novo nordisk fonden

DHI

The Novo Nordisk Foundation Water Summit

Making a Big Splash for a Sustainable Future

A collaboration with DHI

15–16 January 2020

Contents

Water Summit photographs taken by Jesper Ludvigsen

Preface

'Making a Big Splash for a Sustainable Future' was a summit organised by the Novo Nordisk Foundation (NNF) in collaboration with DHI. The purpose of the summit was to bring university researchers together with public and private water sector experts to identify and prioritise the challenges facing the world in terms of water sustainability, while beginning to shape potential avenues for life science and interdisciplinary research that should help to address these challenges.

About NNF

The Novo Nordisk Foundation is an independent Danish foundation with corporate interests. The history of the Foundation dates back to 1922, when Nobel Laureate August Krogh returned home to Denmark from Canada with permission to manufacture insulin in Scandinavia. This was the starting point for developing world-class diabetes medicine and a Danish business and export venture. It also led to the establishment of several foundations that, many years later, merged into today's Novo Nordisk Foundation.

The Novo Nordisk Foundation's vision is to contribute significantly to research and development that improves the lives of people and the sustainability of society.

With Denmark as its centre of gravity, the Foundation's focus is to improve the lives of people by improving health, education and developing a knowledge-based sustainable society. To fulfil its vision, the Foundation pursues a three-pronged mission:

- to enable Novo Nordisk A/S and Novozymes A/S to create world-class business results and contribute to growth,
- to develop knowledge-based environments in which innovative and talented people can carry out research of the highest quality and translate discoveries into new treatments and solutions,
- to inspire and enable children and young people to learn.

The Foundation recently expanded its scope while increasing its grants for scientific, social and humanitarian purposes. In 2019, NNF paid out €485 million for projects within a broad range of areas. The ambition is to reach approximately €670 million in 2023. Existing grant areas within the health sciences have been augmented to support research in natural and technical sciences, including interdisciplinary projects. Support for life science research has also expanded to industrial applications promoting sustainability. Related to this expansion, NNF is interested in exploring the needs and opportunities for new initiatives in water biotechnology and interdisciplinary research. As a first step, the Foundation collaborated with DHI to organise the Water Summit.

Read more about the Novo Nordisk Foundation at novonordiskfonden.dk/en.

About DHI

Founded in 1964 as a spin-off from the Technical University of Denmark, DHI provides consulting and technological solutions across all water environments – from rivers and reservoirs, to oceans, coastlines and cities. DHI is a Danish government-approved Research and Technology Organisation (a GTS institute) that builds and communicates technological competences to the Danish business community and plays an important role in the Danish innovation system. Headquartered outside of Copenhagen in Hørsholm, DHI has offices in more than 30 countries across the globe and has amassed 55 years of dedicated research and real-life experience from more than 140 countries. DHI continuously invests in research and innovation and collaborates with partners and customers to develop new solutions and services for solving challenges in water environments. In addition, DHI hosts the UNEP-DHI Centre for Water and Environment, which is a United Nations Environment Programme centre of expertise dedicated to improving the management of freshwater resources.

Given the unrivalled expertise in water environments, DHI co-organised this event to bring together experts from Denmark and abroad to discuss, identify and explore solutions for key research challenges.

Read more about DHI at dhigroup.com/.

Executive Summary

By 2050, the global population will be close to 10 billion. This presents significant challenges to ensuring sufficient clean water and sanitation to meet everyone's needs, as well as producing enough food and energy, which are heavily dependent on water. Two-thirds of these people will be living in cities, overwhelming current water infrastructure. Growing economies also bring with them increasing wastewater contaminants, both in terms of the range of compounds and their concentrations. To bring about a sustainable future for water, we need to do more with a finite resource. But this simple statement masks an incredibly complex array of variables and challenges, with stark differences in these challenges in different regions of the world. To further understand these global challenges and begin to define areas of scientific research for potential solutions, NNF collaborated with DHI to develop and organise a 1.5-day Water Summit: *'Making a Big Splash for a Sustainable Future'*.

The summit brought together 45 stakeholders and leading experts in various aspects of water planning, management, treatment and research. The majority of summit participants were from Denmark, representing academic research, industry and water utilities, with additional participants coming from the US, The Netherlands, France, Sweden and Norway. Prior to the meeting, delegates were surveyed to define each person's top challenges to securing a supply of sustainable water for the future and the responses were used to define working groups for the meeting: (1) sustainable water supply; (2) micropollutants, contaminants and microbes as emerging threats; (3) wastewater treatment, re-use and resource recovery; (4) the urban water cycle and circular economy; and (5) urban water management in the developing world. Groups were tasked with detailing the challenges and potential solutions to address these challenges within each theme.

The following challenges were identified as the greatest priorities:

1. Water quantity: fit-for-purpose water for 10 billion people

As the global population increases, demand for water increases. New solutions are needed for more efficient infrastructure, agricultural practices and 'fit-for-purpose' water solutions (different water for different uses).

2. Micropollutant removal by biological systems

In order to design low-energy, decentralised water treatment systems, a clear understanding of the interactions between contaminants and the microbial communities needed to degrade them is required.

3. Limited recovery of resources

Currently, there is little recovery of products like nitrogen and phosphorous from wastewater. Not only is there a lack of efficient technology, there are neither economic nor regulatory frameworks to support such recovery.

4. Capturing multiple 'wanted' resources to create a circular economy

Currently, we use and lose a lot of resources via water, which will only intensify and limit growth until solved. The complete resource–water system is highly complex and there is a general lack of understanding of the system.

5. Managing 'unwanted' substances to enable a circular economy

To create a viable circular economy, unwanted components need to be removed. This represents a complex system with many unknowns, especially the unknown risks of human and ecosystem exposure to multiple low-level contaminants.

6. Megacities

We lack a sustainable model for the development of megacities. Existing water infrastructure solutions do not scale, and megacities create unpredictable problems for the urban environment. Identifying new solutions, business models and technologies to support megacity development will benefit all countries as such cities become more commonplace.

In response to these challenges, a range of potential avenues for research were proposed, explored and refined. At the conclusion of the summit, the following strategic recommendations were made, presented in order of perceived timeframe to potential impact, from short- to more long-term impact:

1. Creating a conceptual model for a circular economy in water systems

Before any decisions can be made on how to transform the water economy, a model must be established that incorporates physiochemical, economic, market and behavioural elements. This model can be tested and evaluated against a range of scenarios assessing desirability, viability and feasibility.

2. The megalopolis future

Processes and business models for sustainable urban development, especially water infrastructure, will need to be designed to cope with the megacities of the future. Novel business models and financial schemes for implementation will need to balance public good and the interests of the individual. Such schemes will undoubtedly require political support, necessitating robust interdisciplinary collaboration and consensus to gain endorsement at the political level and secure investment.

3. Water infrastructure 4.0

The challenges in developing the next generation of urban water infrastructure are not limited to providing drinking water: it is also management of wastewater, recreational water and the implementation of efficient, high-capacity drainage/sewerage systems. Key elements to establishing what the next generation of water infrastructure looks like include knowledge of chemical/microbiological processes and applying the three Rs: reduce, reuse and recycle. New digital technologies, sensor developments and data science will also be crucial to improving effectiveness and efficiency of water infrastructure.

4. Enabling a circular urban water economy

A circular water economy is the only way to ensure continued growth in big cities. However, individual end goals may differ. If water is being reused, what is it being reused for? What is the source of the wastewater? What are the acceptable levels of pollution? A multitude of factors come into play and new digital tools are required to make sense of the data in order to accelerate and improve decision making. Furthermore, cross-disciplinary expertise is required as these systems touch technical, medical, health and social sciences, as well as economics.

5. Bio-analytical detection methods

In order to remove the 'unwanted' components of cycled water, one needs to be able to detect, identify and quantify pollutants. The more 'closed down' a water cycle becomes (i.e., the closer drinking water infrastructure is to wastewater infrastructure), the greater the demand for stringency to ensure confidence in the system. Novel bio-analytical methods may be faster and more sensitive than existing chemical methods, but it is unclear if they can be cost effective.

6. How do microbial systems degrade micropollutants?

The main problem with micropollutants is the 'unknown unknowns': what is in the water, what are the impacts and how do existing interactions and processes work? These questions must be addressed before it is possible to optimise treatment systems. We need to assess the nature, extent and collective impact of organic micropollutants, not just in our water supply but also in the wider natural systems in which these contaminants (currently) eventually end up. A huge diversity of compounds is present at low concentrations, and it is not feasible to target one contaminant at a time. The only practical solution is to find a generalisable mechanism that will allow the targeting of large groups of compounds.

7. How can we ensure more crop per drop?

Approximately 70% of water is used by agriculture and, by 2050, agriculture will need to increase output by 50% to feed a growing population. This increased output will need to be achieved using existing resources; thus, we need to optimise what we have. There needs to be an interdisciplinary collaboration of scientists with clear communication with industry and the public. The challenge is not just 'more crop per drop', but 'more crop per drop in a way that is accepted and adopted by farmers and consumers'.

8. Resource recovery to catalyse a circular bio-economy

Wastewater contains a complex mix of carbon and other molecules that can be recycled. Efforts to recover these products should range from an initial focus on recovering simple molecules, to developing processes for complex molecules. A better understanding of microbial ecology allows biological processes to be harnessed and products recovered. This then increases sustainability potential by encouraging a circular economy. The approach taken should be collaborative, with microbial ecologists, analytical chemists, chemical engineers, bioinformaticians, artificial intelligence experts, process engineers and industrial/business economists.

9. Technology transfer between economies

To facilitate transfers of technology for the benefit of low- and middle-income countries and upper middle-income countries, there is a need to find better ways of managing urban water and introduce strategies that benefit both the 'giving' and the 'receiving' countries. A mutually beneficial solution can increase living standards and health while decreasing the risk of conflict.

In summary, three key elements link the research area proposals outlined by the experts:

Models

Key to many proposed solutions is the development of specialised, cross-disciplinary models, incorporating the many components affecting a circular water economy (physiochemical, biological, economic and behavioural). Such models can be applied to develop next-generation water infrastructure for cities large and small, improve agricultural efficiency and drive rational resource recovery.

Safety

The accumulation of micropollutants is inherent to a circular water system. Microbial treatment of wastewater to remove these micropollutants offers the greatest chance of dealing with these contaminants but this requires research – not only into microbial ecology but also into detecting a diverse and ever-expanding mix of contaminants and understanding their collective impact.

Circularity

Extraction of resources from wastewater will be a key element in establishing a viable circular water economy. While these resources may be classed as pollutants, extracting them achieves more than simply improving water safety. Efficient extraction of high-value resources from wastewater limits waste, reduces the need for *de novo* production, and lowers the financial barrier to widespread adoption of circular, sustainable water systems.

There is an undeniable, pressing need to act on water sustainability and the summit allowed a broad range of potential solutions to be explored. The nature of the summit challenged the experts to define and prioritise those areas that can be most appropriately addressed with scientific research. As such, the outputs of the summit provide excellent guidance for the grant-awarding activities of the Novo Nordisk Foundation to drive forward its vision to contribute significantly to research and development that improves the lives of people and the sustainability of society.

1. Background

The United Nations predicts the global population will be close to 10 billion by 2050. This in itself presents significant challenges to ensuring sufficient clean water and sanitation to meet everyone's needs, as well as producing enough food and energy, which are heavily dependent on water. Two-thirds of these 10 billion people will be living in cities, overwhelming current water infrastructure. Growing economies also bring with them increasing wastewater contaminants, both in terms of the range of compounds and their concentrations. The human health and ecological consequences of many of these chemical and microbial contaminants is currently unknown.

Water sustainability: the ability to meet the water needs of the present without compromising the ability of future generations to do the same.

In 2015, the United Nations General Assembly set the Sustainable Development Goals (SDGs), a collection of 17 global goals designed to be achieved in 2030 as a blueprint for achieving a better and more sustainable future for all. Two of these goals directly relate to water – Clean Water and Sanitation (goal 6) and Life Below Water (goal 14) – acknowledging the importance of targeting water as a key element to a sustainable future.

SDG 6: Clean Water and Sanitation

Clean, accessible water for all is an essential part of the world we want to live in and there is sufficient fresh water on the planet to achieve this. However, due to bad economics or poor infrastructure, millions of people including children die every year from diseases associated with inadequate water supply, sanitation and hygiene.

Water scarcity, poor water quality and inadequate sanitation negatively impact food security, livelihood choices and educational opportunities for poor families across the world. At the current time, more than 2 billion people are living with the risk of reduced access to freshwater resources and by 2050, at least one in four people is likely to live in a country affected by chronic or recurring shortages of fresh water. Drought afflicts some of the world's poorest countries, worsening hunger and malnutrition. Fortunately, there has been great progress made in the past decade regarding drinking sources and sanitation, whereby over 90% of the world's population now has access to improved sources of drinking water.

To improve sanitation and access to drinking water, there needs to be increased investment in management of freshwater ecosystems and sanitation facilities on a local level in several developing countries within Sub-Saharan Africa, Central Asia, Southern Asia, Eastern Asia and South-Eastern Asia.

To bring about a sustainable future for water, we need to do more with a finite resource. But this simple statement masks an incredibly complex array of variables and challenges, with stark differences in these challenges in different regions of the world. For example, wastewater challenges in Denmark, which can utilise high levels of technology, are significantly different to those in India, where process management tools are limited and wastewater treatment plants are more dispersed. The Water Summit was convened in an attempt to further understand these global challenges and begin to mould potential solutions. The expertise of the participants and the discussions at the event centred on challenges and solutions within the urban water environment. Therefore, the Water Summit strongly supports SDG 6.

"The earth, the air, the land and the water are not an inheritance from our forefathers but on loan from our children. So, we have to hand over to them at least as it was handed over to us"
Mahatma Gandhi

2. Introduction to The Water Summit

The summit brought together 45 stakeholders and leading experts in various aspects of water planning, management, treatment and research. The majority of summit participants were from Denmark, representing academic research, industry and water utilities, with additional participants coming from the US, The Netherlands, France, Sweden and Norway. Although themes explored at the summit were kept broad, most of the participants from Danish academia had expertise in water biotechnology. Representatives from NNF participated in the meeting as active listeners.

Prior to the meeting, delegates were invited to submit a short description of what they foresee as the three key challenges to securing a supply of sustainable water for the future, with these submissions informing the agenda for the meeting itself. Delegates were encouraged to discuss challenges and explore potential solutions freely at the summit. There were two areas of focus to the discussions: scientific exploration and economics & policy. While these areas overlap and both need to be addressed in order to achieve success (scientific solutions are of limited value without the economic or political will to implement them), they differ in the approaches required to achieve outcomes. Given the grant-awarding activities of the Foundation, delegates were asked to consider the 'appropriateness of scientific research to address the problem' when assessing their potential solutions.

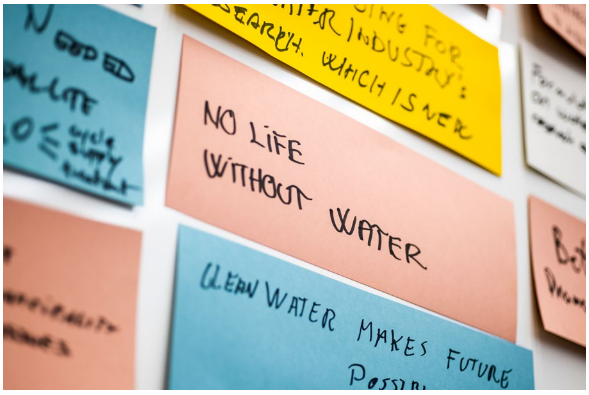
The summit opened with a welcome from Claus Felby (Senior Vice President, Biotech) and an introduction by Niels Peder Nielsen (Deputy CEO) from NNF. They highlighted that this is a new area for the Foundation and that a sustainable water future has a clear impact on both health and wellness, with the potential to provide synergy with a number of initiatives already supported by NNF. Antoine Labrosse (CEO of DHI) then gave a scene-setting talk introducing the major water challenges facing the world, articulating them around the UN's Sustainable Development Goals. Following these introductions, and an ice-breaker session where participants got to know one another while outlining what they each hoped to get out of the summit, the sub-group themes for the following day-and-a-half were introduced. These five themes were based on the lists of three key challenges for water sustainability supplied by delegates in advance of the meeting.

1. Sustainable water supply
2. Micropollutants, contaminants and microbes as emerging threats
3. Wastewater treatment, re-use and resource recovery
4. The urban water cycle and circular economy
5. Urban water management in the developing world

Given the intense interest in topic 2, two groups worked on this theme. Thus, there were six groups in total and participants were divided for the first day and (to a large extent based on their own expressed wish) tasked with detailing the challenges and potential solutions to address these challenges within each theme. On the second day, six new groups were formed around the six most impactful opportunities arising out of day one. Participants were given a free choice over which group they joined on the second day, up to a maximum of eight per group. The incorporation of feedback sessions and 'gallery walks' ensured that solutions were not developed in isolation; rather, each selected solution was discussed and validated by the complete delegation.

Many topics were discussed at the summit. The outputs from the meeting described herein should be viewed neither as a verbatim report of discussions nor as a concrete set of recommendations. Rather, this report distils and, where necessary, combines discussions from different groups and serves as an initial draft of recommended avenues for further exploration and validation.


CRITICAL THEMES WITHIN SUSTAINABLE WATER
#1 SUSTAINABLE WATER SUPPLY
#2 MICROPOLLUTANTS, CONTAMINANTS, AND MICROBES AS EMERGING THREATS
#3 WASTEWATER TREATMENT, RE-USE AND RESOURCE RECOVERY
#4 THE URBAN WATER CYCLE AND CIRCULAR ECONOMY
#5 URBAN WATER MANAGEMENT IN THE DEVELOPING WORLD
#3 WASTEWATER TREATMENT, RE-USE, AND RESOURCE RECOVERY


NO LIFE WITHOUT WATER
CLEAN WATER MAKES FUTURE


#2 MICROPOLLUTANTS, CONTAMINANTS, AND MICROBES AS EMERGING THREATS
(2 GROUPS)


The Novo Nordisk Foundation Water Summit
Making a Big Splash for a Sustainable Future
Niels Peder Nielsen
Deputy CEO
Novo Nordisk Foundation


WALL OF IMPORTANCE

3. Crucial Challenges

Each group brainstormed problems within their theme, initially as individuals and then as a group. Problems were assessed according to both the scale of the problem and the appropriateness of scientific research to overcome it. Larger-scale problems, with the potential to be addressed by scientific research, were selected as a priority according to the summit's remit. Combining feedback across groups, the following challenges were identified as the greatest priorities:

1. Water quantity: fit-for-purpose water for 10 billion people

As the global population increases, demand for water increases, including water-intensive food production. New solutions are required for more efficient water infrastructure, new agricultural practices ('more crop per drop'), and 'fit-for-purpose' water solutions: different water for different uses.

2. Micropollutant removal by biological systems

In order to design low-energy, decentralised water treatment systems, a clear understanding of the interactions between contaminants and the microbial communities needed to degrade them is required. Such knowledge is also required to understand impacts on natural systems (wetlands, rivers, lakes etc.).

3. Limited recovery of resources

Currently, there is little recovery of products like nitrogen and phosphorous from wastewater. Not only is there a lack of efficient technology, there are neither economic nor regulatory frameworks to support such recovery.

4. Capturing multiple 'wanted' resources to create a circular economy

Currently, we use and lose a lot of resources, both from freshwater and wastewater, which will only intensify with increasing urbanism and will limit growth until solved. The complete resource–water system is highly complex and there is a general lack of understanding of the system.

5. Managing 'unwanted' substances to enable a circular economy

Similarly, to create a viable circular economy in the face of increasing urbanisation, unwanted components need to be removed. This also represents a complex system with many unknowns, especially the unknown risks of human and ecosystem exposure to multiple low-level contaminants.

6. Megacities

We lack a sustainable model for the development of megacities. Existing water infrastructure solutions do not scale, and megacities create unpredictable problems for the urban environment. New solutions, business models and technologies are required. Initially discussed with the developing world in mind, applying these models and solutions to megacities will create a 'knock-on effect' and benefit all countries globally as megacities become more commonplace.

Additional challenges identified, but either not selected as priority areas or sufficiently covered in the challenges above, included:

1. Lack of understanding of micropollutants

Micropollutants remain a problem but their impact is largely unknown. Micropollutants occur at low levels and, as such, are inherently difficult to identify and quantify in high-flow systems. Furthermore, we currently only have a partial understanding of how they accumulate and interact with other pollutants. Without a broader understanding, it is difficult to assess the risks posed by micropollutants and make informed decisions on how to qualify when water is fit for use.

2. Micropollutants: lack of technology development and decision support

In addition to the lack of understanding of micropollutants, there is an absence of practical and cost-effective technologies to identify, quantify and process them. New and updated technologies that utilise modern digital practices (such as machine learning and artificial intelligence) are required.

3. Antimicrobial resistance in residual waters

This problem can be divided into two components: (1) the direct consequences of antibiotic-resistant microbes in wastewater, and (2) the role of the water cycle itself in the propagation of antibiotic resistance. Antibiotic resistance is a major health issue and the role of wastewater in this phenomenon remains unclear but may be smaller in scale than other more immediately actionable factors.

4. Current design and operation of wastewater treatment plants do not meet future demand

Future requirements for resource recovery, clean water and energy/greenhouse gas efficiency will not be met by expanding current designs. New designs incorporating better process monitoring and control will be needed for every big city in 10–20 years.

5. Lack of relevant business models and cheap, simple technology to support low- and middle-income countries

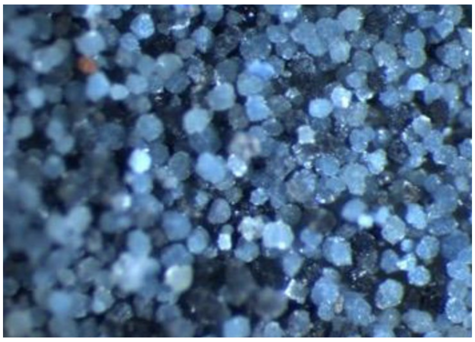
Existing urban water systems are too complex, expensive and not always sustainable for low- and middle-income countries. Without solutions, including financial systems that work, the development of cities in these countries will face major challenges.

Reflections on leading impactful biotechnology research for sustainable water

Professor Mark van Loosdrecht
Delft University of Technology, The Netherlands

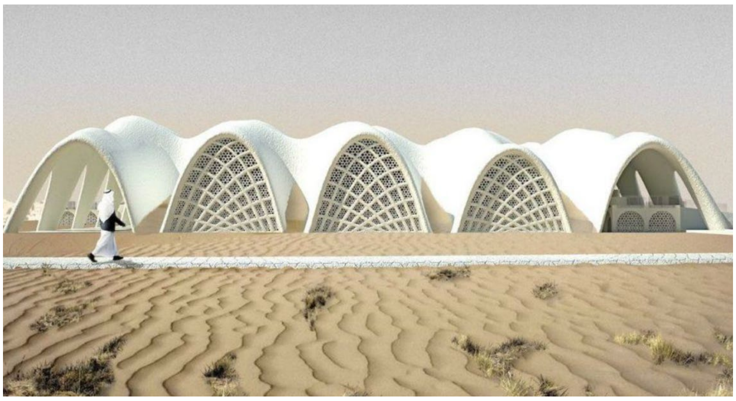
Mark van Loosdrecht is Chair Professor in Environmental Biotechnology at Delft University of Technology, The Netherlands. He is also an active member of the International Water Association (IWA) and sits on the editorial board of the IWA's journal *Water Research*. He is the recipient of several prestigious prizes for his work, including the Lee Kuan Yew Singapore Water Prize and the Stockholm Water Prize. Professor van Loosdrecht's research into wastewater treatment and resource recovery is characterised by the combination of scientific understanding of complex systems and development of new processes, which made him an excellent choice for giving an inspirational talk on innovation to his peers.

In front of a rapt audience of Water Summit attendees, Professor van Loosdrecht began by comparing the process of innovation to that of one of his favourite pastimes, hiking: if you see a signpost pointing in three different directions, then try to find a fourth way, since these other routes have already been explored. In the same way, true innovation in water treatment requires more than a problem to solve – it requires curiosity. From an academic perspective, curiosity-driven research is incredibly important because it lets us take time to learn what is really going on and, from this, maybe discover new options for recovery that we wouldn't have otherwise thought of. He stressed that curiosity-driven knowledge generation – something that typically happens in academia – can only lead to innovation in the water sector if there is a good interaction with the utilities and industry.



As an example, Professor van Loosdrecht discussed a reduced iron phosphate mineral called vivianite ($Fe_3[PO_4]_2 \cdot 8H_2O$) as a starting point for new phosphate recovery techniques. Phosphate recovery from sewage sludge is essential in a circular economy, and vivianite has long been a neglected species due to complicated analysis. Yet, recent research has shown that not only is vivianite often a major source of phosphate in sludge – having been observed in all plants for which iron is used for phosphate removal – it can be removed using a magnetic separator. Current work focuses on the use of recovered vivianite as fertiliser.

Often, innovation is not necessarily bound up in how to recover resources but in identifying what to do with the resources that can be recovered. "We need to think outside of the obvious.", Professor van Loosdrecht commented, giving the example of brine processing in Bolivia, where the locals are able to use leftover salt to craft bricks for use in construction. "Environmental engineering tends to jump to the first solution and ignore the rest," he told the audience with several environmental engineers in the room. Asking novel questions, opening up new avenues of research and developing innovative solutions requires a combination of disciplines.

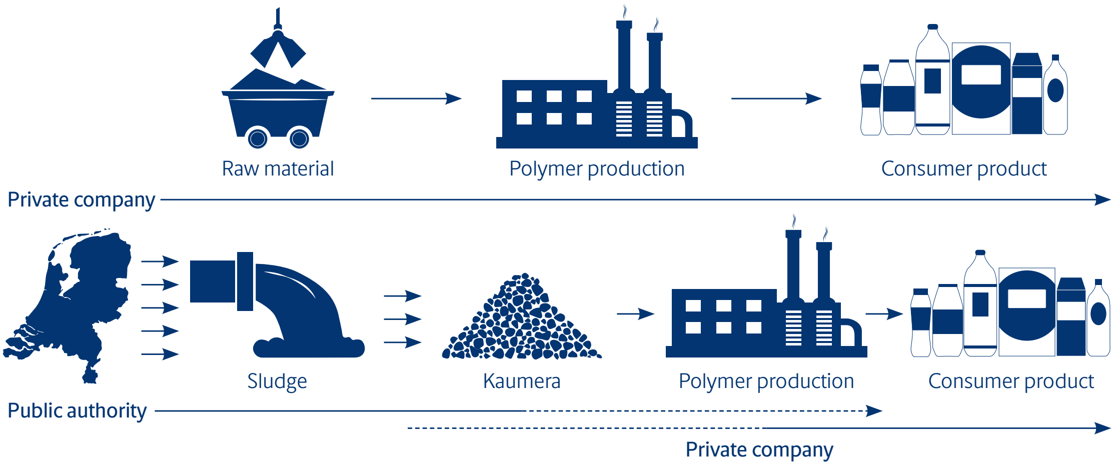


Professor van Loosdrecht's own research has led to the widely used Anammox and Nereda technologies for wastewater treatment, and the bulk of his talk concerned the recovery of high-performance biopolymers from 'waste' sludge with the hope that these would contribute to a more circular economy in the future. Stemming from the very curiosity-driven research he'd discussed earlier, Professor van Loosdrecht explained how the Nereda technology is based on granulation of bacteria, which – once you understand the interaction between biology and process technology – allows a mechanically simpler and cheaper municipal wastewater treatment process. Other benefits include the fact that a Nereda plant requires much less land and energy than conventional methods. Like with his example of the salt bricks in Bolivia, there were local factors that helped enable success, such as the nature of the Dutch water board system, instead of municipality responsibility, and a national research programme that offered a 10-year commitment. Only at the end of the process did they realise they had formed a public-private partnership as a way to bring the idea to the market.


Images copyright Yuemei Lin

So far, resource recovery projects have been research- and technology-driven rather than market-driven. But Professor van Loosdrecht showed how this does not have to be the case, with the example of Kaumera: a bio-based extracellular polymer or gum that can be extracted from aerobic sludge granules that form during the Nereda wastewater treatment process. Usually, production of such extracellular polymers is at too small a scale – and therefore expensive – but can now be produced by wastewater plants and developed cheaply in large volumes. Not only does extraction of the polymer reduce sludge volume, but there is already a market for this polymer, which, when combined with clay, has been shown to be comparable to fibre-reinforced polyesters with additional high heat and flame resistance. As proof that recovery doesn't have to be unattractive, Professor van Loosdrecht demonstrated how Kaumera jewellery, with its appealing pearlescent sheen, could show what one can make "from what you flush down the toilet."

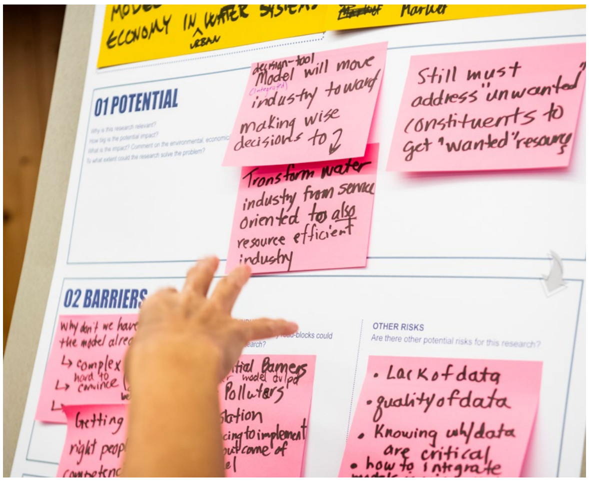
Professor van Loosdrecht went on to say that a major challenge for innovation in the water sector, particularly with respect to catalysing a circular economy, is that the entire process – from raw material to putting a product in the hands of the consumer – takes place within the private sector. Most of the chemical and fertiliser industry is accustomed to one big supplier, but it's a very different situation with wastewater-derived polymers. There isn't one supplier, there are several, even hundreds, and the organisation usually involves a public authority. He likened this situation to that of the milk board, where milk is taken from lots of small-scale operations, but it is a large-scale production when viewed in totality.



Professor van Loosdrecht concluded with a summary of the main opportunities and challenges. By integrating omics and exploiting environmental selection, "you don't need to know what microbes to use, just create the correct conditions and the environment will select for you," removing the need for extensive upfront research and development. With regards to contributing to global health, Professor van Loosdrecht made a compelling case that the benefit of sanitation is comparable to that of medicine, but at a much lower cost. Finally, in terms of challenges, especially in low-income countries, technology and cost are not the issues; the issue is that any successful process must be adaptable to the local economy/governance.

4. Solution Exploration

In response to the challenges described above, the groups began to break down the problems in order to explore potential avenues for research questions. Prioritised challenges and their nascent research areas were further refined by six new working groups. At the conclusion of these refinements, and the summit itself, the following strategic recommendations were made. They are presented in order according to the perceived timeframe in which impact from the research might be expected.



SHORT-TERM IMPACT (1–2 YEARS)

4.1. Creating a conceptual model for a circular economy in water systems

Before any decisions can be made on how to transform the water economy, a model must be established that incorporates physiochemical, economic, market and behavioural elements. This model can be tested and evaluated against a range of scenarios assessing desirability, viability and feasibility. The end result is a decision-support tool that will move the water industry, as well as academic and public institutions, towards making informed decisions. The reason no such model currently exists is because of both the complexity of current systems and the reluctance of some stakeholders to change (e.g., big polluters or those reluctant to accept the financing required to implement outcomes of the model). Getting the right people together to build, test (in a case study), validate and refine the model would be the essence of this initiative. The initial impact of this initiative could be felt within a year but would also form the first step in developing other initiatives and solutions based on the model.

4.2. The megalopolis future

As two-thirds of the predicted 10 billion global population in 2050 will be living in cities, we will see an increasing number of large, densely populated megalopolis cities. Processes and business models for sustainable urban development, especially water infrastructure, will need to be designed. However, there is currently a lack of business process understanding, creating a major constraint for future development. In many cases, the technology needed to address the water challenges of the megalopolis already exists, but there are financial and educational barriers to implementation of this technology. Novel business models and financial schemes for implementation will need to balance public good and the interests of the individual. Such schemes will undoubtedly require political support, necessitating robust interdisciplinary collaboration and consensus to gain endorsement at the political level and secure investment. Urban development is also often fragmented, meaning centralisation of water infrastructure does not provide consistency across a megalopolis. Decentralisation can address such intra-megalopolis inconsistencies and may in fact reduce the complexity of infrastructure needed.

MEDIUM-TERM IMPACT (3–5 YEARS)

4.3. Water infrastructure 4.0

Research is needed to inform the development of the next generation of urban water infrastructure. The challenge is not limited to providing drinking water: it is also management of wastewater, recreational water and the implementation of efficient, high-capacity drainage/sewerage systems. In the current conservative mindset, water is too often considered an unlimited resource to which everyone is entitled, rather than a limited product, which impedes informed decision making. This needs to change and a commitment to addressing the challenges is required if we are to avoid conflict and crises. Key elements to establishing what the next generation of water infrastructure looks like include many of the elements included in other recommendations, such as knowledge of chemical/microbiological processes and applying the three Rs: reduce, reuse and recycle. New digital technologies, sensor developments and data science will also be crucial to improving effectiveness and efficiency of water infrastructure.

4.4. Enabling a circular urban water economy

A circular water economy is the only way to ensure continued growth in big cities. However, individual end goals may differ. If water is being reused, what is it being reused for? What is the source of the wastewater? What are the acceptable levels of pollution? A multitude of factors come into play and new digital tools are required to make sense of the data in order to accelerate and improve decision making. Furthermore, cross-disciplinary expertise is required as these systems touch technical, medical, health and social sciences, as well as economics. A consortium or alliance should be established to look at economic and technical challenges to urban water cycling. This must be done from a global, cross-disciplinary level and have sufficient gravitas to overcome political (and industrial) inertia. Once this is established, the group can look to use a reference city to test models and scenarios and gather further information to define a new model for the economics of water.

LONG-TERM IMPACT (5–10 YEARS)

4.5. Bio-analytical detection methods

In order to remove the 'unwanted' components of cycled water, one needs to be able to detect, identify and quantify pollutants. The more 'closed down' a water cycle becomes (i.e., the closer drinking water infrastructure is to wastewater infrastructure), the greater the demand for stringency to ensure confidence in the system. Novel bio-analytical methods may be faster and more sensitive than existing chemical methods, but it is unclear if they can be cost effective. One avenue of investigation would be to determine whether different tools can be developed for different scales (i.e., water system, urban system or household system). Tools will also be needed to utilise data from new detection methodologies. Crucially, this work cannot be carried out in isolation but will require coordination of a number of stakeholders. Coordination with policymakers will also be necessary to ensure a complete picture and the making of informed decisions. The suggested approach is to first establish a cross-disciplinary research consortium, which will then develop a state-of-the-art analysis built on existing data. This will enable a prioritised approach to iterative R&D efforts for detection of contaminants of interest.

4.6. How do microbial systems degrade micropollutants?

The main problem with micropollutants is the 'unknown unknowns': what is in the water, what are the impacts and how do existing interactions and processes work? These questions must be addressed before it is possible to optimise treatment systems to deliver improvements to human health and ecological status. We need to assess the nature, extent and impact of organic micropollutants, not just in our water supply but also in the wider natural systems (rivers, lakes, wetlands, and coastal & deep ocean) in which these contaminants (currently) eventually end up. The challenge cannot be overestimated: there is a huge diversity of compounds present at low concentrations that are difficult to degrade. It is not feasible to target one contaminant at a time, meaning the only practical solution is to find a generalisable mechanism that will allow the targeting of large groups of compounds. Other barriers include acknowledgement that micropollutants are a problem in the first place, and scepticism that solving the challenge is even achievable. The cost will be high, and resolution will not be speedy (not least because new micropollutants are being developed all the time, so there will be future contaminants we don't yet know about). Addressing this will require deep insight into microbial consortia and processes, itself dependent on the experience, competence and synergy of a cross-disciplinary team (involving analytical chemists, microbial ecologists, hydrologists, biochemists and bioprocess engineers, among others); with lab-based, pilot-based and eventually full-scale bioreactors needed to allow for testing of technologies at scale. Ongoing monitoring and adaptation will be required to adjust processes as new contaminating compounds emerge and are identified.

4.7. How can we ensure more crop per drop?

Approximately 70% of water is used by agriculture. By 2050, agriculture will need to increase output by 50% to feed a growing population. As water and land are limited, this increased output will need to be achieved using existing resources; thus, we need to optimise what we have. Work is already progressing, so the outlook for this proposal is a focus on changes in a 7–10-year timeframe, beyond low-hanging fruit that is already being picked. Potential barriers are both technical (crop fields are often in areas without power or internet for monitoring) and cultural (farming tends to be conservative and consumers are often cautious over changes to food-production practices). There is also the potential for unintended consequences. Therefore, there needs to be an interdisciplinary collaboration of a range of scientists, with clear communication with industry and the public. The challenge is not just 'more crop per drop', but 'more crop per drop in a way that is accepted and adopted by farmers and consumers'.

4.8. Resource recovery to catalyse a circular bio-economy

Wastewater contains a complex mix of carbon and other molecules that can be recycled, including bioproducts, metals and gases. This proposal aims to discover and recover these products, from an initial focus on recovering simple molecules, to developing processes for complex molecules. A better understanding of microbial ecology allows biological processes to be harnessed and products recovered. This then increases sustainability potential by encouraging a circular economy. Key questions are: Which products should we recover? How can we put recovered materials into the market and how can value chains be scaled up? How do we balance quantity against demand? How can we enable a public 'prosumer' (producer & consumer) mindset? For consumer products generated from recovered materials, there may also be issues over social acceptance. Developing analytical tools would allow new opportunities to be discovered while contributing to the generation of public health information and informing risk assessment models. In addition to process analysis tools, pilot facilities with the ability to scale processes are required. The approach taken should be collaborative, with microbial ecologists, analytical chemists, chemical engineers, bioinformaticians and artificial intelligence experts, process engineers and industrial/business economists. While there is a high likelihood of finding and characterising novel processes, the picture is complex and there is a high degree of uncertainty in the ability to bring products to a market complicated by regulatory limitations, market penetration and implementation.

4.9. Technology transfer between economies

To facilitate transfers of technology for the benefit of low- and middle-income countries and upper middle-income countries, there is a need to find better ways of managing urban water and introduce strategies that benefit both the 'giving' and the 'receiving' countries. A mutually beneficial solution can increase living standards and health while decreasing the risk of conflict. High-income countries can contribute to improving conventional systems in low- and middle-income countries, allowing them to 'leap-frog' technologies, as illustrated by the adoption of mobile telephony in developing countries. However, it is also possible that a solution is required that does not yet exist. Barriers to success of such a solution are likely to depend on context. For example, if water is scarce then a circular system is required; in a water-rich context, avoiding flooding is required. It is also important to bear in mind that today's technologies are not carbon neutral. New solutions need to be developed with a sustainable mindset; this might be the 'leap-frog' of technology that systems in the developing world take. From a practical perspective, research programmes would need to be developed before implementation could be considered and are likely to require collaborations between multiple foundations, financial institutions and local governments.

5. Perspectives

Water is a fundamental resource for life – but it is a limited resource. As populations and economies continue to expand, provision of sufficient, fit-for-purpose water – already a challenge in many regions – will only become more difficult. Moreover, climate change adds its own suite of challenges. Addressing this diverse array of challenges that vary from region to region and country to country requires scientific and technological solutions backed by economic incentive and political will. As such, the discussions at the Water Summit reflected both sides of this equation and many topics were explored. Captured in this report are the areas of scientific research that the participants believed would have the greatest impact, if funded and implemented.

There are three key elements linking the proposals that were developed by the expert groups:

5.1. Models

Key to many proposed solutions is the development of specialised, cross-disciplinary models, incorporating the many components affecting a circular water economy (physiochemical, biological, economic and behavioural). Such models can be applied to develop next-generation water infrastructure for cities large and small, improve agricultural efficiency and drive rational resource recovery. Leveraging research within data science and artificial intelligence to improve decision making will be a key component in the development of such models.

5.2. Safety

The accumulation of micropollutants is inherent to a circular water system. Microbial treatment of wastewater to remove these micropollutants offers the greatest chance of dealing with these contaminants but this requires research – not only into microbial ecology but also into detecting a diverse and ever-expanding mix of contaminants and understanding their collective impact.

5.3. Circularity

Extraction of resources from wastewater will be a key element in establishing a viable circular water economy. While these resources may be classed as pollutants, extracting them achieves more than simply improving water safety. Efficient extraction of high-value resources from wastewater limits waste, reduces the need for *de novo* production, and lowers the financial barrier to widespread adoption of circular, sustainable water systems. However, the technological and economic challenges to such efficient extraction cannot be underestimated, making this likely to be the most difficult area in which to achieve success.

There is an undeniable, pressing need to address water sustainability – and a lot to be done. Many of the participant groups at the Water Summit identified the formation of a cross-disciplinary team as the starting point for any future research work. The expertise and enthusiasm demonstrated at the summit shows that a robust talent pool exists to help meet these global problems head-on.

6. Appendix: Summit Participants

Hans-Jørgen Albrechtsen, Technical University of Denmark
Peter Steen Mikkelsen, Technical University of Denmark
Claus Hélix-Nielsen, Technical University of Denmark
Irini Angelidaki, Technical University of Denmark
Barth F. Smets, Technical University of Denmark
Lars Ditlev Mørck Ottosen, Aarhus University
Niels Peter Revsbech, Aarhus University
Kai Bester, Aarhus University
Jes Vollertsen, Aalborg University
Per Halkjær Nielsen, Aalborg University
Ronnie N. Glud, University of Southern Denmark
Marina Bergen Jensen, University of Copenhagen
Søren Balling Engelsen, University of Copenhagen
Peter Engelund Holm, University of Copenhagen
Lars Schrøder, Aarhus Vand
Dines Thornberg, BIOFOS
Søren Støvring, Hillerød Utilities
Peter Underlin, Hillerød Utilities
Ole Pedersen Johnsen, Billund Water and Energy
Hans-Martin Friis Møller, Kalundborg Utilities
Mark van Loosdrecht, Delft University of Technology
David L. Sedlak, University of California-Berkeley
Bruce Rittmann, Arizona State University
Dragan Savic, KWR Watercycle Research Institute
Philippe Gourbesville, University of Nice-Sophia Antipolis
Vipin Kumar, University of Minnesota
Paul Westerhoff, Arizona State University
Nancy G. Love, University of Michigan
Amy Pruden, Virginia Tech University
Hallvard Ødegaard, Norwegian University of Science and Technology
Jóannes J. Gaard, Danish Ministry of the Environment and Food
Hanne Bach, Danish Center for Environment and Energy
Carl-Emil Larsen, DANVA
Heidi C. Barlebo, GEUS
Per Falholt, Per Falholt Global R&D Advisory Services
Søren Nøhr Bak, NIRAS
Jes la Cour Jansen, Lund University
Rikke Eriksen Gissel, Grundfos
Leif Bentsen, Krüger
Kristian Rokkjær, Kamstrup
Bodil Højland Lorentzen, Danish Technological Institute
Ole Larsen, CALL Copenhagen (HOFOR)
Henrik Madsen, DHI
Erik Gormsen, Novozymes
Henriette Draborg, Novozymes