Water in transition: Managing excess and deficit

Prof.dr Ruud P. Bartholomeus

Inaugural lecture upon taking up the position of Special Professor Plant Water Stress and Regional Water Management at Wageningen University & Research on 14 February 2025

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Esteemed Rector Magnificus, thank you for the introduction. Dear colleagues, family and friends, those here in the room with us, and those joining us online.
My journey into the field of eco-hydrology began in the early 2000s while I was working on my Bachelor-thesis with my friend Rob van Dongen. We investigated the impact of regional water management on site conditions for vegetation in a brook valley in the southern part of the Netherlands. The study resulted in a report called *'Eerst het water, de rest komt later'* ('first the water, the rest comes later') also published in the journal H_2O[1]. Although we've known for a while that water is important, the topic has gained increasing attention in recent years and will continue to do so for years to come.

Set the scene

The European summers of 2018, 2019, and 2020 were characterised by low precipitation and high temperatures, which caused intense large-scale droughts[2]. These events, by some sectors felt as one multi-year drought, set a new benchmark in Europe[3]. Extremely dry summers may become our new norm. However, along came the summer flood of 2021[4] and the extreme amount of precipitation in 2023-2024[5,6]. How are we going to manage these contrasting extremes?

The impacts of a surplus of water are often clearly visible: rivers overflowing or our basements flooding. However, drought events and water deficits have major impacts on many functions too, such as terrestrial and aquatic ecosystems, infrastructure, including buildings, as well as sectoral water uses like irrigation and drinking water[5].

As I guide you through this topic I want to point out some of the significant challenges that we will face in the coming decades. First, we need to understand the hydrological cycle, how we use the water system, and how climate change and anthropogenic uses of water affect water availability for other functions, like vegetation. I will then go into more detail on the specific aims of the special chair. I would also like to use this opportunity to reflect on the role of scientists and policy makers in bridging science to practice and policy and on the need of scientists to be open for interdisciplinary research in water system management.

Hydrological cycle over land surfaces

In the water system, everything is connected. One part of precipitation evaporates from surfaces, another part recharges the root zone of the vegetation where water is taken up by plant roots and transpires, and yet another part recharges the groundwater, recharging the regional groundwater system and eventually discharging via surface water. This process has been nicely visualised by the Global Commission on the Economics of Water in their recent report on 'Valuing the hydrological cycle as a global common good'[6].

The groundwater system is an indispensable resource for many functions on the land surface, like terrestrial ecosystems. The 'natural' or hydrological water system also provides a crucial resource: freshwater used for many anthropogenic (or 'human') functions.

Anthropogenic water use

As humans, we extensively make use of the water system (Figure 1). We exploit the water system for food production, industrial purposes, and drinking water supply. We drain water from the land to prevent it from being too wet and unusable for our purposes. We pump groundwater to be used in irrigation, industrial processes, and drinking water supplies. We also pave surfaces, effectively diverting the natural flow of water. Doing so, we intervene in the natural groundwater flows.

As a result of our activities, groundwater levels have dropped systematically over the last several decades[9, 10]. This impacts functions occurring at the land surface. Vegetation is greatly affected by this since too deep groundwater tables limit groundwater to reach the root zone of plants.

In a temperate climate like the Netherlands, we have a precipitation surplus on a yearly basis. During summer months, however, there is a precipitation deficit, which means that the atmospheric demand for water exceeds the amount of precipitation. Observations and climate projections indicate that prolonged dry periods during the growing season will increase and the precipitation events that do occur will be more intense[11, 12].

Problems arise when the combination of anthropogenic water use and more prolonged dry periods lead to increased water shortages for functions that are dependent on

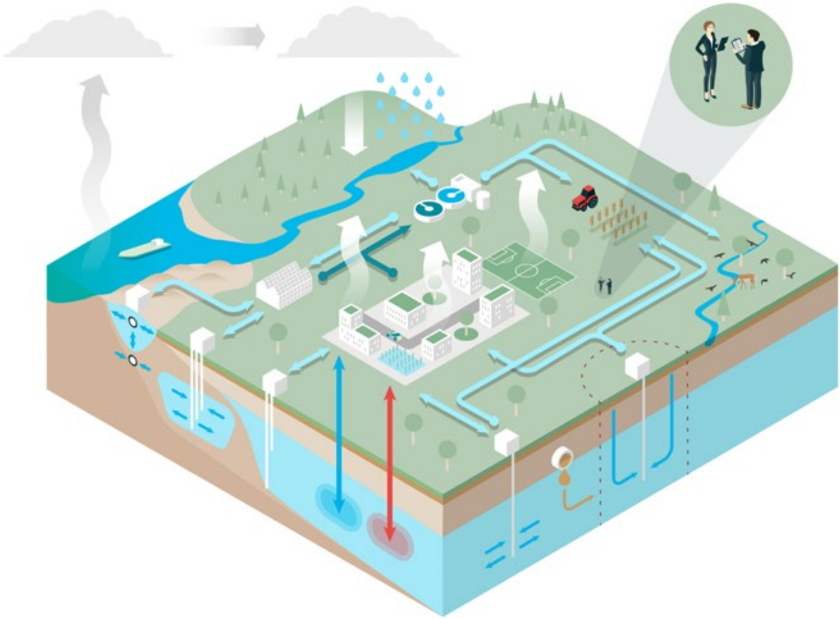

Figure 1 *We extensively make use of the water system. The hydrological water system and urban water cycle are closely connected. Source: kwrwater.nl*

groundwater, like the water availability for plants, both in nature and agriculture. Given the already decreasing groundwater levels, longer dry periods, higher atmospheric water demand for evaporation, and increased anthropogenic water use, the gap between regional water availability and demand will continue to increase. In order to better quantify this gap, and subsequently define required adaptation measures, we need to understand, and be able to model, the water-related growing requirements of plants, also called ‘site conditions’[13-16]. Let me explain.

Plant water stress

Plants have their roots in the soil, where they take up water to transpire and oxygen to respire (or ‘breathe’). When groundwater levels are deep, plants are mainly dependent on precipitation for their water supply – so-called groundwater independent vegetation.

For groundwater dependent vegetation, the water supply is also determined by the water supplied by the groundwater, due to capillary rise. If the distance between the root zone and the groundwater level is too large, plants may suffer from water deficit or drought stress: the availability of water is insufficient to meet the water demand for transpiration[17].

When groundwater levels are too shallow, there can be an excess of water. In this case, soil pores become filled with water, which limits oxygen transport from the atmosphere to the soil and could result in oxygen stress: the availability of oxygen in the soil is insufficient to meet the oxygen requirement for root respiration[14, 17, 18].

Plants can adapt to prevent water excess and deficit. For example, plants can create a more shallow root system, have tissue to transport oxygen to the roots or have hairy leaves or sunken stomata to limit the water demand for transpiration. For agricultural crops, conditions of water excess can be prevented by drainage. Water deficits can be addressed using irrigation. Although these solutions improve the water and oxygen availability for plants growing in agricultural fields, they also have a large impact on water resources on a regional scale.

Both climate change and anthropogenic activities 'at the soil surface' have additive impacts on water resources. Water resources, in turn, determine the suitability of areas for agriculture[15] and specific nature targets[16]. The shallow subsurface connects atmospheric conditions with plant functioning, land use and groundwater[19]. It is this shallow subsurface that is the focus of my research.

Plant water stress and regional water management

Small changes in groundwater levels can have large impacts on plant water availability[13, 14, 20, 21]. For example, a 20 cm deeper or more shallow groundwater level, may already result in unfavourable conditions for plants, due to a water deficit or water excess, respectively. This makes finding the 'sweet spot' for the right moisture conditions at the right time challenging[22].

Even areas like the Netherlands, are increasingly confronted with water deficits in agriculture and nature and growing pressure on the availability of high-quality water for critical applications such as the production of drinking water[3, 23, 24]. Anthropogenic water demand cannot easily be met by just exploiting more groundwater, because, as just explained, only a small part of the total groundwater stored can be sustainably exploited.

We can't take too much groundwater without negatively impacting other critical functions like nature. However, we cannot just raise groundwater levels without analysing the impact of potential water excess either. Thus, we must carefully balance how we manage and use our water resources in order to mediate how our actions impact groundwater dependent functions at the soil surface (Figure 2).

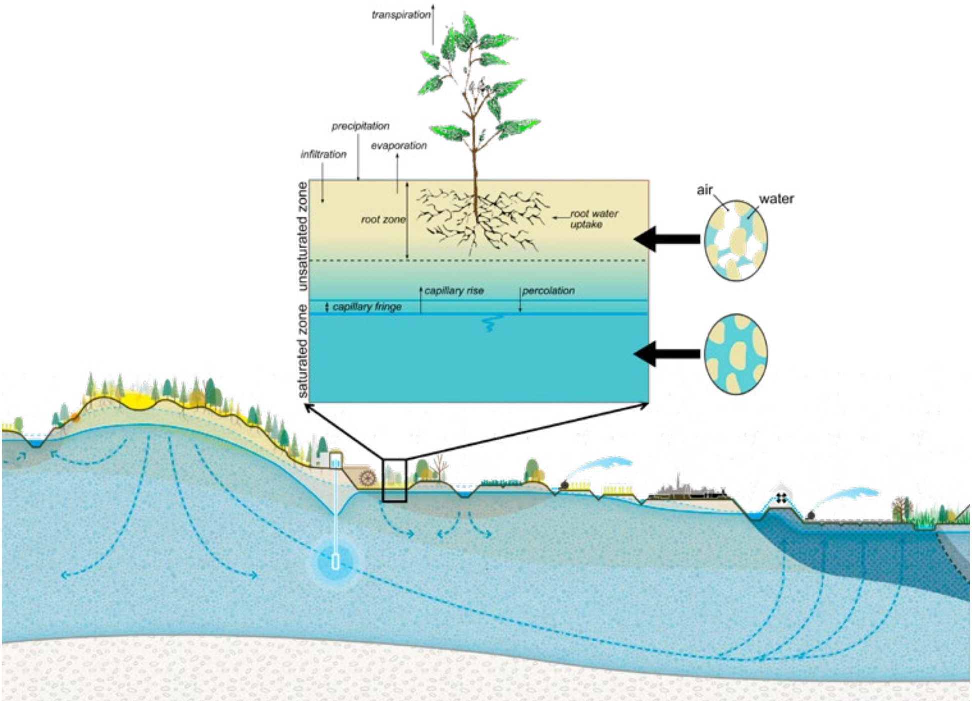

Figure 2: A delicate balance - small changes in groundwater levels can have major effects on nature and agriculture. Only a small part of the available (ground)water can be used without negative effects on functions 'at soil surface'. Landscape cross-section obtained from 'Zonder water, geen later'[25] – SMV – (edited).

It is important to realise that we need to determine the critical site conditions for plants as well as understand how changes in water management will affect these conditions. A measure taken at a specific location, or in a specific subsystem, will not only affect local conditions. In fact, the opposite is true. In the water system, groundwater, surface water, land use and water use, are closely linked. This means that a measure taken will propagate through the water system, positively or negatively impacting areas and functions elsewhere. Imagine adding a drop of water to a pond. The drop creates ripples that affect other parts of the system – visualised here by M.C. Escher (see front cover). A measure taken anywhere in the water system could affect the water availability for plants.

Understanding the interlinkages between hydrological processes at the interface of groundwater – soil moisture – plant and atmosphere are indispensable in this context. In fact, it is a significant part of research within the field of eco-hydrology. In this field of expertise, we embed plot scale knowledge of relationships between groundwater, soil moisture, and vegetation in a regional context, where climate change and anthropogenic activities influence groundwater and soil moisture conditions.

Recent years have shown us that our current water system is not robust. It is not able to cope and withstand climate-induced amplification of dry and wet extremes and the increased water use across all sectors, while maintaining water availability for different functions. These changes necessitate a significant structural redesign of the water system as well as the use of freshwater resources[26].

To define climate robust water systems, which we will call 'Waterscapes' to emphasise the guiding role of water in the landscape[27], interactions among site conditions and water management practices need to be fully understood and be made available for decision making.

Research aims of the special chair

General

In line with the background information I have sketched, the main research aims of this special chair are to assess the gap between plant water supply and demand, and to identify the opportunities and trade-offs of adaptation measures to increase local and regional water availability all in an effort to reduce this gap.

We will contribute to the knowledge development of the responsible use of water resources on a plot to regional scale. The chair will study the propagation of water management and (cross-sectoral) adaptation measures concerning the gap between water supply and demand, as defined by critical water-related site conditions for plant growth in nature and agriculture. This will be done by continuing collaboration with staff from the Department of Soil Physics and Land Management, MSc-students and PhD-candidates, and ongoing collaborations with other academic groups, both within and outside Wageningen University. My chair aims to bridge scientific insights to society, building upon a strong existing network of societal partners. For this, being part of an applied research institute, and collaborating with other institutes, is key. I will come back to this point later.

Studies will provide knowledge of adaptation measures, which will be focused on the interface between the (natural) water system and (anthropogenic) water use. Adaptation measures should reduce the effects of anthropogenic water use on plant water stress that arise due to changes in climate and water demand. This requires the combination of two aspects of water management, namely i) process-based knowledge on water-related site conditions for optimal plant growth (investigated at the plot scale), and ii) the potential of adaptation measures to reduce the regional net use of water resources, alleviating pressure on plant water availability (investigated at the regional scale). I will go into it briefly here.

Critical water-related site conditions for plants

Knowledge about water-related site conditions for vegetation and the critical limits for water excess and deficit is required to quantify the amount of water that can be exploited regionally without impacting other functions, and the effect of adaptation measures (Figure 2). To predict the impacts of environmental conditions in a reliable manner, process-based relationships between site conditions and plant response (either nature or agriculture) are a prerequisite[28]. Traditionally, many models / decision-support tools make use of indirect relationships or expert knowledge, limiting their general applicability. More recently, the focus has been on the development of process-based knowledge of the soil-water-atmosphere-plant interface. These relationships replace empirical ones[14, 18, 28] and are part of the process-based cores of two instruments: Waterwijzer Landbouw (WWL) and Waterwijzer Natuur (WWN) (waterwijzer.nl,[15, 16, 29]). In the Netherlands and Flanders, these tools are being applied on local to regional scales by researchers, provinces, water management authorities, and policy makers to quantify the effect of water management on agricultural crop yields and nature targets.

I am grateful for the collaboration with Flip Witte, Mirjam Hack and Rob Ruijtenberg who were at the forefront in the development of these tools.

The worldwide applied plot scale unsaturated zone model SWAP[30, 31] is being used in both WWL and WWN to simulate the effects of water excess and deficit for crops and natural vegetation, respectively. SWAP has also been incorporated into the automated control of subsurface drainage/irrigation systems to anticipate amplifying wet and dry extremes in relation to plant water stress in agricultural fields[32, 33], finding a new balance in water discharge, retention, and recharge[34, 35] (Figure 3). Although WWL, WWN, and SWAP are operational, a better understanding of critical soil conditions for crops and natural vegetation (both wet and dry extremes) is essential. Within this context, the special chair will focus specifically on adequate model improvement and parametrisation and subsequently simulation of the impact of increasing wet and dry extremes on water excess and deficit (oxygen and water availability) for plant roots. This allows researchers and research consultants to identify the extent to which adaptation measures in water management are required.

It has been a pleasure to collaborate with colleagues and PhD-candidates Janine de Wit and Mark van den Brink on these plot scale issues, and not to forget Jos van Dam and colleagues at Wageningen Environmental Research.

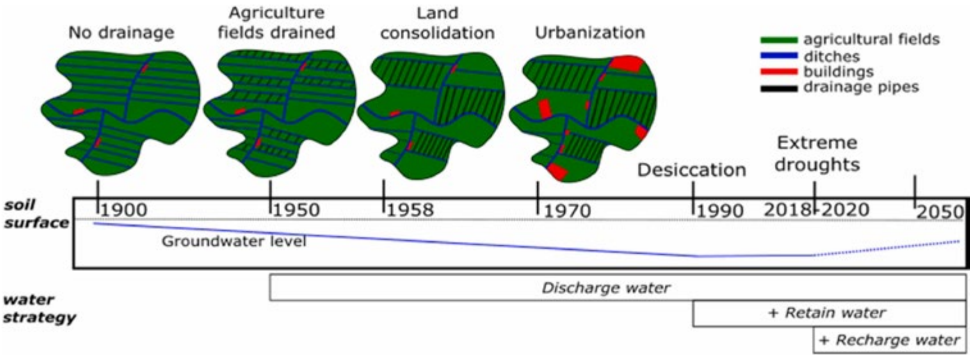

Figure 3: Timeline with developments which impacted the landscape design and the groundwater levels in the Netherlands. From 2018 onwards the agricultural management changed more to i) discharge water to avoid flooding or waterlogging, ii) retain water in the soil during rainfall, and iii) recharge water to prevent agricultural and hydrological drought. Source: De Wit et al.[34]

Adaptation measures - from linear to circular approaches

Although the natural water system and urban water cycle are traditionally considered to be separate systems, they are physically strongly connected: the water system forms the resource for anthropogenic use, while after use, the water is released from the urban water cycle to the water system as treated waste water[26]. Within a range of possible adaptation measures to increase the regional water availability, solutions connecting the 'natural' water system and urban water cycle are under-exposed. Exploitation of water resources other than groundwater or surface water, like wastewater from industrial or domestic origin, are just being explored in the Netherlands, as a supplement to existing resources[36-39] (Figure 4).

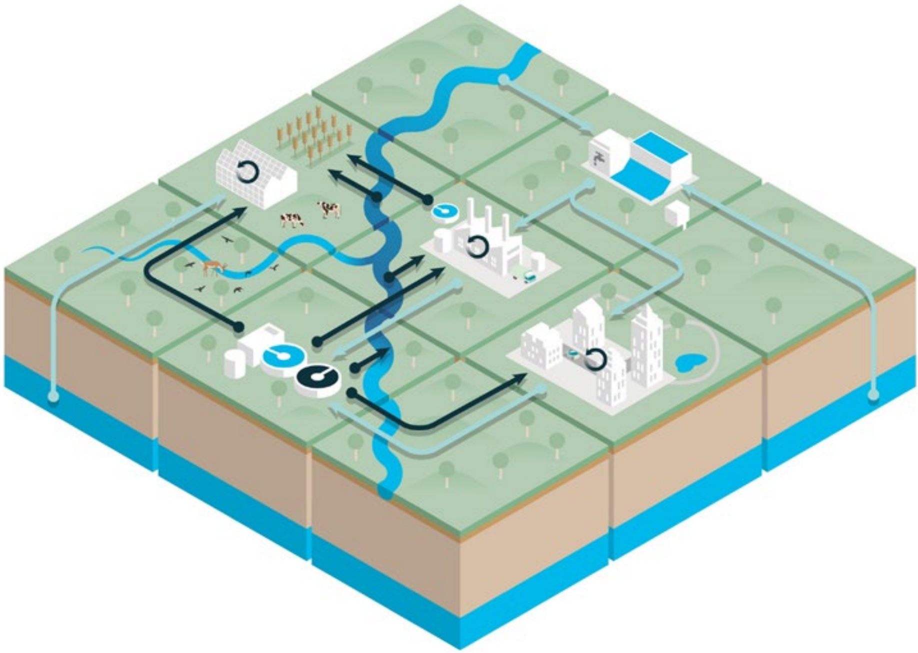

Figure 4: Conceptual representation of water reuse across sectors. Source: kwrwater.nl

A more circular approach, rather than a linear approach, provides new opportunities for water allocation to protect the environment that depends so heavily on water resources. There are some examples where the benefits and risks of cross-sectoral measures have been explored. Think about the 'Boer Bier Water' initiative of the Swinkels (Bavaria) Brewery in the south of the Netherlands, focusing on subsurface irrigation using residual water to alleviate plant water stress in agriculture. Such approaches have the potential to alleviate pressure on water resources which could benefit other water-dependent functions. However, in order to quantify the true potential of such (cross-sectoral) approaches, a system perspective is needed. The propagation through the regional water system and the trade-offs of measures need to be identified. Which part of residual water can be used or reused to alleviate plant water stress in agriculture, for example, and what is the net effect on functions like nature? Rather than investigating the technical details of cross-sectoral adaptation measures, research should first focus on providing insight into the quantitative impacts, both positive and negative, of these measures.

I would like to take a small sidestep from explaining the scientific goals of the chair. Studies on adaptation measures should not be done solely from the ivory tower that a university oftentimes is. It is crucial to embed research in a real-world environment, to embed activities and insights directly into the daily work of stakeholders like farmers, water managers, drinking water companies, and policy makers. This facilitates co-creation and understanding and puts the overly detailed scientific work into a broader societal context. Additionally, it will provide inspiring examples of the relevance of the research within education. In doing so, we hope to get students interested in the field, ultimately mentoring our future water experts. One of my nephews happens to be on track to becoming one of these experts.

We have been working on combining applied research with more fundamental research with the NWO programme Closed Cycles (nwo.nl/en/closed-cycles-magazine), for example. Together with Dominique Narain and Darrell Tang, who both successfully defended their PhD-thesis[40, 41], we demonstrated how applied research can be combined with fundamental research to make an impact. One of the most important aspects of this research was the fact that it was a true collaboration with partners in the field, like with Bas Worm and Gé van den Eertwegh in the Haaksbergen case[37, 38, 42-48], and Marthijn Junggeburth and Bart Bardoel in the Boer Bier Water case[49-51]. And of course, we can't forget the role of the land owners René and Wilfried whose fields were treated with wastewater for subsurface irrigation purposes. The project also inspired communication by artists, like in the work of Anna Andrejew, depicting the spreading of water and solutes in the subsurface and plants over time, by applying photosensitive liquids on paper made from corn as grown in the field (Figure 5).

It takes courage to stick your neck out and be ahead of the troops. The field applications, combined with scientific research and communication efforts, proved appealing to policy makers and professionals from around the world. It also provided many insights and improved understanding of what can be done, and under which conditions. Stakeholders also came to realise what we really shouldn't want. These collaborations also showed me that when all parties keep an open mind and really try to view things from all perspectives, along with a bit of creativity to get things funded, developments in science, practice, and policy can go hand-in-hand. I hope to play a role in creating more of these examples.

Let's go back to talking about scientific approaches and evaluating the implementation of local scale measures in the regional water system. I would like to talk about the concept of water systems thinking and modelling. Implementation of local scale measures in the regional water system requires an integrated, catchment-wide approach[34, 52]. As mentioned before, water flows within the water system, and the natural water system and the urban water cycle are connected; measures taken in one place will propagate through

Figure 5: Impression from field work and artistic impression from the 'Haaksbergen case', focussing on water reuse for agriculture using subsurface irrigation. Photo credits: Anna Andrejew, Bas Worm and Ruud Bartholomeus.

the system, impacting water excess and deficit – remember the ripples in the illustration by Escher. Therefore, single adaptation measures cannot be set apart from the total system. Responsible water use and reuse requires a multidisciplinary approach with knowledge not only on water demand and availability, but also on water quality and health, as well as technology and governance[53]. A systematic evaluation of these aspects can help determine when (cross-sectoral) adaptation measures are, or are not (!), a viable part of a regional strategy. This integrative context, involving water systems thinking and modelling to identify risks and benefits, is essential for a successful implementation of adaptation measures in practice. Attempting to capture the full complexity of interactions between the natural water system and the urban water cycle by a model will be very challenging, however.

As hydrologists, we often appear to have the desire to use our complex (numerical) modelling tools to solve every problem. However, we need to ask ourselves if a tool really serves the purpose[54]. Specific models can be very useful in understanding some parts of the system, but are not necessarily suitable in cases where a more holistic view is required, or where the same result could be achieved using a lighter instrument. As my former mentor Paul Torfs at Wageningen University illustrated during my thesis work: "why would you use a drill hammer to drive a nail into the wall?". For many applications, we might rely on a more conceptual understanding of the system, supported by relatively simple calculations of water storage and fluxes.

Water systems thinking and modelling is being used more often to understand complex dynamic systems, also in groundwater hydrology[55, 56], and are helpful in studying multiple water uses and planning. For example, the use of Sankey diagram visualisations[26], related causal loop diagrams, and resulting modelling frameworks provide valuable tools to explore and evaluate the regional application of water (re)use, its potential to reduce groundwater and surface water demand, and the possible synergies and trade-offs between sectors. These are challenges that go beyond the goals that could be achieved by this chair alone and that obviously require collaboration between disciplines. Studies from this chair will contribute to the development of methods for water systems thinking and modelling that quantify the propagation of measures through the water system. I am curious to uncover the potential of this interdisciplinary approach, see how it could act as a communication framework to involve stakeholders and facilitate users/ policy makers in understanding all the interlinkages, benefits, and trade-offs of measures.

It's great to take this journey of discovery with postdoc Nikola Rakonjac, PhD-candidates Mina Yazdani, Valdrich Fernandes and Janine de Wit and the KWR colleagues Sija Stofberg, Marjolein van Huijgevoort, Henk Krajenbrink, Peter van Thienen and Klaasjan Raat.

From science to practice and policy

I already touched upon some aspects of bridging science to practice and policy.

I mentioned that scientists have a responsibility to translate their scientific insights and developments into usable knowledge for practitioners and policy makers. Our knowledge should flow and propagate, just like water through the water system. This demands other approaches that can help tell the story and requires other competences beyond being able to execute and publish high quality disciplinary research. It might be even more important to get into the minds of people rather than just fill the online shelves with an endless number of reports and papers. Let's just be honest with ourselves, as researchers, we have a very limited amount of time to study literature. Stakeholders and policy advisors have even less.

Additionally, scientists need to dare to advise policy makers even when uncertainties remain. Oftentimes, we know the general direction we need to take. A quote from climate scientist Dr. Roger Pulwarty comes to mind here: "If we first need to agree on the mechanics of walking, we will never take a walk together" (Roger Pulwarty, NOAA, October 2nd 2024, Geneve, Drought Resilience +10 Conference). The endless search for an even better understanding of something limits policy advice. However, this same strategy is also used by policy makers to postpone decisions. We need to avoid a so-called "research lock-in", especially during transitions that could take decades and where it is impossible to know all the details beforehand.

Applied research institutes play a pivotal role in bridging science to practice. It is the motto of KWR Water Research Institute, and it is what the institute does. In order to bridge science to practice, research institutes like KWR need to ensure that they have a solid scientific base. Part of this includes establishing strong connections with universities. These connections have two different functions: linking fundamental research to applied research and embedding societal questions in applied and fundamental research programmes. Collaboration in research programmes like AquaConnect, Waterscape and programmes within the National Science Agenda are all a part of this. Giving research institutes an active role and responsibility in academic projects to translate scientific achievements to more practical insights, for example by embedding academic projects in longer term applied research programmes with their stakeholders, could strongly increase the societal impact of academic research.

Bridging science to practice, and I would like to specifically add policy here as well, is not only a task for the scientific community. Policy makers have an equally important role here. Too often, results that don't fit within a certain political agenda or are a bit too difficult to easily understand are being neglected or considered to be 'just an opinion'. This happens at different layers, from national governments to stakeholder organisations and regional water management authorities. The use of 'alternative facts' and the selective interpretation of numbers for the benefit of a single sector has also found its way into the water sector. This could be a phase of the transition we are in, where it is difficult to say goodbye to what we had while hoping to keep what we have. In this context, I can understand this reaction to some extent.

In any case, the challenges described here should not be determined by politics or lobbies, but should be seen as a joint responsibility. We can neglect the impact of climate change and our anthropogenic activities but we should still recognise that continuing like this will impact all of us. Even maintaining the water availability that we have now will require significant adjustments. Not everything is possible everywhere. For drought however, transformations seem to pose specific challenges[7] (Figure 6). We are caught in the hydro-illogical cycle[57], where we worry during dry periods and panic when droughts last too long, but we go right back to what we used to do when the rain comes again. In doing so, we stick to the bias of adapting to wet conditions, while failing to be prepared for the droughts that will come.

Of course, such a change is not easy. I don't want to give the impression that I think that I have all the wisdom here, quite the contrary. However, as I argued earlier with colleagues in the field: even though we know what direction to take, coming to a consensus as to what needs to be done and who needs to do it may be the biggest challenge we face when bringing about any change. In order to realise a required transition in water management, a long-term vision (decennia) and a plan are needed. Continuing with the 'water and soil as guiding principles' initiative might be a good direction to take for a more climate robust water system, with special attention to spatial land management in relation to regional water use and water availability.

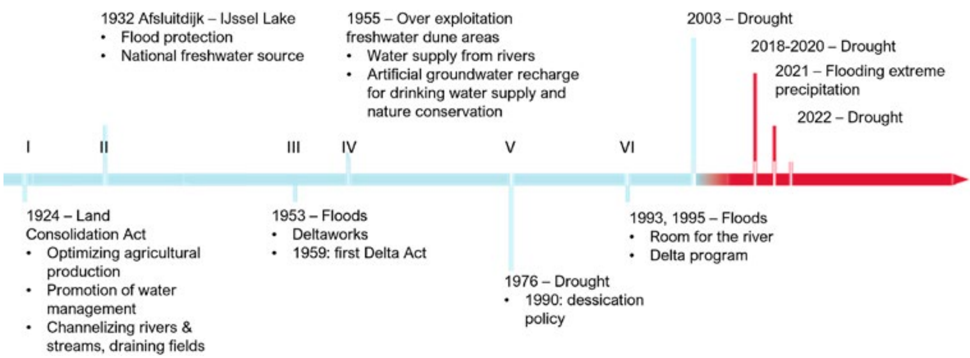

Figure 6: Timeline of events of both wet and dry extremes in the Netherlands over the last century and, where applicable, important management or governance changes. Source: Bartholomeus et al.[7]

Water system: physical system and water system governance

With this, you might think that I am very critical on how we have done things and how we are currently doing things and that for me the glass is half empty. To some degree, it is true: if we have learned anything from the past, we can see that it seems to be very hard to implement structural measures to reduce the impact of droughts and we even have aggravated these impacts by (over)adaptation to water excess. We know that there are huge challenges with respect to both water excess and water deficit ahead of us. Any changes seem to go too slowly.

There are many reasons to be optimistic, however, and that's what I am. The glass is actually half full. Water management authorities are searching for options that will allow us to hold more water while at the same time testing the boundaries therein. Guidelines that include drought management in addition to flood prevention are being explored, industries are researching alternative water sources for their production processes, and drinking water companies are creating partnerships to work on so-called drinking water landscapes. Perhaps most importantly, young water professionals are pulling together to create new long-term perspectives and are breaking through old structures (Figure 7). Within the water sector, we are all taking steps to change.

Figure 7: Perspective of the water system of the future as generated by young water professionals within the GRROW-project: Generation and Radical Rethinking of the Water sector. Source: Van Aalderen et al.[58] kwrwater.nl/grrow

I am confident that true collaborations between natural sciences and social sciences are needed. I see researchers from both disciplines going outside of their comfort zones (me included) and developing new inter-disciplinary methodologies that should facilitate the transition process. Initiatives like Waterscape, Water in the Circular Economy (WiCE), and Public design for water develop tools that aim to safeguard the value of water using an integrated approach that involves all stakeholders, calling on knowledge from both the physical water system and water system governance.

Finally, I am convinced that every citizen, each one of us, wants to have a healthy environment where we can all live comfortably. We all want an environment where the societal functions of water (cooling, biodiversity, drinking water supply, food production) along with the economic functions (industry, agriculture) are met. We are all responsible for working towards a healthy and safe environment for our collective future. The process won't go smoothly – there will be ripples, just like in Escher's work. We will succeed if we keep track of the long-term goals.

Although I now have the title of professor, it does not change who I am or what I do. I am still just Ruud who has a passion for water. I'm a researcher who recognises the added value of collaborating across disciplines and institutes. I want to contribute whatever I can to a fair, just, and robust water system, helping to create an environment that is good for humans and nature, ensuring a healthy environment for future generations.

Acknowledgements - *Dankwoord*

I would like to take this opportunity to say a few words to specific people that have helped me or joined me on this journey so far.

First, I would like to take a moment to reflect on the passing of Prof.dr.ir. Reinder Feddes last month. We should be very grateful to him for his incredible contribution to the field of eco- and agrohydrology. I had the privilege of having Professor Feddes on the review committee for my dissertation. His reflections on my work were invaluable to me.
I am thankful for all the collaborations with many of my colleagues, those within KWR and those from other institutes as well as those at this university and other universities. I am also thankful for the collaborations with people in industry, drinking water companies, consultancies, water management authorities, and ministries. Rob, Perry, Bas, Mirjam, Rob, Gé, Marthijn, Bernard, Gijsbert, Sija, Bernard, Milou, Anne, Michelle, Marc, Annemarie, Stefan, Nora … just to name a few.

Figure 8: Chapel of St. Valentinus, Westerhoven. Source: Tusse de haai en d'ekker[59]

Regarding the collaboration at WUR with the Soil Physics and Land Management department, Coen Ritsema and Jos van Dam specifically – thanks for the years of working together and realising the added value in connecting me to WUR. It was an honour collaborating with Professor Sjoerd van der Zee. Special thanks to the director of the Environmental Sciences group, board of promotors, board of directors and the Rector Magnificus for the positive evaluation.

Thanks to the colleagues within the water sector who gradually made me realise that this position would suit me well.

Mariëlle, Dragan, Idsart and Edu: thanks for all the support and motivation from KWR. Jan Willem and Klaasjan, thanks for all the moments of reflection.

With regard to Waterscape-partners, and especially the instigators involved from the very beginning, Wieke Pot and Niko Wanders: let's make Waterscape a success and hopefully be an example of truly interdisciplinary research, bridging science to practice and policy.

To KWR, the water sector and the drinking water sector specifically: let's keep building on our strong knowledge base and network and remain critical clients. Working for sufficient and healthy water comes with great responsibility, but it is also a wonderful task. Thanks for all the opportunities. I am looking forward to continuing my journey with all of you. Colleagues from Eco and Geo at KWR: I wish everyone such collegiality. Let's keep up the good work.

For the PhD-candidates whom I have the honour of supporting on their own journeys. You are all an inspiration. Let's have fun in the sometimes difficult environment of academics. This is what I learned from my former mentor, Professor Flip Witte, to whom I owe a lot.

Flip, via Jos van Dam kwam ik bij jou en KWR als PhD-student. Het plezier in het doen van onderzoek dat jij me hebt gebracht, en met name de relevantie voor het werkveld ervan, neem ik nog elke dag met me mee. Qua loopbaan had me niks beters kunnen overkomen.

Koen, Harm, familie, studievrienden, muziekvrienden, 303: bedankt voor jullie interesse en over het algemeen het leven eenvoudig te houden. Schoonfamilie – het staat 2-1 voor de koude kant, waarvan akte. Harm, de verwarring hier in Wageningen zal nog wel even blijven. Ik zal je studenten proberen netjes goedendag te zeggen.

Inaugural lecture Ruud Bartholomeus. Photo: Guy Ackermans

Pa en ma, we wijden er meestal niet teveel woorden aan. Maar de gelegde basis is goed en een voorbeeld. Fijn om ouders te hebben die er juist wat de rem op zetten. Als het erin zit komt het met de tijd wel. Alleen de grootst mogelijke dank past voor jullie. En het beeld van de Valentinuskapel (Figure 8) aan de Keersop in onze geboorteplaats Westerhoven past natuurlijk mooi op deze dag, 14 februari.

Lieve Hanneke, Elise en Vere, wat zou ik toch zonder jullie moeten.

Hanneke, wat een mooi pad bewandelen we vanaf onze start in Velp. Privé natuurlijk, maar ook qua onderzoeksloopbaan. Ik heb het je al vaker gezegd, maar het onderzoek dat jij doet is pas echt indrukwekkend. Ik ben ontzettend trots op jou, op wie je bent, hoe je het allemaal voor elkaar krijgt en blij met hoe je me bij de les houdt. Maar ook op hoe wij samen de boel runnen, met en voor onze knappe dochters.

Elise en Vere, dit ziet er misschien allemaal wat interessant uit, maar het is uiteindelijk ook maar gewoon werk en verandert iemand niet. Blijf altijd jezelf, doe gewoon je best, geniet vooral. En doe samen leuke en goede dingen.

En dat wil ik u eigenlijk allemaal meegeven.

I have spoken – *Ik heb gezegd*

Endnote

1. Bartholomeus, R.P., R.J.J. Van Dongen, and P.G.B. De Louw, *Onderzoek naar kwelafhankelijke vegetatie in beekdal het Merkske.* H2O, 2004. 10: p. 27-30.
2. Philip, S.Y., S.F. Kew, K. van der Wiel, N. Wanders, and G.J. van Oldenborgh, *Regional differentiation in climate change induced drought trends in the Netherlands.* Environmental Research Letters, 2020. 15(9): p. 094081.
3. Rakovec, O., L. Samaniego, V. Hari, Y. Markonis, V. Moravec, S. Thober, ... R. Kumar, *The 2018–2020 Multi-Year Drought Sets a New Benchmark in Europe*. Earth's Future, 2022. 10(3): p. e2021EF002394.
4. Lehmkuhl, F., H. Schüttrumpf, J. Schwarzbauer, C. Brüll, M. Dietze, P. Letmathe, ... H. Hollert, *Assessment of the 2021 summer flood in Central Europe. Environmental Sciences Europe*, 2022. 34(1): p. 107.
5. KNMI, *De staat van ons klimaat 2023; Nederlands weer in tijden van klimaatverandering, KNMI, De Bilt,* KNMI-Publicatie 24-01. 2024.
6. KNMI, *De staat van ons klimaat 2024; Nederlands weer in tijden van klimaatverandering, KNMI, De Bilt,* KNMI-Publicatie 25-01. 2025.
7. Bartholomeus, R.P., K. van der Wiel, A.F. van Loon, M.H.J. van Huijgevoort, M.T.H. van Vliet, M. Mens, ... W. Pot, *Managing water across the flood–drought spectrum: Experiences from and challenges for the Netherlands.* Cambridge Prisms: Water, 2023. 1: p. e2.
8. Mazzucato, M., N. Okonjo-Iweala, J. Rockström, and T. Shanmugaratnam, *The economics of water: Valuing the hydrological cycle as a global common good*. 2024.
9. Witte, J.-P.M., W.J. Zaadnoordijk, and J.J. Buyse, *Forensic hydrology reveals why groundwater tables in the province of Noord Brabant (the Netherlands) dropped more than expected.* Water, 2019. 11(3): p. 478.
10. Knotters, M. and P.C. Jansen, *Honderd jaar verdroging in kaart.* Stromingen : vakblad voor hydrologen, 2005. 11(4): p. 19-32.
11. Hänsel, S., A. Hoy, C. Brendel, and M. Maugeri, *Record summers in Europe: Variations in drought and heavy precipitation during 1901–2018*. International Journal of Climatology, 2022. 42(12): p. 6235-6257.
12. Van der Wiel, K., J. Beersma, H. van den Brink, F. Krikken, F. Selten, C. Severijns, ... R. van Dorland, *KNMI'23 Climate Scenarios for the Netherlands: Storyline Scenarios of Regional Climate Change.* Earth's Future, 2024. 12(2): p. e2023EF003983.
13. Runhaar, J., J.P.M. Witte, and P.H. Verburg, *Ground-water level, moisture supply, and vegetation in the Netherlands.* Wetlands, 1997. 17(4): p. 528-538.
14. Bartholomeus, R.P., J.-P.M. Witte, P.M. van Bodegom, J.C. van Dam, and R. Aerts, *Climate change threatens endangered plant species by stronger and interacting water-related stresses.* Journal of Geophysical Research, 2011. 116(G4): p. G04023.
15. Hack-ten Broeke, M.J.D., J.G. Kroes, R.P. Bartholomeus, J.C. van Dam, A.J.W. de Wit, I. Supit, ... R. Ruijtenberg, *Quantification of the impact of hydrology on agricultural production as a result of too dry, too wet or too saline conditions*. SOIL, 2016. 2(3): p. 391-402.
16. Witte, J.-P.M., R.P. Bartholomeus, P.M. van Bodegom, D.G. Cirkel, R. van Ek, Y. Fujita, ... H. Runhaar, *A probabilistic eco-hydrological model to predict the effects of climate change on natural vegetation at a regional scale.* Landscape Ecology, 2015(30): p. 835-854.
17. Feddes, R.A., P. Kowalik, K. Kolinska-Malinka, and H. Zaradny, *Simulation of field water uptake by plants using a soil water dependent root extraction function.* Journal of Hydrology, 1976. 31: p. 13-26.
18. Bartholomeus, R.P., J.P.M. Witte, P.M. Van Bodegom, J.C. Van Dam, and R. Aerts, *Critical soil conditions for oxygen stress to plant roots: substituting the Feddes-function by a process-based model.* Journal of Hydrology, 2008. 360: p. 147-165.
19. Jarvis, N., M. Larsbo, E. Lewan, and S. Garre, *Improved descriptions of soil hydrology in crop models: The elephant in the room?* Agricultural Systems, 2022. 202: p. 103477.
20. Glanville, K., F. Sheldon, D. Butler, and S. Capon, *Effects and significance of groundwater for vegetation: A systematic review.* Science of The Total Environment, 2023. 875: p. 162577.
21. Bartholomeus, R.P., J.P.M. Witte, P.M. Van Bodegom, and R. Aerts, *The need of data harmonization to derive robust empirical relationships between soil conditions and vegetation.* Journal of Vegetation Science, 2008. 19: p. 799-808.

22. Feddes, R.A., *Waar blijft het water*. 1990.
23. Garnier, M. and I. Holman, *Critical Review of Adaptation Measures to Reduce the Vulnerability of European Drinking Water Resources to the Pressures of Climate Change*. Environmental Management, 2019. 64(2): p. 138-153.
24. Brakkee, E., M.H.J. van Huijgevoort, and R.P. Bartholomeus, *Improved understanding of regional groundwater drought development through time series modelling: the 2018–2019 drought in the Netherlands.* Hydrol. Earth Syst. Sci., 2022. 26(3): p. 551-569.
25. Adviescommissie Droogte, *Zonder water geen later. Naar een omslag in (grond)waterbeheer in Noord-Brabant.* 2022.
26. Pronk, G., S. Stofberg, T. Van Dooren, M. Dingemans, J. Frijns, N. Koeman-Stein, ... R. Bartholomeus*, Increasing Water System Robustness in the Netherlands: Potential of Cross-Sectoral Water Reuse*. Water Resources Management, 2021: p. 1-15.
27. Bartholomeus, R.P., N. Wanders, and W. Pot, *Waterscape: Waterbeheer in een klimaat van extremen vraagt om een transformatie in watersysteem en water governance*. Water Governance, 2023. 3/2023: p. 24-33.
28. Bartholomeus, R.P., J.-P.M. Witte, P.M. van Bodegom, J.C. van Dam, P. de Becker, and R. Aerts, *Process-based proxy of oxygen stress surpasses indirect ones in predicting vegetation characteristics.* Ecohydrology, 2012. 5(6): p. 746-758.
29. Bartholomeus, R.P., M.J.D. Hack-ten Broeke, H.M. Mulder, J. Kroes, R.E. Ruijtenberg, J. Runhaar, and J.P.M. Witte, *Waterwijzers Landbouw en Natuur.* Landschap, 2018. 1: p. 15-23.
30. Kroes, J.G., J.C. Van Dam, R.P. Bartholomeus, P. Groenendijk, M. Heinen, R.F.A. Hendriks, ... P.E.V. Van Walsum, *SWAP version 4, Theory description and user manual*. 2017, Wageningen Environmental Research: Wageningen.
31. Heinen, M., M. Mulder, J. van Dam, R. Bartholomeus, Q. de Jong van Lier, J. de Wit, ... M. Hack - ten Broeke, *SWAP 50 years: Advances in modelling soil-water-atmosphere-plant interactions.* Agricultural Water Management, 2024. 298: p. 108883.
32. Bartholomeus, R.P., G.A.P.H. Van den Eertwegh, and G.W.H. Simons, *Naar online en optimale sturing van Klimaat Adaptieve Drainage.* Stromingen, 2015. 24(4): p. 27-41.
33. De Wit, J.A., J.C. van Dam, G.A.P.H. van den Eertwegh, M.H.J. van Huijgevoort, C.J. Ritsema, and R.P. Bartholomeus, *Controlled drainage with subirrigation systems: Reduce water supply by automatic control.* Agricultural Water Management, 2024. 303: p. 109022.
34. De Wit, J.A., C.J. Ritsema, J.C. Van Dam, G.A.P.H. Van den Eertwegh, and R.P. Bartholomeus, *Development of subsurface drainage systems: Discharge – retention – recharge.* Agricultural Water Management, 2022. 269: p. 107677.
35. De Wit, J.A., M.H.J. Van Huijgevoort, J.C. Van Dam, G.A.P.H. Van den Eertwegh, D. Van Deijl, C.J. Ritsema, and R.P. Bartholomeus, *Hydrological consequences of controlled drainage with subirrigation.* Journal of Hydrology, 2024. 628: p. 130432.
36. Narain, D., R. Bartholomeus, S. Dekker, and A. Van Wezel, *Natural purification through soils: Risks and opportunities of sewage effluent reuse in sub-surface irrigation.* Rev. Environ. Contam. Toxicol, 2020.
37. Narain-Ford, D., R. Bartholomeus, B. Raterman, I. van Zaanen, T. ter Laak, A.P. van Wezel, and S.C. Dekker, *Shifting the imbalance: Intentional reuse of Dutch sewage effluent in sub-surface irrigation*. Science of The Total Environment, 2020: p. 142214.
38. Narain-Ford, D.M., A.P. van Wezel, R. Helmus, S.C. Dekker, and R.P. Bartholomeus, *Soil self-cleaning capacity: Removal of organic compounds during sub-surface irrigation with sewage effluent.* Water Research, 2022. 226: p. 119303.
39. Tang, D., S.E.A.T.M. Van der Zee, D. Narain-Ford, G.A.P.H. Van den Eertwegh, and R.P. Bartholomeus, *Aquifer Recharge for Irrigation and Wastewater Treatment.* Environmental Science & Technology, under review.
40. Narain, D., *Water is too precious to waste: Trade-offs of sewage effluent reuse in agricultural sub-surface irrigation.* 2023.
41. Tang, D.W., *Managed aquifer recharge with marginal water for irrigation and contaminant attenuation.* 2022, Wageningen University and Research.

42. Narain, D.M., R.P. Bartholomeus, S.C. Dekker, and A.P. Van Wezel, *Natural purification through soils: Risks and opportunities of sewage effluent reuse in sub-surface irrigation*. Reviews of Environmental Contamination and Toxicology, 2020. in press.
43. Ore, A., R. Helmus, D.M. Narain-Ford, R.P. Bartholomeus, N.B. Sutton, and A. van Wezel, *Presence of Micropollutants and Transformation Products During Subsurface Irrigation with Treated Wastewater Assessed by Non-Target Screening Analysis*. ACS ES&T Water, 2025.
44. Bartholomeus, R.P., G.A.P.H. Van den Eertwegh, and D.G. Cirkel, *Hergebruik restwater voor zoetwatervoorziening in het landelijk gebied: Monitoring sub-irrigatie met RWZI-effluent Haaksbergen*. BTO 2016.050. 2016, KWR Watercycle Research Institute: Nieuwegein.
45. Stofberg, S.F., R.P. Bartholomeus, G.A.P.H. Van den Eertwegh, and K. Raat, *Restwaterhergebruik in de landbouw - Subirrigatie met RWZI-effluent Haaksbergen 2015-2019. KWR2021.026. KWR, Nieuwegein.* 2021.
46. Tang, D.W.S., S. Van der Zee, D.M. Narain-Ford, G. van den Eertwegh, and R.P. Bartholomeus, *Managed Phreatic Zone Recharge for Irrigation and Wastewater Treatment.* Journal of Hydrology, 2023: p. 130208.
47. Tang, D.W.S., R.P. Bartholomeus, and C.J. Ritsema, *Wastewater irrigation beneath the water table: analytical model of crop contamination risks.* Agricultural Water Management, 2024. 298: p. 108848.
48. Tang, D.W.S., S.E.A.T.M. Van der Zee, and R.P. Bartholomeus, *Phreatic zone wastewater irrigation: Sensitivity analysis of contaminant fate.* Journal of Hydrology, 2024: p. 132263.
49. Bartholomeus, R.P., A.H. Van Loon, and M.H.J. Van Huijgevoort, *Hergebruik van industrieel restwater voor de watervoorziening van de landbouw - Praktijkproef subirrigatie met gezuiverd restwater van Bavaria.* KWR 2018.089. 2018, KWR: Nieuwegein.
50. Bartholomeus, R.P., M. Van Huijgevoort, J. Rozema, and A. Van Loon, *Watertekorten in de landbouw terugdringen met hergebruik industrieel restwater.* H2O Water Matters, 2019. April 2019: p. 20-23.
51. Brakkee, E., C. Van Rens, M. Van Huijgevoort, and R. Bartholomeus, *Hergebruik industrieel restwater Bavaria: inzicht in effecten van opschaling van subirrigatie voor de landbouwwatervoorziening.* KWR 2021.022. 2021.
52. Bartholomeus, R.P. (red.), *Programma Lumbricus: integrale benadering van een klimaatrobuuste inrichting en beheer van stroomgebieden – een overzicht.* 2021.
53. Dingemans, M.M., P.W. Smeets, G. Medema, J. Frijns, K.J. Raat, A.P.v. Wezel, and R.P. Bartholomeus, *Responsible Water Reuse Needs an Interdisciplinary Approach to Balance Risks and Benefits.* Water, 2020. 12(5): p. 1264.
54. Melsen, L.A., *It Takes a Village to Run a Model—The Social Practices of Hydrological Modeling.* Water Resources Research, 2022. 58(2): p. e2021WR030600.
55. Ram, S.A. and Z.B. Irfan, *Application of System Thinking Causal Loop Modelling in understanding water Crisis in India: A case for sustainable Integrated Water resources management across sectors.* HydroResearch, 2021. 4: p. 1-10.
56. Phan, T.D., E. Bertone, and R.A. Stewart, *Critical review of system dynamics modelling applications for water resources planning and management.* Cleaner Environmental Systems, 2021. 2: p. 100031.
57. Wilhite, D.A., *Changing the Paradigm for Drought Management: Can We Break the Hydro-Illogical Cycle?* Water Resources Impact, 2014. 16(1): p. 21-23.
58. Van Aalderen, N., F. Van Berkel, E. Van der Roest, N. Meekel, and R. Van den Berg, *GRROW: Generational Radical Rethinking of the Water sector. BTO 2023.033. KWR.* 2023.
59. Roelofs, W., W. Van Nuenen, and F. Hoppenbrouwers, *Tusse de haai en d'ekker. Een greep uit de geschiedenis van Westerhoven.* 1986: Stichting Gemeenschapswerk Westerhoven & Comité Eeuwfeest Kerkgebouw Westerhoven.

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