes, thereby reducing water consumption. This also

Figure 5: Research data on the challenge of water scarcity and global resources



Source: © Prognos AG, 2025

includes the desalination methods mentioned above. The research trends in this challenge are closely linked to those of the challenge "Substance inputs into water and other contaminants", as water pollution also has an impact on water scarcity and the protection of global resources.

Electrodialysis for water treatment and resource recovery: Electrodialysis plays a central role in wastewater treatment and desalination processes. This is a process that utilises special membranes that specifically remove ions from the salt solution. It can be used to desalinate seawater, but also to purify wastewater and remove salts and other pollutants. The advantages of electrodialysis compared to other processes include higher water recovery rates, simple operation and a long service life for the membranes. A key challenge is the high energy requirement of the process. Technological advances have already improved the energy efficiency of electrodialysis processes for water treatment, but there is still a need for research to ensure that the process has the potential to be used on a large scale in the future.[16] The integration of electrodialysis into the various applications of water management supports sustainable resource management and thus helps to protect resources and overcome water scarcity.[17]

Solar-powered interfacial evaporation and desalination: Another method of seawater desalination is a further development of classic evaporation: by placing materials on the surface of the water, the solar heat is concentrated on the interface and the seawater turns into vapour more quickly, which can then be condensed into fresh water. The technology, which is still being developed, can help to counteract the global shortage of fresh water. Among other things, research is focussing on improving evaporation rates, with innovative designs and materials playing a key role. For example, the addition of certain minerals[18] or the utilisation of water currents[19] can increase the evaporation rate of seawater.

Recycling and treatment of olive oil mill wastewater: Over 3 million tonnes of olive oil are produced in the Mediterranean region every year. Olive oil mills produce large quantities of wastewater, which leads to environmental pollution and high consumption of the already scarce freshwater reserves in the countries where the oil is produced.[20] The worldwide export of olive oil also makes it a globally relevant issue. In order protect the scarce freshwater resources, it would be of great importance to be able to fall back on innovative and economically viable processes for the treatment of olive oil mill water. Various innovative strategies are being researched for implementation, which are currently still lacking in economic viability but show potential for the future. Although the research area is characterised by a high future score, it is not very dynamic and has relatively few publications compared to the two topics mentioned above. However, it is clear that even small-scale changes can make a contribution to the sustainable use of water resources.

Assessment of the results

The results show that there are already a number of significant research contributions to combating water scarcity and protecting global resources. These focus in particular on water treatment processes. In nominal terms, the research contributions from NRW account for a small proportion. However, in terms of technical relevance, NRW stands out in the fields of water desalination and solvent-based water treatment.

3.2 Risks from incoming substances and other impurities

The challenge – what's it all about?

In films, advertising or travel ads, the depiction of water is characterised above all by two properties. It is clear and pure. People can drink it or bathe, splash and swim in it without hesitation. In reality, however, this ideal can unfortunately often not be realised. This is because surface water in all its forms – whether as a spring, pond, river, lake or sea – is exposed to massive pollution from microplastics, chemicals, pharmaceuticals, fertilisers and pesticides. According to recent figures from the Heinrich Böll Foundation, more than half of Germany's rivers have excessive phosphorus pollution, over 150 pharmaceuticals (such antibiotics) can be detected in German waters and more than 1,500 locations in Germany are hotspots for water pollution caused by industrial chemicals. All of this jeopardises ecosystems, animal health and, last but not least, human health.[21]

From a global perspective, many people are also suffering from water pollution. For example, Anja du Plessis, a researcher at the University of South Africa, states in an article from 2022 that global water quality has deteriorated since the 1990s and that a global water emergency could occur if the pollution is not counteracted.[22] 2025 can be stated: This water emergency is already a reality for many people and is having brutal consequences. In Niger, for , 73.6 % of people live without secure access to sufficiently clean water sources. In Chad the figure is 81.6 % and in Ethiopia 82.2 %. For many people, this lack of or poor access to drinking water and sanitation has health consequences that can range from illness to death.[23]

But what exactly are the key challenges when it comes to water contamination? Or to put it another way: what dangers need to be combated so that people have sufficient clean water available? The key aspects are described below for NRW, Germany and the global context. It is important to note that this challenge is only about the treatment of water but not about making sufficient water available.

In NRW, water quality has improved considerably compared to the 20th century, yet not even 10 % of water bodies are rated "good" when it comes to water quality.[24] Too many pollutants have found their way into water bodies in the past and are still finding their way into groundwater today. Some key (micro)pollutants deserve more attention in the future when it comes to protecting water bodies:

1. **Synthetic fertilisers as well as pesticides and plant protection products** used in agriculture, for example, are a major cause of algae growth, oxygen deficiency and fish mortality in bodies of water because plants can only absorb a portion of the nutrients. The rest leads to high levels of nitrogen, nitrate and phosphorus pollution in surface waters and groundwater. Pesticides and plant protection products can also lead to environmental damage.

2. **Perfluorinated and polyfluorinated alkyl compounds (PFAS),** also known as perpetuating chemicals, are extremely persistent compounds that can cause damage to the human body. They increase the risk of diabetes and cancer, for example, and are also ingested by humans via drinking water.[25] They enter the environment via the disposal of industrial chemicals, via PFAS-contaminated sewage sludge used as fertiliser or as a component of incorrectly disposed single-use plastic waste.

3. **Pharmaceutical residues** are continuously detected in surface waters worldwide (e.g. in wastewater treatment plant effluents, rivers or lakes). This pollution could even increase in the coming years due to the increasing consumption of medicines worldwide, which is caused by an ageing population and the use of medicines in intensive animal husbandry.[26] The most frequently detected drugs anti-epileptics, analgesics (painkillers), antibiotics, antihypertensives and X-ray contrast media. Even if there is no health risk to date, the increased intake of substances could pose a threat in the future that must be prevented.[27]

4. **Antibiotic-resistant germs** enter wastewater treatment plants via manure intensive livestock farming and clinical or domestic wastewater, for example, and then directly into the environment as treated wastewater. From there, they can find their way back to humans (e.g. in bathing waters). According to the Federal Environment Agency, the extent of multi-resistant pathogens in Germany is reaching "threatening proportions"[28] and can lead to infections that can no longer be treated with conventional antibiotics. Around 33,000 people died from such infections in Europe in 2018.[29] The challenge for water management is to prevent antibiotic-resistant germs from entering the environment.

5. **Industrial consumer products and chemicals** can also enter bodies of water or the water cycle via wastewater. This applies, for example, to materials such as textile impregnations, lubricants, coolants and refriger-

ants or materials containing PFAS. In order to limit these substance inputs and the resulting environmental damage, not only must the operational handling of chemicals be improved, but also wastewater treatment processes that filter out the substances.[30] The urgency becomes apparent when considering the global scale of the problem, as 300 to 400 megatonnes of polluted wastewater are released into the environment every year. This leads to extreme environmental pollution and damage to health. In Indonesia, up to 50,000 deaths can be attributed to the pollution of the Citarum River, along the course of which around 2,000 factories are located and discharge their wastewater.[31]

Solutions: Filter incoming substances and other impurities!

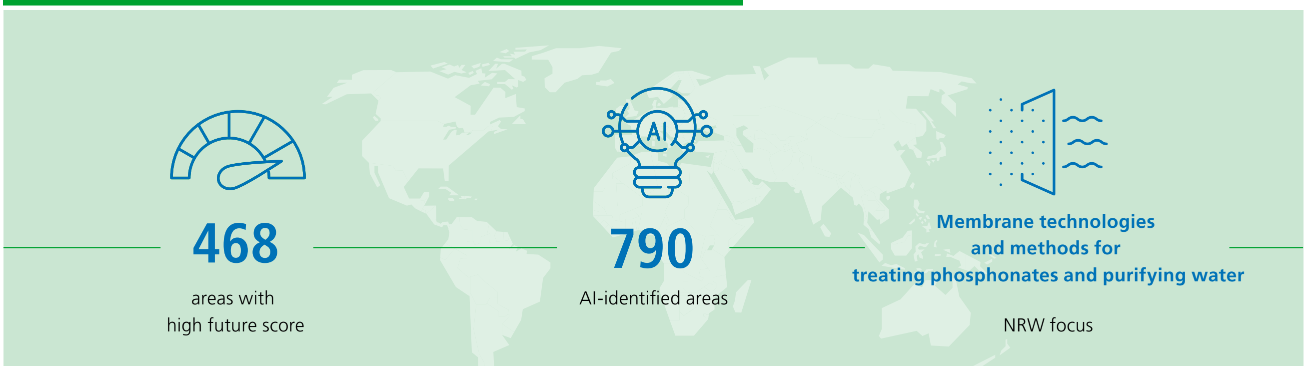
"Substance inputs and contamination of water" proved to be a central field of research in the analysis. A total of 790 different research fields were identified in the analysis for this area. Of these 790 research fields, 468 have a high or rather high future score. Research institutes from NRW are also involved in this research to a significant extent. In 14 of the 468 research fields on the challenge of "Substance inputs and other contaminants in water" with a high future score, researchers from NRW are involved in 5 – 23 % of global publications since 2020. Examples of publications in the respective research fields can be found in the endnotes. Five topics stand out in which intensive research is being conducted in NRW:

Techniques for the removal and treatment of phosphonates: Phosphonates are chemical compounds that are difficult to break down and enter bodies of water via wastewater – often as part of detergents and cleaning agents[32] Their removal, treatment and recovery is an important area of research. However, there is still no cost-effective technology for recovering phosphonates from wastewater. This is where current research comes in. It is being investigated which substances and techniques bind phosphonates best and most efficiently and remove them from the water. The use of granular iron hydroxide or clay minerals as well as other material compounds seem promising here.[33]

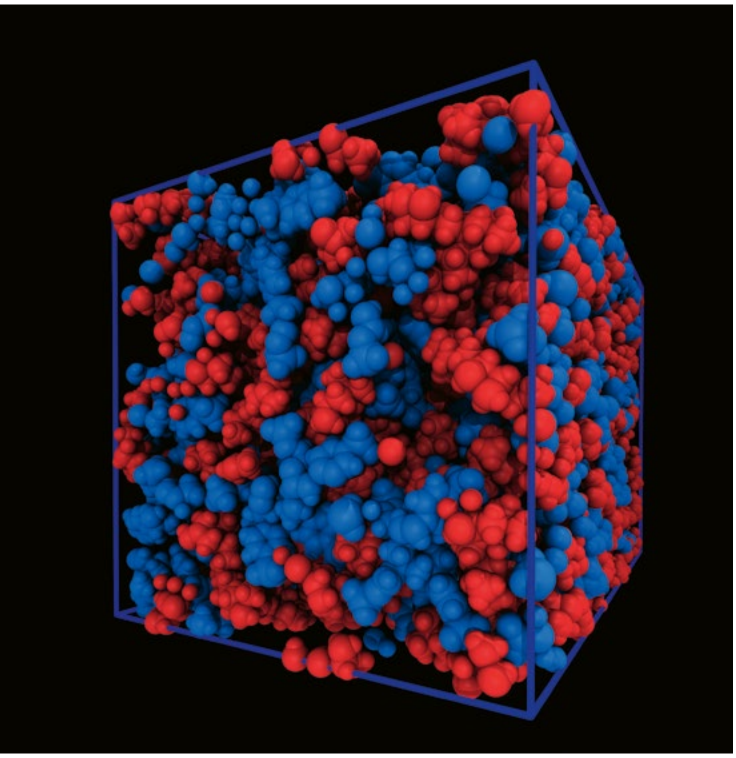
Technical pioneers from North Rhine-Westphalia: With the PerfluorAd® treatment technology, Fraunhofer UMSICHT and Cornelsen Umwelttechnologie GmbH have developed a market-ready process that removes PFAS cost-effectively and efficiently from aqueous media.

Analysing and quantifying microplastics: As already described, microplastics are among the substances that pollute the environment and animals in the long term. Research is being carried out into a) methods that allow microplastics to be physically characterised (e.g. using dynamic light or laser diffraction), b) approaches that classify microplastics more precisely in chemical terms in order to separate them and c) analytical methods that allow microplastics to be analysed quantitatively in order

Figure 6: Research data on the challenge of pollution and contaminants entering water sources



Source: © Prognos AG, 2025



The Process Engineering department (AVT) at RWTH Aachen University is researching innovative membranes – shown here is a molecular dynamics simulation (MD) of a polyelectrolyte membrane.

to better understand the large-scale pollution of the environment and water bodies and to record local concentrations. The fields of research are very different in themselves and cannot be described in detail here.[34]

Patterned membranes for separating and controlling pollution: As we have already seen in the analysis of global trends, membrane technologies are among the most important developments when it comes to filtering pollutants from water. However, membranes themselves also become contaminated over time. This results in costs (replacement or cleaning) that stand in the way of even more widespread use of the technology. Patterned membranes are intended to solve this problem. This is because the topographies on the membrane surface improve the hydrodynamic properties of the membrane (e.g. movement and tension) so that less soiling forms on its surface.[35] In addition, the patterning of the membrane reduces the contact area with fouling particles, which means that less can be deposited on the membranes.[36]

Polyelectrolyte multilayer membranes for water treatment: Another sub-cluster in the field of membranes in which NRW is heavily involved in international research is polyelectrolyte multilayer membranes. These are membranes which, due to their specific coating, are able to filter out even the smallest and smallest particles, microbes and dissolved substances from the water. This means that polyelectrolyte multi-layer membranes can also effectively filter traces of medicines or pesticides from wastewater, thereby contributing to the treatment of wastewater and the supply of drinking water.[37]

Antibiotic degradation through disinfection with chlorine: Chlorine has long been used as a disinfectant in the water industry. It is generally known in Germany through its use in swimming pools. Due to its chemical properties, chlorine is well suited to preventing contamination of water with bacteria and pathogens (viruses). In the context of antibiotic degradation, chlorine is often combined with various other substances (e.g. ozone) or techniques (e.g. UV light) to achieve the elimination of antibiotic residues in water.[38] However, further research and development is still needed in order to produce truly relevant innovations and possibly even a technology that can be used in water management to really advance the degradation of antibiotics in water.

In addition to these topics of global relevance, which are anchored in the North Rhine-Westphalian research landscape, there are international research priorities in China, the USA and Canada, in which NRW is less strongly represented. The innovations that emerge from these international research centres also contribute to solving the challenge of substance inputs and water pollution. The top three international research topics are presented below. They were derived by analysing the most publications worldwide combined with the number of papers published on the topic since 2020.

Covalent organic frameworks are a class of polymers. Thanks to their porous structure, which is characterised by a large number of microscopically small cavities and holes, they make it possible to store and filter or separate gases and liquids such as hydrogen or methane. The potential of covalent organic frameworks for water management has only been discovered in recent years and has since become the focus of more research. The hope is that the structure, which can be adapted to its task, could be used for nanofiltration in mixed membranes, for example, to desalinate water, remove organic impurities (e.g. dyes) or absorb metal ions (heavy metals.[39] With over 1,600 papers published on the topic of covalent organic frameworks, 69 % of which were published after 2020, this is a dynamic and emerging field of research.

Superhydrophobic membranes for the separation of oil and water: In this field of research, the focus is on materials that are as water-repellent as possible (superhydrophobic) on the one hand and attract oil (oleophilic) on the other. If such materials are processed together in membranes, they can enable the efficient separation of oil and water. Membranes of this type are already in use and have proven their worth: In the selective separation of oil-water mixtures, they have been able to achieve an oil separation efficiency of over 99 %. However, there is still a need for research into the effects of crude oil (and its components) on the separation performance of the membrane, for example, as well as the fouling behaviour of the membrane itself when it comes into contact with oil.[40]

Oxidative water treatment / advanced oxidation: This is a group of processes for effective and sustainable water treatment. The research field summarises various processes for the chemical treatment of water, in each of which hydroxyl radicals, ozone or hydrogen peroxide (or a combination of these) are used. Hydroxyl radicals are compounds of hydrogen and oxygen atoms that react with substances that are difficult to break down chemically and biologically. Oxidation is used to purify industrial, process and waste water containing substances that are not degraded in a purely biological treatment stage (e.g. pesticides, biocides and pharmaceuticals).[41] This makes oxidative water treatment a promising group of methods for water treatment. However, it is not yet clear which method could be widely used in water management.[42]

Assessment of the results

When categorising the challenge of "Risks from substance inputs and other contaminants", it became clear how many individual substances enter water bodies around the world, in Germany and in NRW via different routes. It also showed that innovative solutions are needed to either maintain or improve water quality. The analysis of the research trends shows: whether with innovative membrane technologies, the use of chemical substances, light or other processes – the entry of substances into water and the filtering out of these substances is a central component of research. This statement applies to most of the substances described above that find their way into our groundwater, be it fertilisers, microplastics, pharmaceutical residues or chemicals. This gives us hope for progress. It has also been shown that the research landscape in NRW is making an important contribution to international research in the field of membrane technology and is therefore a focal point in the development of a future key technology.

Filtering critical raw materials from the water

In addition to the increased availability of clean water, filtering polluted water using membrane technologies offers another advantage: critical raw materials can be recycled from it. Critical raw materials are of great economic importance, especially for renewable energies. However, due to the concentration of supply sources and the lack of recycling and substitution options, there is a high risk of supply disruptions – which is why they are labelled as critical.[43] The exciting thing is that these raw materials, such as manganese, phosphorus or even rare earths in some cases, can be detected again and again in different bodies of water. On the one hand, this offers the potential to recycle them and, on the other, the challenge of cleaning water bodies so that no harm is caused to humans, animals or the environment. However, research into this is currently still in its infancy and implementation is still very costly, at least for wastewater. Some of the technologies are already being used in the treatment of mine water in the mining industry.[44] More information on critical raw materials and their relevance for NRW can be found in Green Economy Paper #2.

3.3 Protection of aquatic ecosystems

The challenge – what's it all about?

In addition to water supply, global aquatic ecosystems are also facing increasing challenges due to climate change, urbanisation and industry. This is despite the fact that they fulfil several vital functions: They purify, regulate and store water, protect against flooding, stabilise the global climate and contribute to the preservation of biodiversity.[45] On the one hand, global water ecosystems are under great pressure as nature reserves, while at the same time their protection and management is proving to be an essential task for water management in order to make water supply and flood protection more resilient. The challenges to be overcome, depending on the region, the type of water body and the geographical conditions. The protection or restoration of rivers and lakes to a near-natural state, the protection of glaciers and the protection of soils and their capacity to absorb and store water (preservation of soil moisture) are key. A look at the waters of the European Union shows that the protection of aquatic ecosystems across the EU leaves much to be desired. Only 38 % of surface waters in the EU have an ecological status of "good" or better. Countries such as Luxembourg and the Netherlands currently have no surface waters in good status. The Czech Republic and Germany also only have a low proportion of ecologically good water bodies.[46]

The dual challenge is therefore to improve water quality and mitigate the consequences of climate change for water bodies. The focus here is on maintaining or restoring the ecological functions and biodiversity of water ecosystems, taking into account natural processes such as the self-purification capacity of water bodies and the natural water balance. The protection of water ecosystems therefore consists of the sustainable utilisation of water resources, the restoration of near-natural structures such as natural streams and rivers and the restoration of near-natural riparian zones as well as measures to improve water quality.[47] In order to improve water quality, it is also necessary to minimise risks from substance inputs and other pollutants, which is an additional challenge that has already been described in Chapter 3.2. In contrast to the specific risks posed by substance inputs, such as pesticides, microplastics or drug residues, the protection of aquatic ecosystems considers the entire ecosystem.

Germany and NRW must also face up to the challenge and approach the protection of aquatic ecosystems differently depending on how they are affected: Germany is divided into three types of landscape that have an influence on the respective aquatic communities: the North German Lowlands, the Central Uplands and the Alpine region. The three ecoregions differ in the types of water bodies they contain – the North German Plain is characterised by lake-rich, hilly moraine landscapes, the north-west by moors and heathland, and the Alpine region by numerous lakes. Germany is also characterised by ten river basin districts. What these different water ecosystems have in common is that they are under high pressure of utilisation and change due to shipping, settlement development and agriculture. Floodplains and natural habitats have been lost due to the expansion of waterways as federal waterways and the regulation of dams. Waters and their organisms are also polluted by the extraction of water by industry and agriculture and the introduction of chemicals, such as pharmaceuticals or biocides, and nutrients.[48] In addition, transverse structures, i.e. artificial installations in the river bed, can lead to the retention of sediments. In combination with the straightening of rivers, there is often a deficit in floodplain dynamics and redistribution possibilities. As a result of all this, only around 10 % of all watercourses in North Rhine-Westphalia, for example, can be assessed as having a very good or good ecological status.[49] Most of the moorland areas that are important for the water balance have also been drained, to provide more space for agriculture or settlements. In Germany, only 2 % of the original moorland areas are currently considered to be near-natural.[50]

In addition to the protection of biodiversity, measures such as the eco-restoration of rivers or the rewetting of moors have other advantages: near-natural watercourses and floodplains have a high capacity to store carbon from the air and thus serve as a natural climate protection measure. At the same time, they offer an opportunity to prepare for various extreme weather events, such as heat, flooding or heavy rainfall, and thus become more climate-resilient. By rewetting peatlands, they can also act as a sponge during heavy rainfall events and floods and thus protect against flooding. Furthermore, from a global perspective, natural peatlands store twice as much carbon as forests, even though they cover a much smaller proportion of the world's land area.

It is clear that the various challenges facing water management are closely linked. On the one hand, the protection of water ecosystems is dependent on measures that serve to reduce substance inputs and pollution. On the other hand, water protection measures also favour the possibilities for climate adaptation. The protection and restoration of river-floodplain ecosystems has therefore been prioritised as part of the EU Biodiversity Strategy, based on the Green New Deal. Applications in water management can therefore go beyond aspects of security of supply and also contribute to the protection of natural water ecosystems, which are essential in the context of the increasing demands of a sustainable and resilient future.[51]

Solutions: Protect aquatic ecosystems!

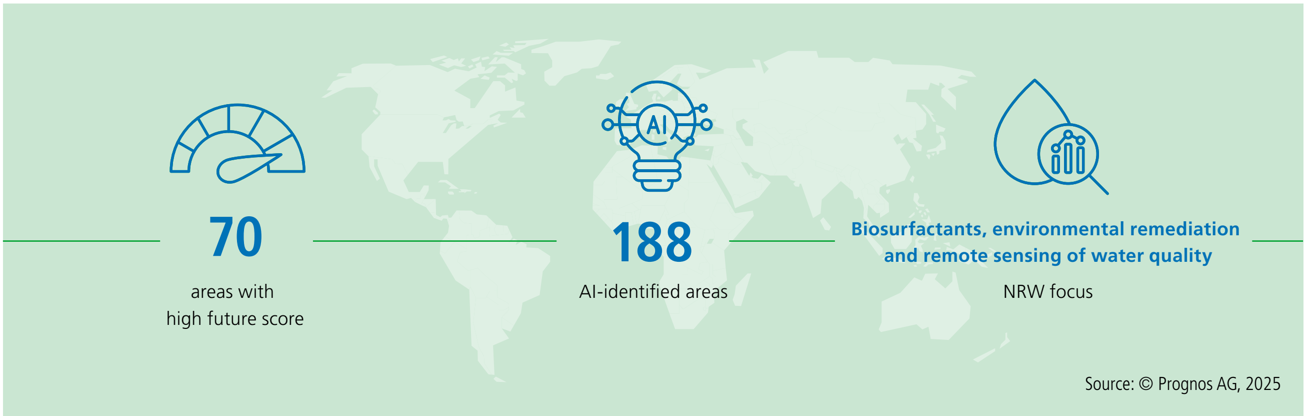
The challenge of "protecting aquatic ecosystems" was linked to a total of 188 topics from research into water management issues. 70 of these topics have a high or rather high future score. The research landscape in NRW is less focussed on these research fields. This is why NRW also has a rather low proportion of publications compared to the global research landscape. Research institutes from China and the USA account for the largest share of research in this area, but research from smaller countries such as Ireland also plays a recognisable role. Thematic overlaps are particularly evident with the topic of "substance inputs and other water contaminants", as an adapted filter technology for cleaning wastewater is indispensable for water protection (see chapter 3.2). In the following, pure filter technologies are excluded and the focus is placed specifically on innovations that specifically emphasise the protection of aquatic ecosystems.

Biosurfactants for environmental applications: Surfactants have the special property of mixing hydrophilic and hydrophobic substances with each other and are used, for example, to dissolve oil in water. They are therefore an important component of cleaning agents.[52] Biosurfactants are produced with the help of microorganisms and, unlike chemically produced surfactants, are biodegradable, environmentally friendly and less toxic. They are becoming increasingly important in soil remediation in particular. One example of their effectiveness is a biosurfactant made from yeast, which was able to remove up to 97.8 % of the poorly soluble pollutant from sand contaminated with crude oil.[53] As conventional surfactants themselves often contribute to environmental pollution, biosurfactants offer a sustainable and environmentally friendly alternative for wide-ranging industrial and environmentally friendly applications.[54]

Biochar-based environmental remediation: Contaminated soils have a dangerous impact on ecosystems. Remediation processes are used to contain and eliminate soil contamination by removing pollutants through various methods, such as soil washing or flushing. Biochar is increasingly being used to remediate contaminated soils, in particular to bind heavy metals. In soils with a high pH value, the surface of the biochar acts like a magnet and attracts the pollutants.[55] As a result, the pollutants are fixed and can no longer be absorbed by plants or washed into the groundwater. At the same time, the application can positively influence the growth of certain organisms. Among other things, research refers to the combination of biochar with other materials in order to enhance the effect of binding pollutants.[56] However, the literature repeatedly mentions that further research is needed in this field in order to investigate and minimise the potential ecological and environmental risks of biochar application, such as toxicity. It should be mentioned here that research work in this field can also be found in NRW, but NRW only accounts for a small proportion of the total publications in recent years.

Remote sensing for monitoring and assessing inland water quality: Monitoring water quality is highly relevant for the protection of aquatic ecosystems in order to be able to intervene in good time, e.g. in the event of acute pollution incidents. In particular, the extensive, area-wide sampling of water bodies requires new solutions to ensure dynamic and accurate monitoring of water quality.[57] Remote sensing for monitoring and assessing water quality in inland waters offers new opportunities for research. By using satellite imagery and advanced algorithms, researchers can efficiently collect data on various water quality parameters (such as the concentration of algae, suspended solids such as sand and clay or coloured dissolved organic matter) across spatial and temporal constraints. Water sampling

Figure 7: Research data on the challenge of protecting aquatic ecosystems



The bioSpectre project by Okeanos GmbH in Bochum aims to measure hard-to-detect wastewater quality parameters almost in real time using innovative sensors.

and the assessment of water quality, based on indicators such as pH or temperature, are also central and challenging topics in remote sensing of water bodies. In recent years, however, this area of research has made considerable progress through the use of drones and AI.[58]

Assessment of the results

One research focus with regard to the protection of aquatic ecosystems is the application of advanced technologies and methods in environmental and water remediation. These can be used to improve water quality and the ecological status of bodies of water. In future, remote sensing, sensor technology and machine learning can be used to monitor water quality. Research therefore contributes to the challenge of "protecting aquatic ecosystems" in two ways: Firstly, better monitoring will make it possible to respond more quickly to the pollution of aquatic ecosystems. Secondly, advanced methods ensure more effective and environmentally friendly protection. However, according to the data analysed here, research institutes from NRW have not yet made a significant contribution with their publications in these areas.

3.4 Climate adaptation of water infrastructure

The challenge – what's it all about?

The water infrastructure in Germany supplies 97 – 99 % of households, businesses and public institutions across all sectors with water. This supply is guaranteed by a 554,000 km long drinking water network and a 606,000 km long wastewater network.[59] In addition, there are numerous connected infrastructures, such as sewage treatment plants, dams, reservoirs, wells and hydropower plants. Water management and water supply infrastructure is a public service and critical infrastructure whose functional and operational safety is increasingly jeopardised by the rise in extreme weather events. This applies not only to Germany, but all over the world. According to the Federal Environment Agency (UBA), the water cycle is "highly sensitive to climate change" and is considered one of the "highly vulnerable areas".[60] It is therefore clear that the water infrastructure in NRW, Germany and the world must adapt to the increasing challenges posed by climate change so that it can continue to reliably guarantee its supply functions.

Last year alone (2024) highlighted the devastating consequences of extreme weather events for water infrastructure: in September, one of the worst floods in three decades put large parts of Central Europe under water. People in Germany, Austria, Poland, Romania and the Czech Republic were affected.[61] In October, the Valencia region in Spain was hit by a devastating flood,[62] which in Germany was reminiscent of the disaster in the Ahr Valley in July 2021. Extreme rainfall can overwhelm existing water infrastructure within a very short time. Rivers (which have often been straightened in the past) burst their banks, as do reservoirs. Water can no longer run off via the usual channels and quickly collects at the lowest point of a village. Sealed surfaces often mean that the water initially stands there and cannot drain away. If it does run off, the dirty rainwater or river water mixes with dirty water in the sewage system and is sometimes discharged unfiltered. This can have consequences for the receiving ecosystems. These developments often take place at breakneck speed and not only paralyse the water supply. In fact, every flood event poses a threat to businesses and homes as well as to life and limb. Once the flood has been overcome, high amounts of damage usually have to be settled. The flood in Central Europe in 2024 described above alone caused damage of 1.3 billion euros in Austria.[63] Against this backdrop, it quickly becomes clear why it is important to prepare the existing water infrastructure for the growing challenges posed by heavy rainfall and flooding as far as is technically possible. What's more, the water industry's precipitation forecasts – and therefore also the expected water load that infrastructure such as sewer networks and retention basins have to cope with – are based on data from the last century, which cannot be transferred to an age of dynamic extreme weather events and are changing due to climate change.[64] To deal with this problem, new ways of analysing and recording data are needed that anticipate sudden and unusual events at an early stage.

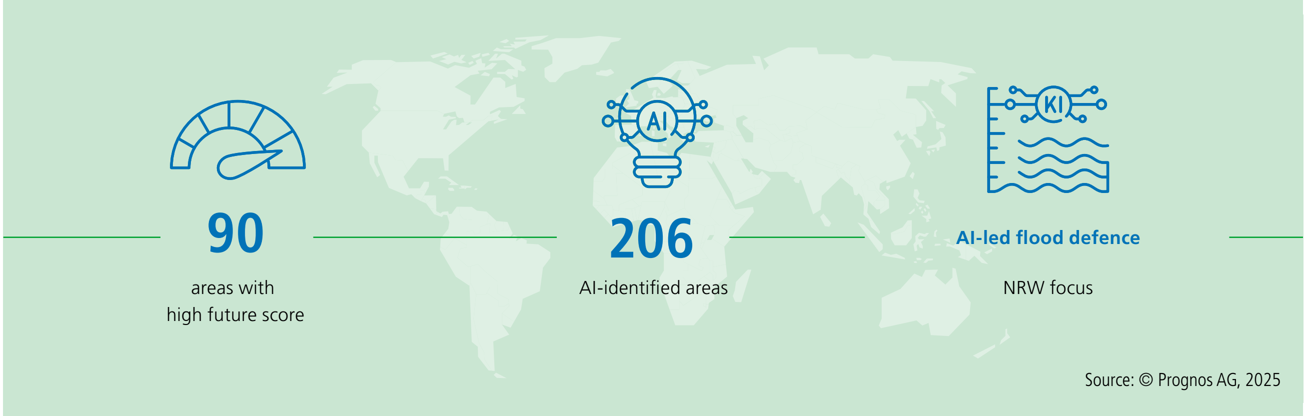
Solutions: Adapting infrastructure to climate change and extreme weather!

206 research topics relating to the climate adaptation of water infrastructure were identified in the data analysed. Of these 206 research topics, 90 have a high or rather high future score. Outstanding contributions from NRW and its research landscape on the topic of "Climate adaptation of water infrastructure" were identified from the data analysed, particularly in one area. When it comes to the development of applications that predict floods with the help of artificial intelligence, research institutions from NRW are heavily involved in international research and development:

Artificial intelligence for predicting floods and inundations: Floods and inundations are a consequence of the global increase in extreme weather events due to climate change, which jeopardise both infrastructure and human lives. Accurate forecasting of water levels, floods and flooding areas is crucial in order to maximise protection against incoming water masses and ensure advance warning times for disaster prevention. This is why AI and deep learning-based forecasting models are increasingly being developed to predict the course of flood situations on the basis of historical data, sensors, weather forecasts and/or hydrological models. Such AI applications can be used in water management to identify areas and infrastructure at risk of flooding at an early stage and to better prepare them for extreme weather events or to be able to react better in acute flood situations. The first applications of this kind are currently approaching or have already reached market maturity.[65]

In addition to the use of AI for the early detection, warning and forecasting of floods, other international research topics are characterised by a high level of innovation. Institutions from China and Canada are particularly active here, but also from European countries such as the Netherlands and France. Two of these topics, which result from the most publications since 2020 in conjunction with a high future score, are presented in more detail below. Modern technologies such as AI and sensor technology also play a key role here:

Figure 8: Research data on the challenge of climate-resilient water infrastructure



Deep learning-based prediction of dam failures: Extreme weather events such as heavy rainfall and flooding place extreme pressure on water infrastructure. Dams and reservoirs, for example, have to hold back significantly more water than under normal conditions. This can lead to damage, deformation and, in the worst case, even breaches in the protective infrastructure. Until now, it has been difficult to calculate when and under what pressure a dam or reservoir could be damaged. Deep learning technologies could provide a better data basis here in the future. By taking real-time weather data and various early warning factors into account, deep learning applications could provide early warning of infrastructure overload and thus enable timely action to be taken.[66]

Detection and localisation of leaks in water distribution networks: In summer and during hot spells, there is a shortage of water supply in many parts of the world. Given the increasing frequency of hot days, this problem could become even more acute. This makes it all the more problematic that currently around 30 % of the water that flows through water distribution systems worldwide is lost through old and leaking pipes, for example.[67] In order to reduce this water loss, research is being carried out into various methods that serve to quantify, recognise leaks at an early stage and prevent them. Networked sensors that record the water flow and generate data are fundamental. Pressure and flow measurements are used to create calculation models to detect leaks in the water distribution system, but AI models are also being developed for this purpose.[68] These methods or technologies can ensure that less water is lost in the future. Synergies can also be created here with the challenge of "water-compatible and climate-resilient land use in urban and rural areas", as the water saved can be used in urban and rural regions.

Assessment of the results

One innovation trend is clearly visible in the area of climate-adapted water infrastructure: the implementation of digitalisation technologies such as AI, sensors and algorithms. This development is sensible and promising, as it significantly upgrades existing and functioning infrastructure and makes it more efficient. AI applications help to manage extreme weather events and monitor the condition of water infrastructure. A digitalised water infrastructure can thus better counteract the increasing frequency of extreme weather events. In addition to research in NRW, initiatives from industry are also driving the digitalisation trend. Accordingly, it can be stated: When it comes to adapting existing infrastructure to the climate or developing new infrastructure, promising innovation paths can be recognised in NRW.

3.5 Water-compatible and climate-resilient land use in urban and rural areas

The challenge – what's it all about?

The way we use soils and land significantly shapes the future of our livelihoods. Sustainable land use is not only crucial for achieving greenhouse gas neutrality and preserving flora and fauna, but also for stabilising the near-natural water balance and protecting our water resources. At the same time, a stable water balance is a necessary condition for sustainable land use.[69]

Around a third of the total area of our planet – 4.78 billion hectares – is currently used for agricultural purposes,[70] in NRW it is even almost half of the land area.[71] No other sector consumes as much water as agriculture: 72 % of the fresh water used worldwide is used for food production. There is no question that agriculture plays a key role in supplying our societies with food and animal feed – especially against the backdrop of a growing world population and rising living standards. However, these developments are also accompanied by a higher demand for resources, which results in the expansion of agricultural land, an intensification of land use and an increasing demand for and consumption of water. As a result, a steadily increasing proportion of agricultural land has to be irrigated artificially, which now accounts for around 20 % of the world's arable land – a doubling since 1961.[72]

The situation is further exacerbated by the consequences of climate change, which are already limiting the availability of water for agriculture with significant regional differences. Even though Germany is one of the most water-rich countries in the EU, artificial irrigation is increasingly necessary here too, especially in vegetable cultivation.[73] In order to maintain the crops currently grown, the need for irrigation in NRW is expected to increase twenty-fold by the end of the century.[74]

However, intensified land use not only leads to an increased demand for water, but also influences water quality. For example, more nitrogen is being applied in the form of mineral fertilisers. The result is an excess of nitrogen, some of which enters ground and surface waters as nitrate, causing considerable damage to water resources. The situation is similar with pesticide pollution (see section 3.2). This is clear: Water quality is closely linked to the type and intensity of land use.

Urbanisation is continuing to increase rapidly worldwide. According to forecasts, around 70 % of the world's population will live in cities by 2050.[75] In 2016, over 30 % of the urban population already lived in areas with water scarcity. This is driven by a lack of surface water, soil sealing, groundwater overuse and the increase in water demand due to rapid urbanisation and rising per capita demand. Climate change will further increase droughts worldwide and exacerbate this situation.[76] The number of people living in cities with water scarcity worldwide could rise from more than 933 million in 2016 to between 1.6 and 2.3 billion people in 2050. A study by Oxford University also found that increasing urbanisation and the associated high demand for water in cities is leading to water being diverted from rural areas to cities. As a result, the risk of droughts and conflicts increases in rural areas.[77] Without adequate treatment of urban wastewater, it can also represent a major burden for ground and surface waters.

The increase in extreme weather events also poses enormous challenges for our current water infrastructures, as already described in chapter 3.4. Increasingly, heavy rainfall means that the sewerage system and urban waterways are no longer able to cope with the increased surface runoff, resulting in more flash floods and flooding. In addition, the increased land consumption in cities and the high level of surface sealing mean that there are insufficient areas for infiltration. Furthermore, the high levels of urban sealing and lack of green spaces lead to the increased occurrence of heat islands.[78]

In principle, cities are highly dependent on the surrounding area for their water supply. Local land use and land use changes therefore have a considerable influence on the water supply of cities. Water utilisation in cities can in turn lead to competition with uses in the surrounding area, for example between different water users such as agriculture, public water supply, nature conservation or tourism and irrigation in urban areas. Different land use requirements can also lead to conflicts between the city and the surrounding area. This can be the case, for example, if areas that are actually intended for flood risk management (such as retention areas) or water supply (such as water protection areas) are converted in favour of urban areas in the surrounding countryside for other purposes such as energy production or the cultivation of food or animal feed.[79]

Solutions: Making urban and rural land use water-friendly and climate-resilient!

A total of 72 research topics related to the challenge of "Water-compatible and climate-resilient land use in urban and rural areas" were identified. Of these, only 16 have a high or rather high future score. The North Rhine-Westphalian research landscape has a share of over 6 % of the publications in one of the 16 research fields and is therefore significantly involved in international research work:

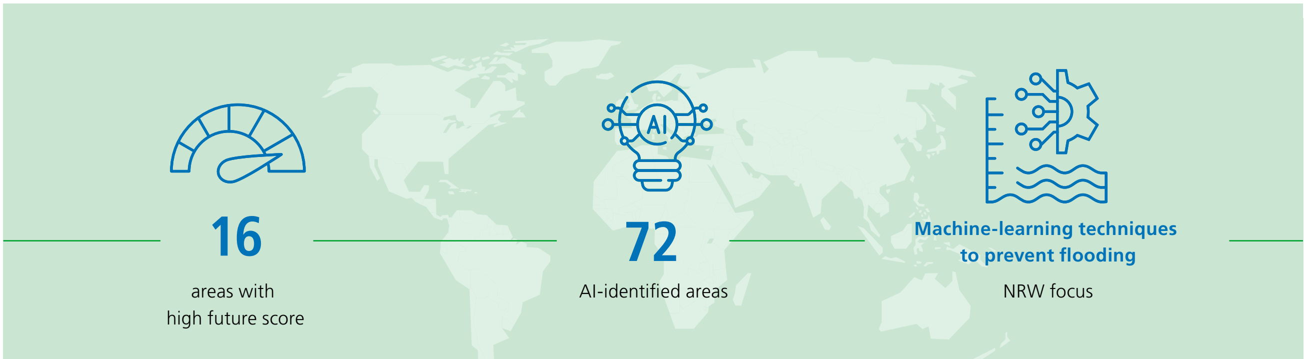
Predicting and modelling flooding in cities using machine learning: As cities are particularly affected by flooding due to high population density and a high degree of sealing, the timing of the warning is a key factor in cushioning the consequences of such disasters in the best possible way, preparing infrastructure appropriately and saving human lives. To this end, the use of AI and machine learning for predicting flood situations and flooding has become increasingly important in recent years, which is also reflected in the fact that a great deal has been published on this topic. In particular, data-driven models that use artificial neural networks show promising results and shorten the calculation times of physically based simulations.[80] The use of AI-supported flood forecasting technology is not limited to applications in the area of critical infrastructure, as described above. Rather, companies and local authorities can also benefit from the use of such technology in urban areas in order to improve their own flood protection and recognise weak points and hazards.

Although NRW has a small share of relevant research fields in all other publications identified since 2020, further research priorities can be recognised in the international context that contribute to solving the challenge, particularly with regard to addressing water scarcity in rural areas. Research from institutions in China, the USA, Spain and South Korea, among others, is strongly represented in these areas. Three further important innovation topics are presented below. These were determined using a combination of the most publications since 2020 in conjunction with a high or rather high future score.

Nature-inspired technologies for water extraction from fog: This approach refers to the development of technologies for efficient water extraction based on bionics, i.e. the transfer of natural phenomena to technology. The Namib Desert beetle, spiders (webs) or plant species such as cacti, which are at home in particularly dry regions of the world, serve as models here. Especially in hot and dry conditions, water often evaporates before it can be collected. However, water can still be extracted using certain materials and transported away quickly. Current research is therefore focussing on the development of highly efficient fog collectors that rely on surface structures similar to those found on the backs of desert beetles or the spines of cacti, for example.[81] Fog is particularly common in coastal and mountainous regions and can be collected by fog collectors or fog nets and used for water supply. This field of research has particular potential for regions with little access to clean water.

Optimised water management for fruit trees in arid / semi-arid (very dry / dry) regions: In order to counteract drought and drought risks and at the same time maintain productivity and contribute to food security, the adaptation of irrigation and irrigation techniques is also becoming increasingly necessary in crop production.[82] Against this background, the research field is dedicated to the question of how water and fertilisers can be used optimally in fruit growing in arid and semi-arid regions. Research has shown that traditional irrigation is not a sustainable solution due to climate change and the associated water shortage, while at the same time there are competing uses for water. Intensive research is therefore being carried out into the development of energy-efficient, water-saving irrigation technologies in order to increase yields and prevent soil degradation, e.g. through underground irrigation with ceramic nozzles.[83] In addition, various water-saving techniques such as rainwater harvesting and drip irrigation in apple orchards are compared in terms of their water utilisation efficiency[84] or it is

Figure 9: Research data on the challenge of water-compatible land use in urban and rural areas



Source: © Prognos AG, 2025

The world's largest fog collector installation, made up of CloudFisher units from the WaterFoundation, is located on Mount Boutmezguida in Morocco.

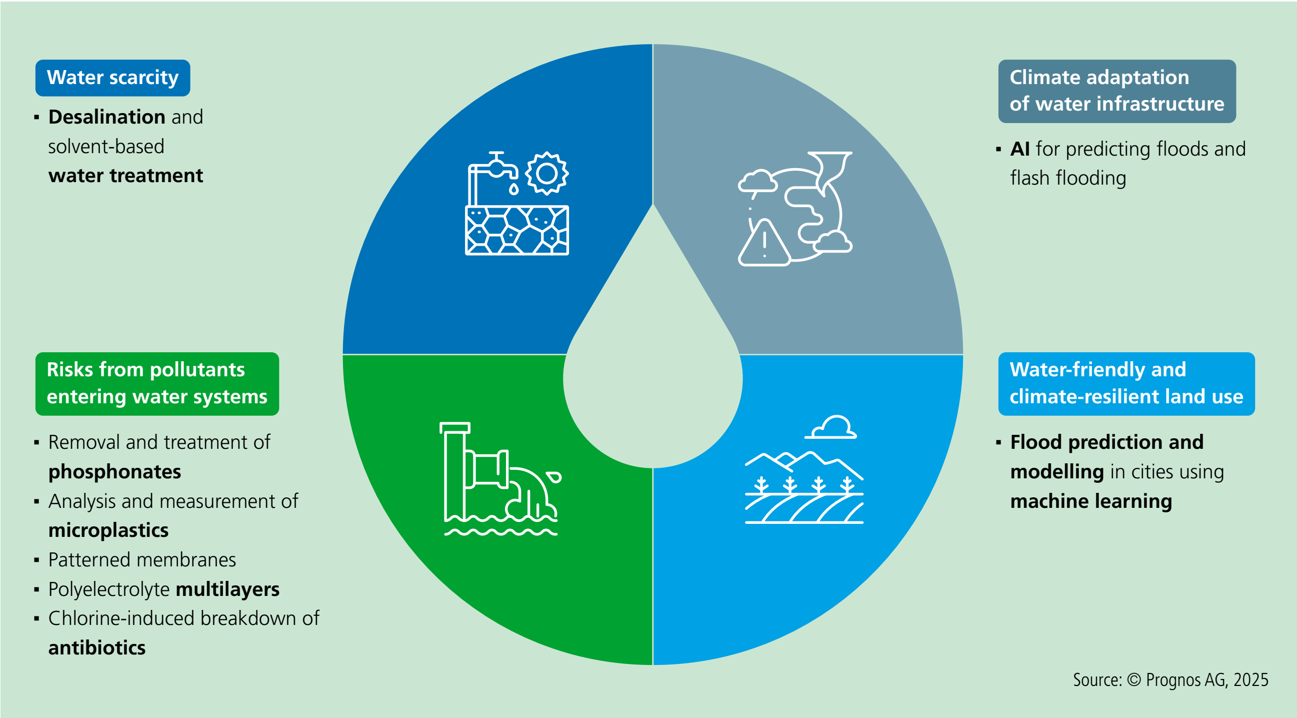
being investigated how much water can be saved by deficit irrigation* in various fruit trees.[85] Other studies are focussing on the development of models for real-time irrigation using thermal images of tree crowns.[86]

Use of hydrogels in agriculture: The hydrogels that we constantly encounter in everyday life, for example in cosmetics or hygiene products such as nappies or in the packaging industry[87] are also attracting increasing attention in agriculture worldwide. Hydrogels are super-absorbent polymers (SAPs) that can absorb and store large quantities of water and plant nutrients. As a result, they can significantly increase the efficiency of water and nutrient utilisation in agriculture and support plants, particularly during dry periods.[88] Research shows, for example, that water stored in hydrogels at the plant root is slowly released as soon as the soil begins to dry out. not only increases the efficiency of water utilisation, but also extends the intervals between irrigation, while at the same time reducing irrigation costs and supplying plants with the necessary nutrients.[89] Against the backdrop of increasing water demand in agriculture and simultaneously decreasing water supply, hydrogels can play an important role in more efficient water utilisation.

Electrochemical nitrogen reduction for ammonia synthesis: Ammonia (NH_3) , a compound of nitrogen and hydrogen, is one of the most important chemicals in the world. Around 80 % of the NH_3 produced is used as a fertiliser. On the one hand, the chemical is therefore of great importance for the world's food supply.[90] On the other hand, most of the nitrate that enters the environment today and increasingly pollutes our surface waters and groundwater comes from the excessive use of nitrogenous fertilisers. The conventional Haber-Bosch process enables large-scale ammonia production.[91] In this process, a reaction between hydrogen and nitrogen takes place under high temperature and pressure conditions – a very energy-intensive process that is responsible for around 1 % of annual greenhouse gas emissions worldwide.[92] Against this backdrop, research into sustainable processes for ammonia production has been stepped up in recent years, with electrochemical nitrogen reduction in particular being seen as a promising approach. In contrast to the Haber-Bosch process, the process extracts the nitrogen from nitrate-containing (waste) water and can ideally be carried out using electricity from sustainable sources such as wind and solar energy. Overall, electrochemical nitrogen reduction for ammonia synthesis offers the potential to promote more sustainable agriculture by making the production of ammonia fertilisers more environmentally friendly and reducing both CO_2 emissions and nitrate pollution in wastewater streams. The possibility of decentralised production and the use of renewable energies make this process a promising technology for greener, more resource-efficient and water-friendly agriculture.

* Deficit irrigation refers to the targeted irrigation of crops with less water than their actual requirements in order to maximise production per unit of water used.

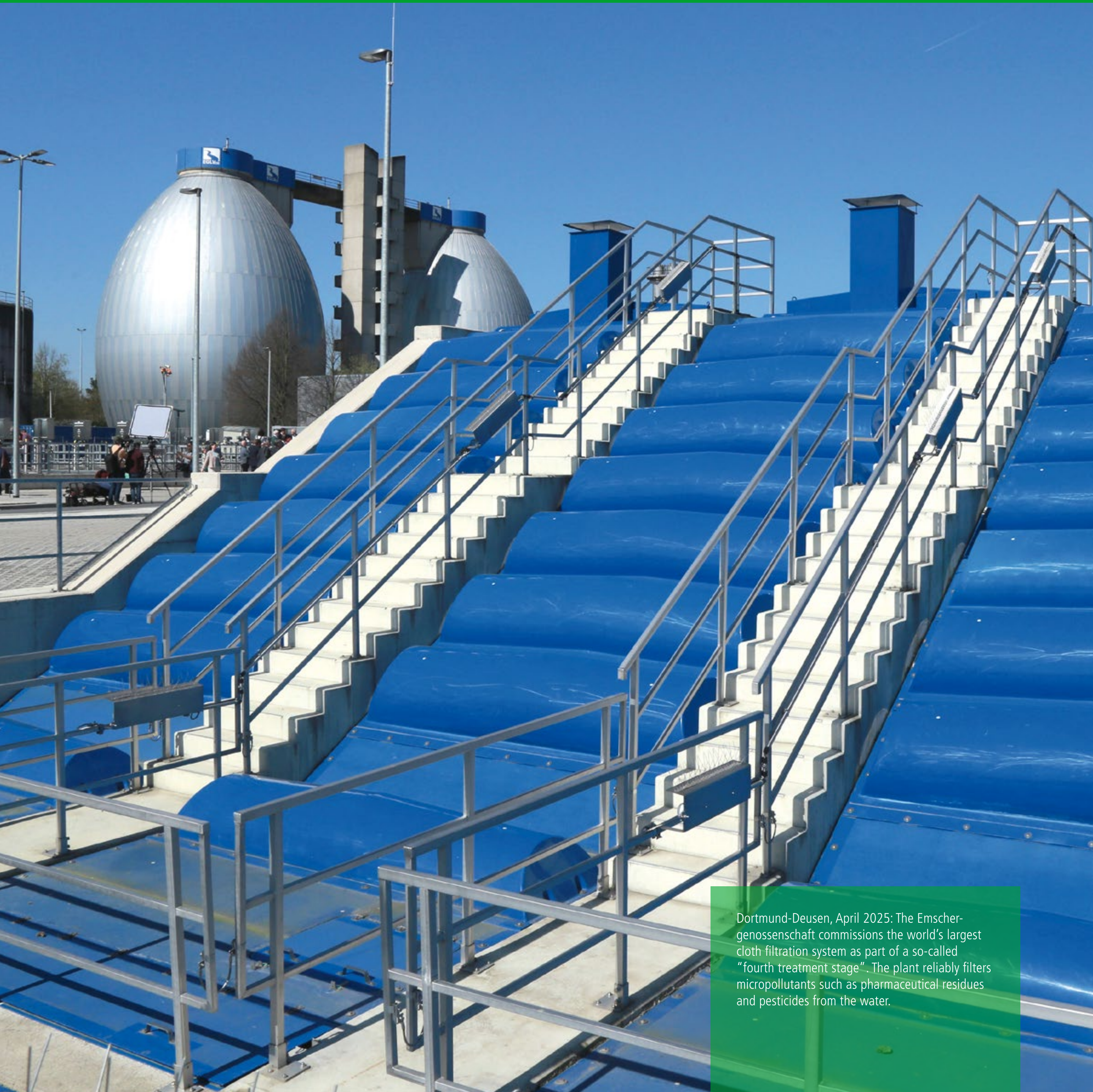
Figure 10: Research priorities in NRW, assigned to the water management challenges that they contribute to solving



Assessment of the results

IOverall, it can be said that NRW has made research contributions that are strongly linked to machine learning and flood forecasts based on this and that promote water-related urban climate resilience. In contrast, there are a number of innovative contributions in the international context for optimised water use in rural areas. From contributions to water harvesting in arid regions, to solutions for water conservation in agriculture, to approaches for nitrate reduction in agricultural wastewater with simultaneous ammonia production – overall, the solution approaches have a clear focus on ecological sustainability. All research priorities from North Rhine-Westphalia (NRW) have been linked to the relevant challenges they address and are summarised in figure 10.

4 Megatrends and technologies in water management

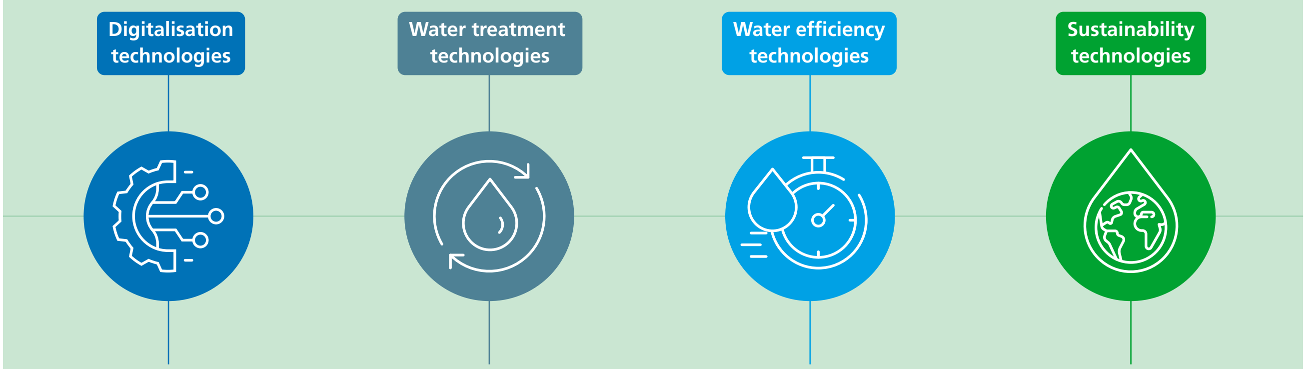


Dortmund-Deusen, April 2025: The Emschergenossenschaft commissions the world's largest cloth filtration system as part of a so-called "fourth treatment stage". The plant reliably filters micropollutants such as pharmaceutical residues and pesticides from the water.

The presentation of the key challenges facing the water industry on the one hand and the analysis of the numerous solutions on the other in the previous chapter have shown one thing: The high level of innovation in the water industry reflects the importance of the topic and the dimensions of the challenges. The research is so comprehensive that not all research developments can be analysed in this paper. However, in order to cover as many results as possible, a systematic search for correlations within all topics was carried out when analysing the data. Four megatrends were identified that make it possible to visualise the broad lines that emerge across the 1,200 topics identified by the AI analysis.

These megatrends are overarching topics that reflect research from many individual subject areas. They can be understood as thematic directions that can be expected to have a significant impact on the global water industry in the coming years. These megatrends are presented in detail below:

Figure 11: The four megatrends in the water sector – a summary at a glance



Key features:
AI and IoT are opening up new possibilities and enabling efficient applications in many areas of the water sector.

Key features:
Pollutants are being filtered out of water with increasing efficiency. Advances in membrane technologies and photocatalysis are playing a key role in this.

Key features:
Water is being used more efficiently without compromising quality or availability. Technological innovations allow for more targeted control and reuse of water.

Key features:
Existing and new technologies in the water sector are being developed with a stronger focus on environmental sustainability.

Source: © Prognos AG, 2025

4.1 Digitalisation technologies

The world has changed radically in terms of intelligent and digital applications over the last five years. Artificial intelligence has found its way into our lives since the release of OpenAI's ChatGPT application in November 2022 at the latest. And the water industry is also affected by these developments on many levels. AI is used to predict heavy rainfall events and flood forecasts in order to better prepare infrastructure and protect urban areas (see 3.4 and 3.5). AI is also used in the management and provision of water. For example, AI tools can use historical data to calculate water consumption (e.g. in a city) at a specific point in time, thereby enabling more efficient and targeted provision of the resource.[93] AI is also used in the treatment of wastewater, e.g. to control the cleaning processes or the fouling of membranes. Research is being conducted into other areas of application in the context of wastewater.[94] The Internet of Things (IoT) is also an innovation factor for the water industry. The use of interconnected and communicating technologies (such sensors and intelligent measuring devices) plays a major role, particularly in the area of process monitoring and control. This makes it possible, to permanently monitor physical and chemical parameters and analyse them in real time in order to be able to react quickly to any changes that occur. IoT applications can also help in the supply of water to agriculture, for example by reporting the irrigation status of plants and thus warning of water shortages and overwatering.[95] The possibilities are also likely to expand significantly in the coming years at the interface of AI and the Internet of Things. For specific digital tools and developments, it is worth taking a look at the previous section 3.2 of this paper.

4.2 Water treatment technologies

As already shown in the description of the challenges for water management in chapter 3 potentially hazardous substances enter the environment via wastewater and jeopardise human and animal health and the condition of ecosystems. This applies, for instance, to antibiotics and other pharmaceutical residues, microplastics, industrial chemicals as well as fertilisers and antibiotic-resistant germs. To ensure that contaminated water does not end up in bodies of water or from the tap in the future, a wide range of research is being conducted into efficient methods of water treatment. In most cases, established fields of research are being advanced. A good example of this is membrane technology (see also section 3.2). It has been used for years to purify water (especially filtration) in order to remove particles (bacteria and viruses) and substances. The technology is constantly being developed further and research is being carried out into new filtration options, i.e. substances that can be extracted from the water through membranes. For example, polyelectrolyte multilayer membranes that filter even the smallest particles and microbes from the water. Patterned membranes, which themselves pollute less quickly, membranes that can filter heavy metals from wastewater[96] or membranes that separate oil and water.[97] Photocatalysis is another technology that has been the subject of increasingly intensive research for some time and is being used more and more for the treatment and purification of water. In this process, materials such as the semiconductors titanium dioxide and zinc oxide are used in combination with light to induce or accelerate chemical reactions in water. With the help of various photocatalysis techniques, pollutants and pathogens in water can be broken down or disinfected.[98] This applies, for example, to certain colourants, pharmaceutical residues, pesticides and industrial chemicals. Another major advantage of photocatalysis is that, unlike many conventional methods, it does not rely on chemicals to realise degradation processes. However, there are still a number of factors that stand in the way of widespread use of the method, e.g. even lower efficiency in some cases than with conventional methods and the need for constant optimal light irradiation, which is not available under all conditions. Other water treatment technologies that are the subject of much research include the use of nanomaterials (e.g. carbon nanotubes, silver and copper nanoparticles) to filter contaminants that are not captured in the first, second and third purification stages.[99]

Connected urban greenery: The City of Bonn is testing real-time soil moisture sensors to optimise irrigation for young trees, which are particularly vulnerable to drought.

4.3 Water efficiency technologies

Another overarching megatrend focuses on the optimised and efficient use of water in various areas of water management and related sectors. For example, the use of sensor technology and AI is being researched for solutions for the precise and rapid detection of leaks in order to avoid unnecessary water losses. This necessity is also reflected in the fact that water losses in most water distribution networks worldwide amount to more than 30 % (see 3.4).[100] Innovative technologies for increasing water utilisation efficiency can play an important role not only for greater efficiency in water infrastructure, but also in water treatment. Water efficiency is also in demand in sectors such as steel, pulp and paper production as well as in the chemical, oil and gas industries – after all, these industries are among the largest consumers of water worldwide. New technologies can play a decisive role here in saving water in the various processes – from production, processing, washing, cooling and transport.[101]

The use of water-efficient technologies is also attracting a great deal of attention in agriculture. In particular, research is being conducted into technologies for intelligent and automated irrigation using IoT and automation. The aim here is to optimise irrigation in line with the water requirements of plants and avoid wasting water unnecessarily.[102] Overall, it can be said: The increasing scarcity of water is driving the development of innovations in the field of water efficiency across various sectors worldwide. The importance of innovation in this area is also reflected in the European Strategy for a Resilient Water Supply announced for the second quarter of 2025. Specifically, the guideline "Water efficiency first" states that "reducing water consumption and abstraction through increased efficiency and a more circular economy[103] is essential for water supply and thus for Europe's well-being and competitiveness.

4.4 Sustainability technologies

With the 2030 Agenda and the European Green Deal, the European Union has set itself the goal of promoting sustainable development worldwide and achieving climate neutrality in the EU by 2050. These resolutions have paved the way for a green transition in all sectors – from industry and transport to the building sector and energy supply. The Clean Industrial Deal presented by the EU Commission in February 2025 also aims to secure the EU's competitiveness and climate neutrality. It is therefore not surprising that this trend is also reflected in the data analysed here. Across all fields of research, it is clear that the further development of (existing) technologies in an eco-

The renewal of the network infrastructure, such as here in Hattingen using the pipe pull-in method, prevents leaks in the pipe network.

Figure 12: Countries with the highest share of high future score publications in water research, 2020–2024

The chart shows the share of global publications with a high future score originating from national scientific institutions

Source: © Prognos AG, 2025

logically sustainable direction is a key issue. For example, water treatment processes are being combined with the use of renewable energy sources, such as in solar-powered desalination processes. At the same time, research shows that more research is being conducted into the use of substances and materials that are far more environmentally friendly and biodegradable than their conventional counterparts, such as the use of biosurfactants to break down pollutants (see section 3.3) or the use of hydrogels for increased water utilisation efficiency (see section 3.5). Overall, this will make existing processes more sustainable and more attractive for future applications.

5 Categorisation of the results with reference to NRW: Bringing innovations together with political strategies and existing structures

Transforming the former opencast mines in the Rhenish lignite region into attractive lake landscapes presents the greatest challenge for the water sector in North Rhine-Westphalia since the start of the Emscher redevelopment.

Water management in NRW, Europe and the world is currently facing a number of disruptive and complex challenges that are often interrelated. Increasing water scarcity, endangered aquatic ecosystems, water contaminated by pollutants, the need to adapt water infrastructure to climate change and the need for more sustainable land use in urban and rural areas – this long list illustrates the need for action in order to maintain the functionality of water management in the future and adapt it to new conditions.

For this to succeed, political action at international, national and NRW state level must be aligned along clear structural guidelines and innovations from research and development must be integrated. Guidance is provided by programmes such as the NRW climate adaptation strategy,* which has already been adopted, and the NRW Water Strategy for the Future, which is currently being developed. Both state strategies are an integral part of a comprehensive policy aimed at securing the water resources in North Rhine-Westphalia in a sustainable and climate-stable manner. Points of contact for the integration of innovation and research can also be found in the state's existing infrastructure and climate adaptation projects. With such an integrated approach, NRW can also play a pioneering role internationally in the implementation of innovations in water management.

The aim of this chapter is to link the results of this third Green Economy Paper with the political strategies in the context of North Rhine-Westphalia in order to bring together specific projects with innovations and solutions. The challenges of water management, the concrete results of the Green Economy Paper and the most important political strategies at NRW level are developed into solutions under four headings. The first about the functions of the water sector in times of climate crisis, the second is about wastewater treatment and water infrastructure, the third is about cooperation with international partners and the fourth is about digital excellence in the water sector.

5.1 Water management functions times of climate crisis

NRW's technology positioning in climate

The dramatic and momentous events of the floods on the Ahr and Erft rivers as well as in the Sauerland region have shown that flood protection must be a high priority in the context of ongoing climate change. This realisation is in line with the analysis of central political strategies, such as the National Water Strategy in Germany and the key points of the Future Water Strategy in NRW. In this context, it is encouraging that the analysis in this paper has shown that research and industry are realising innovative potential, particularly at the interface of extreme weather forecasts and artificial intelligence, which can help to promote flood protection. There are therefore excellent opportunities for NRW to explore new and possibly more efficient ways of upgrading infrastructure in technological terms. To this end, the state's tenders can create scope for innovations and innovative approaches that further develop existing approaches and promote new developments. In addition, the keyword "real-world laboratories" (see NRW Climate Adaptation Strategy) could create the necessary creative space that enables innovative solutions to be implemented through temporary changes to procedures. In the best-case scenario, examples of best practice could even emerge, making NRW a pioneer of climate resilience and laying the foundations for cooperation with international partners who would like to learn from applications in NRW.

In the area of climate adaptation in particular, it is not only clear from political strategies that many projects are already being implemented. The practical example of Resilience Expo – the international trade fair for the climate adaptation economy in NRW – also demonstrates an am-

* NRW's climate adaptation strategy includes 110 measures to protect human health, the environment and infrastructure as well as to improve the quality of life. Water management is an integral part of the canon of measures, e.g. the 10-point work plan "Flood protection in times of climate change" is named and bindingly regulated in its implementation, as is the expansion of risk management for urban flash floods.

A key focus of the RESIST Collaborative Research Centre (Degradation and Recovery of Stream Ecosystems Under Multiple Stressors), involving the University of Duisburg-Essen, is the analysis of drying water bodies – an increasingly frequent stressor in times of climate change.

bitious approach from NRW with an international dimension. The Resilience Expo project in the Rhenish mining district aims to position NRW as a leading player in the provision of climate adaptation technologies. This is also important for the water management sector, as a significant proportion of climate adaptation technologies are developed for the water sector. The Resilience Expo concept includes the targeted involvement of international players and exhibitors in order to ensure the supra-regional appeal of Resilience Expo. As a result, the Expo will be recognised beyond the borders of the Rhenish mining district and create valuable synergies with international developments in the field of climate adaptation. The Expo can also play an important role in the concept and development of the International Building and Technology Exhibition (IBTA) in the Rhineland region.

Green-blue infrastructures, aquatic ecology and biodiversity

As this paper has shown, the challenge of water-compatible and climate-resilient land use in urban and rural areas will be of particular relevance in the future. The state of NRW is already active in this area by promoting green-blue infrastructure. The promotion of green-blue infrastructure focusses on the integration of green spaces (such as parks, gardens and green roofs) and water areas (such as rivers, lakes and rainwater systems) in urban environments. This infrastructure plays a prominent role in improving the quality of life in cities by providing environmental, social and economic benefits. Important here is the modern concept of Nature-based Solutions (NBS), which focuses on measures that utilise natural processes to not only preserve but also enhance ecosystems. The implementation of NBS as a link to a nature-based green-blue infrastructure requires careful planning and cooperation between various stakeholders to ensure its effectiveness and sustainability. The promotion of corresponding projects must be continued and the integration of innovative solutions further expanded.

In addition to urban functions, water ecology and biodiversity must be taken into account in planning and, in some cases, technology. These measures are part of a comprehensive approach to the sustainable management of water resources and the simultaneous promotion of biodiversity. In addition to the renaturalisation of water bodies through the restoration of near-natural river courses and floodplain landscapes, the protection of wetlands as biodiversity hotspots is one of the most important tasks.

5.2 Wastewater treatment and water infrastructure

Expansion of technological leadership in wastewater treatment

In addition to general research trends and global innovation topics relating to water management, one topic was identified in the course of the analysis in which the North Rhine-Westphalian research landscape is particularly strongly represented: membrane technology. In NRW, a high-profile development can already be recognised in the field of membrane technology for water purification, with the help of which it is becoming increasingly possible to filter more complex pollutants from water. The research and business landscape in NRW is thus making an immense contribution to one of the central challenges facing water management worldwide: the increasing pollution of water. In addition, companies and research in the field of membranes are part of the global megatrend of water treatment technologies and are thus leading NRW to a leading position in wastewater technology.

In order for NRW to secure this leading position in wastewater treatment in the long term, it is necessary to develop and implement new technologies to overcome current and future challenges in wastewater disposal. The fields of innovation presented in Chapter 3.2 offer suggestions for this. However, it is also highly relevant to promote and support the implementation of technical solutions through political strategies. This is being done, for instance, as part of the key issues paper on the future water strategy of the state of North Rhine-Westphalia, which aims to promote the implementation of modern wastewater treatment technology.

Water infrastructure as the backbone of key economic and social needs

Securing a reliable water infrastructure for future generations is a central task of water management. Unlike in many other areas of society, infrastructure is managed for several decades once it has been put into operation. It is therefore also necessary to modernise infrastructure once it has been connected and to adapt it to dynamically changing conditions, such as climate change. Without such an approach, there is a risk that existing systems will no longer be able to fulfil their tasks. Innovative approaches from research and development must be consistently implemented. Modernisation measures for water infrastructure can include, for example, the expansion of water systems as well as the disposal and treatment of wastewater (see section "Expanding technological leadership in wastewater treatment"). However, the focus is also on sustainable and reliable water supply. For example, the functions of the reservoirs in North Rhine-Westphalia need to be redefined and reassessed against the backdrop of climate change. Innovations from the megatrend of digitalisation have a special role to play here. For example, in order to reassess the functions of the reservoirs in NRW, digital technologies can be used to provide information about the potential water load in the event of extreme weather events such as heavy rainfall or flooding. On this basis, any necessary capacity adjustments and weak points can be identified and precautionary measures developed.

Viewed as infrastructure, the relevance of water as a resource and of water management for numerous economic sectors can hardly be overestimated. Inland waterway transport, for example, provides an important logistical service that is only possible with the appropriate water infrastructure. The efficient use of water in the manufacturing industry – traditionally for hydropower and increasingly for hydrogen production in electrolysers as well as the implementation of measures to reduce water consumption (water efficiency) – is also of great economic importance in NRW as an industrial location. Against the background of the megatrend of research into water efficiency technologies, NRW offers an important field of application for modern research that can benefit from international cooperation. Such interfaces need to be identified and utilised.

5.3 Promoting cooperation in NRW and with international partners

The NRW water sector can benefit from cooperation with international players.

NRW has an excellently positioned water industry. The sector is characterised by large water management associations as well as renowned research players, large and medium-sized companies and innovative start-ups. Nevertheless, the results of this paper show that some international players are far ahead of NRW in certain relevant fields of research. This also applies to subject areas with a high future score, which could have a significant impact on the development of the water industry in the coming years. China, the USA and India, but also Australia, should be emphasised here.

In addition to these heavyweights, other partner countries of North Rhine-Westphalia are also very well positioned in relation to their size. These include, for example, the Netherlands, Denmark and France. Depending on the challenges to be solved, North Rhine-Westphalia's water management can benefit from topic-specific networking with the other countries. This can include the joint (further) development of research topics, the institutionalisation of an exchange on innovative water management topics at a political level, the promotion of entrepreneurial cooperation and the establishment or consolidation of cooperation at an international level.

Close cooperation with Belgium, the Netherlands and Switzerland as European neighbours in the river basin-related systems of Rur, Meuse and Rhine should be mentioned as a priority. Close coordination should be intensified, joint management measures and protection approaches should be developed, and technological approaches should also be harmonised, as water knows no borders. Against the backdrop of global water-related problems, the German Advisory Council on Global Change (WBGU) is in favour of restructuring international water governance and establishing an international water strategy and a water mapping initiative – consisting of a panel of experts and a scientific platform. The aim is to recognise regional water emergencies at an early stage and use the new body to inform the upcoming UN Water Conferences in 2026 and 2028.[104] The North Rhine-Westphalian knowledge landscape can also contribute to the provision of technical expertise here and water authorities in Germany can benefit from the knowledge of these bodies at a local level.

Dialogues with key players in North Rhine-Westphalia's water management sector provide important impetus for the planned NRW Water Strategy for the Future.

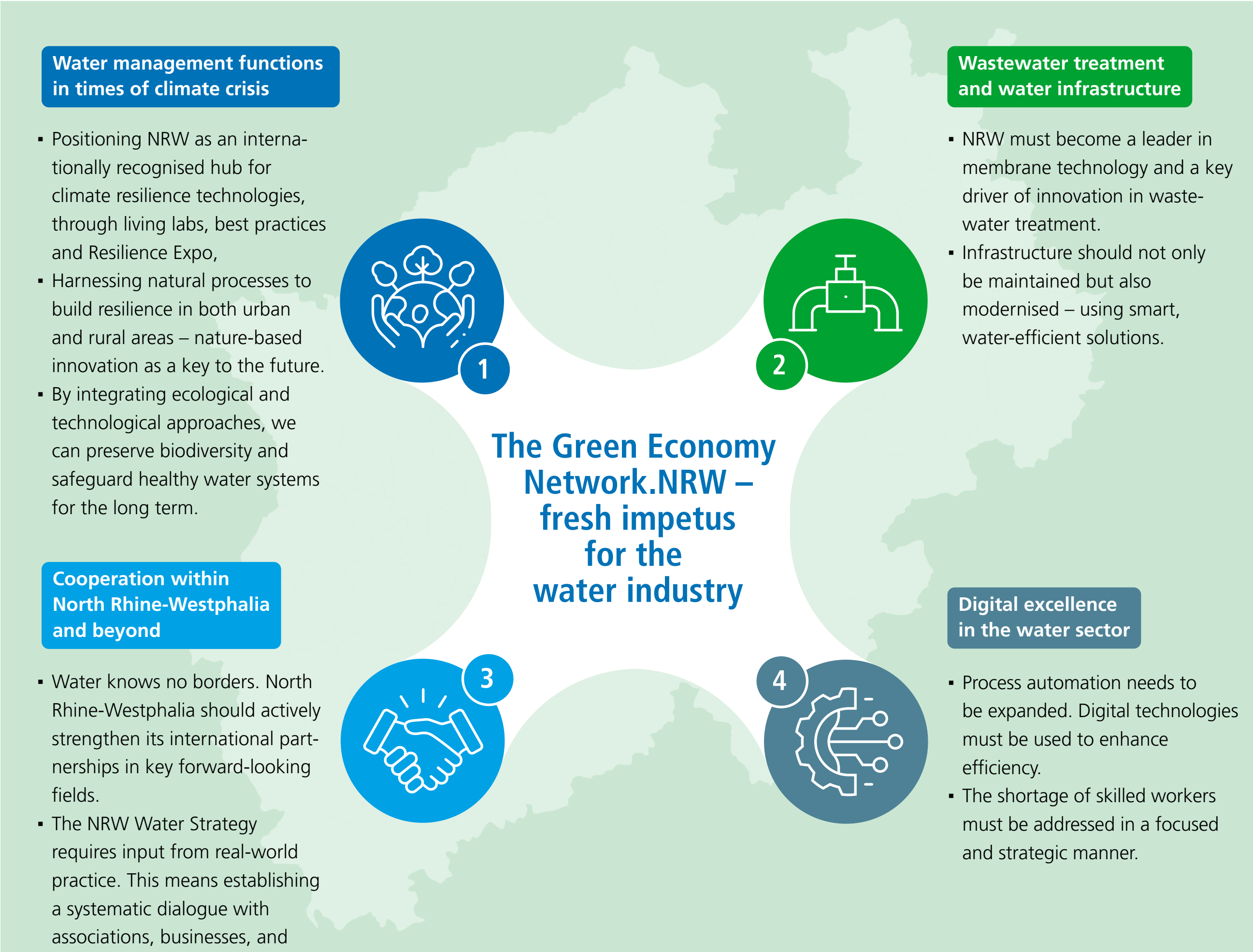
It is not only networking in the international arena that is worthwhile. A large number of research players, associations and companies in NRW are already doing important work today. This is particularly relevant with regard to the planned Water Strategy for the Future for the state of NRW. It is worth seeking dialogue with key players in the North Rhine-Westphalian water industry on key issues and challenges in order to exploit possible synergies between politics, administration and industry. There are already a number of market-ready, innovative solutions from NRW in the field of flood protection. An exchange within the framework of a series of dialogues between economic players on the one hand and associations and politicians on the other could provide important knowledge for the future strategy. In addition, the initiation of new funding programmes is also conceivable, which in turn actively support the further development and scaling of solution approaches from NRW.

5.4 Digital excellence in the water industry

Digitalisation: a disruptive change with great potential for the water industry

The results of these studies show that digitalisation must be seen as a major opportunity: Digitalisation must be seen and used as a great opportunity for the traditional water industry. It is no coincidence that digital technologies are recognisable as an absolute megatrend in global research and will determine developments in the coming years. Even if the introduction of and switch to digital technologies means a major, perhaps even disruptive upheaval, it offers many advantages. Digital technologies lead to more automation and therefore increase the efficiency of processes, which is particularly important in times of a shortage of skilled labour. In addition, digital tools such as sensor technology and AI can be used to collect and analyse a large amount of data that was previously unavailable or only available via complicated measurements. However, it is important to implement measures carefully and not to forego human control and decision-making – especially in an area of critical infrastructure such as the water supply. It is therefore advisable to decide on and pursue the next development steps in close cooperation with water management stakehold-

Figure 13: Strategic impulses from the Green Economy Network.NRW



Source: © Prognos AG, 2025

ers in dialogue. With the Digital Water Management Competence Centre (KDW), which is dedicated to digitalisation and cybersecurity in the water industry on the initiative of the state of North Rhine-Westphalia and in cooperation with leading water management companies, NRW can already build on a strong player in this area.

Overall, it is clear that although the water industry is facing challenges in many areas, at the same time more and more solutions are emerging in research that can be utilised for a successful future in the water industry. Of course, some innovations are being researched far more than others and some innovations are even already being implemented. Overall, however, this chapter shows that in addition to innovations, it is above all the transfer into practice that is important: Innovations must be seen and utilised as solution approaches. In the coming years, it will be increasingly important to integrate innovative approaches into practice. Only then can they help to make our water cleaner, our ecosystem more vibrant, our infrastructure more climate-adapted, water scarcity more manageable and the supply of urban and rural areas more efficient and reliable. Based on subchapters 5.1 to 5.4, the following recommendations for action are proposed from the perspective of the Green Economy Network.NRW. These are shown in figure 13.

6 Invitation to dialogue: Utilisation of results

In the course of this study, it became clear that water as a resource is under increasing pressure in the context of the climate crisis, global demographic developments and the associated consequences, such as increasing water scarcity and rising levels of pollution.

The identification of the key water-related challenges made it clear that there is an urgent need for action! The international community still has five years to achieve the United Nations' Sustainable Development Goal 6 – *Clean Water and Sanitation*. With the announced European Strategy for a Resilient Water Supply, the Federal Government's National Water Strategy and the planned Water Strategy for the Future of the State of North Rhine-Westphalia, this urgency for action is once again finding political expression.

In the context of this Green Economy Paper, it became clear that innovations can make a decisive contribution to overcoming these challenges. NRW is already making significant research contributions to innovative approaches that can be used to tackle the major challenges of water management. On the one hand, contributions from NRW in membrane research and other water treatment technologies, such as the degradation of antibiotics and microplastics, should be emphasised. On the other hand, NRW has a high level of research activity in the field of AI-based prediction of floods and flooding to protect critical infrastructure and in urban areas, thus making a significant contribution to flood protection. In addition, the AI-supported data analysis identified four overarching megatrends at a global level that will continue to have a significant impact on water management in the coming years: (1.) digitalisation technologies, (2.) water treatment technologies, (3.) water efficiency technologies and (4.) a technology development towards sustainability.

This Green Economy Paper provides the content basis for the multi-stage dialogue process of the Green Economy Network.NRW. In the first half of 2025, a series of interviews will be conducted with water management experts from NRW and the North Rhine-Westphalian partner countries Denmark and the Netherlands. The aim is to discuss the results of the paper and enrich them with international perspectives. In addition, the aim is to identify entrepreneurial best practices from NRW and the partner countries and to make these visible as part of a subsequent communication campaign - and to learn from innovative approaches beyond our national borders. In the third quarter of 2025, the Green Economy Network.NRW is also planning an international workshop with water management stakeholders in order to deepen the dialogue on relevant water management innovations, learn from each other and initiate further cooperation. The key findings of the dialogue series will also be made available to the Ministry of the Environment, Nature Conservation and Transport of the State of North Rhine-Westphalia (MUNV) and thus provide an impetus from the perspective of the environmental economy for the further development of the Water Strategy for the Future.

To keep up to date with the series of dialogues, it is worth taking a look at the website or the LinkedIn channel of the Green Economy Network.NRW with one of the largest environmental industry networks in Germany! You can subscribe to our newsletter here: www.knuw.nrw/aktuelles/newsletter.html

List of endnotes

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Green Economy Network.NRW

The Green Economy Network.NRW, funded by the Ministry for Environment, Nature and Transport of North Rhine-Westphalia, supports the growth of the region's environmental economy. It does this by providing services in areas such as networking, information sharing, research and development, international cooperation, and market development.

The Green Economy Network.NRW runs a wide range of information and networking activities. One key event is the annual SUMMIT Green Economy.NRW, which brings together professionals and organisations from North Rhine-Westphalia's environmental sector.

These initiatives aim to encourage collaboration, strengthen networks, and support the transfer of knowledge and technology – helping to find practical solutions to market-related challenges.

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