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Managing water across the flood–drought spectrum: Experiences from and challenges for the Netherlands

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Abstract

Recent impactful hydrometeorological events, on both the extreme wet and dry side of the spectrum, remind policymakers and citizens that climate change is a reality and that a shift in water management solutions is required. A selection of policy-shaping events in the Netherlands shows that both floods and droughts have occurred historically and continue to occur, causing significant impacts and challenges for water resources management. For decades, water management in the Netherlands has focused on implementing flood prevention policies, mostly prompted by specific events. The occurrence of droughts did not lead to comparable significant transitions in water management. The bias toward adaptation measures on the wet part of the spectrum (i.e., floods), increases vulnerability to dry extremes (i.e., droughts) as experienced in 2018–2020 and 2022. A required long-term, integral vision to rethink the existing water management system is challenging as droughts and floods act on different time scales. Furthermore, there is a fierce competition for land use and water use functions. ‘Transformation pathways’, applied across the full flood–drought spectrum, could provide a valuable framework in the development toward a sustainable management of water resources, involving stakeholders for just and equitable transitions and translating long-term visions into pathways for action.

Impact statement

Hydrometeorological extreme events, that is, floods and droughts, have major impacts on ecosystems and sectoral water uses such as shipping, agriculture, industry, energy, and drinking water. From looking back on a selection of historical events in the Netherlands, we learn that significant changes in policy and measures have been implemented in response to extreme hydrological events, especially with regards to floods. However, from recent extreme drought (2018–2020, 2022) and flood conditions (2021) and future climate projections, it has become clear that optimization of the current water management system will not suffice. A transformation is needed to deal with future hydrological extremes, requiring modifications in water system, water management, water use, and governance. We need to design, manage, and use the water system in a way that resilience to both floods and droughts is increased. This requires methods and tools to stress-test the system for both extremes, and knowledge of measures that reduce both risks. In regional adaptation strategies, the full flood–drought spectrum should be managed in a balanced way. A transformation of the current water system and water management will not always and at all locations be beneficial for all sectors. Stakeholder interactions are needed for just and equitable transitions and for translating long-term visions into concrete pathways for action.

Introduction

The European summers of 2018, 2019, and 2020 were characterized by low precipitation and high temperatures, which caused large-scale and intense droughts (Philip et al., 2020; Zscheischler and Fischer, 2020; Turner et al., 2021). These events, by some sectors felt as one multi-year drought, set a new benchmark in Europe (Rakovec et al., 2022), and sparked societal and scientific interest in the nature of drought and event-specific climate projections (van der Wiel et al., 2021, 2022; Aalbers et al., 2022; Blauhut et al., 2022; Gessner et al., 2022). With these droughts on our minds, the contrast to the 2021 summer floods in the Ahr, Erft, Meuse, and its tributaries in Belgium, Germany, and the Netherlands was large. These floods were caused by 2 days of extreme rainfall on hilly terrain and led to more than 200 fatalities and severe infrastructural damage (Kreienkamp et al., 2021; Faranda et al., 2022; Lehmkuhl et al., 2022). This string of very impactful hydrometeorological events, on both sides of the flood–drought spectrum, reminded policymakers and citizens that climate change is a reality and that increases in both droughts and floods require a shift in water management solutions. Additionally, climate change projections for the region (KNMI, 2021; Masson-Delmotte et al., 2021) show strong decreases in mean summer precipitation, increasing winter precipitation, increased rainfall variability, more intense drought events (Cook et al., 2020; Ukkola et al., 2020), and more intense short convective rainfall events (Fowler et al., 2021). This shows that a more anticipatory and adaptive approach to water management will be needed to, on the one hand, prepare for short-term climate-related shocks and, on the other hand, continuously evaluate long-term water management practices.

Hydrometeorological extreme events have major impacts on both terrestrial and aquatic ecosystems (Bartholomeus et al., 2011; Witte et al., 2012; Reyer et al., 2013; Kløve et al., 2014), infrastructure (Vardon, 2015), buildings (Sanders and Phillipson, 2003), greenhouse gas emissions (Stirling et al., 2020) as well as multiple sectoral water uses (Wlostowski et al., 2022). For instance, shipping is hampered by low water levels (Christodoulou et al., 2020; Vinke et al., 2022). Agricultural production is reduced under too wet or dry conditions or due to high salinity (Kroes and Supit, 2011; Hack-ten Broeke et al., 2016; Harkness et al., 2020; Shahzad et al., 2021; de Wit et al., 2022). Industrial and energy water uses are constrained due to low (summer) flow and increased water temperature under droughts and heatwaves (van Vliet et al., 2013; Behrens et al., 2017; Tobin et al., 2018; Moazami et al., 2019). The drinking water sector is challenged by higher water demands during warm summers, increased salinization, and higher concentrations of various chemicals (Delpla et al., 2009; Bonte and Zwolsman, 2010; Koop and van Leeuwen, 2017; Sjerps et al., 2017; Garnier and Holman, 2019; van den Brink et al., 2019; Wolff and van Vliet, 2021). Also, floods affect drinking water supply, by deteriorating water quality and destroying water supply infrastructure (Khan et al., 2015). Overall, sectors depend on both sufficient water availability and suitable water quality (Lissner et al., 2014; van Vliet et al., 2017). When sectoral water demands are not met, this can have major economic impacts (Naumann et al., 2021).

In this short review, we provide our perspective on how the Netherlands and other countries in river deltas could manage water across the flood–drought spectrum for the next century, both from a water management and water governance perspective. Many countries in river deltas are highly engineered and managed (Renaud et al., 2013); the Netherlands is no exception. These countries are densely populated and have intensive agriculture. Because of their location, river delta countries strongly depend on water management and activities in upstream-located countries.

Traditionally, water managers and water utilities in the Netherlands focus on preventing floods, whereas they will also need to anticipate drought (Kabat et al., 2005; Philip et al., 2020; Pronk et al., 2021; Brakkee et al., 2022; Brockhoff et al., 2022; Mens et al., 2022). The Netherlands is a low-lying country, partly below sea level, in the delta of the rivers Rhine and Meuse (Figure 1A). Low-lying regions face challenges such as soil subsidence and salinization (Querner et al., 2012; Raats, 2015). However, there are also free-draining regions in the east and south of the Netherlands (Figure 1B) where droughts impact water availability for nature, agriculture, industry, and drinking water supply (Hendriks et al., 2014).

We will first provide an overview of selected events across the flood–drought spectrum in the Netherlands over the last century that led to significant adaptation measures and associated governance arrangements. We then provide insight into recent (2018 onwards) and future drought and flood events and associated water management implications. Based on this exploration of historical events and future extremes, we provide our perspective on future water management and water governance across the flood–drought spectrum for deltas like the Netherlands.

Floods and droughts in the Netherlands

Policy-shaping events leading to the current water (governance) system

Over the last century, several extreme hydrological events and transformative changes in Dutch water management and water governance occurred. A historical, but not exhaustive, timeline of important events and changes is displayed in Figure 2 and Table 1. First of all, the overview shows that wet (e.g., 1953 flood, Table 1, III) and dry (e.g., drought of 1976, Table 1, V) extremes are not new. For some events, impacts led to the implementation of effective technological measures (e.g., pretreatment and infiltration of river water in dune areas for drinking water production, Table 1, IV) or new governance arrangements (e.g., the Dutch Delta program to prevent floods and safeguard freshwater supply, Table 1, VI).

Important to note is that measures can contribute to the adaptation to both extremes (reduce flood risk and drought risk). The Dutch water management system shows many examples where the system is optimized for the combination of flood protection and freshwater supply, although often with negative ecological consequences. For example, the IJssel Lake (IJsselmeer Area, Figure 1A) is controlled on lower water levels in winter and higher water levels during summer, the opposite of natural water level dynamics for freshwater ecosystems. Similarly, in the low-lying part of the Netherlands, the (ground)water levels are highly controlled, to both avoid flooding in winter and water level decline in summer. One reason for the latter is that peat dikes could dry out and fail, as happened in 2003 (e.g., Bottema et al., 2021). In fact, the main reason to supply water to low-lying areas during summer is to reduce peat oxidation, to reduce both subsidence and greenhouse gas emissions in view of the climate mitigation goals. Adaptation measures to one extreme could, however, also increase the hazard or vulnerability of the extreme at the other side of the spectrum. An example is the dense drainage system to provide optimal farming conditions in the free-draining higher areas (Figure 1B). The drainage system, designed based on extensive drainage research (Feddes, 1988), discharges water quickly, lowering groundwater levels in early spring and reducing waterlogging, which extends the growing season. The lower groundwater levels increase the impact of drought on, for example, agriculture and nature. Additionally, when cost-effective, farmers use groundwater for irrigation to overcome drought events later in summer (van Oort et al., 2023), resulting in a further decline of groundwater levels. Adaptation measures, like drainage and irrigation, could thus contribute to desiccation of groundwater-dependent ecosystems.

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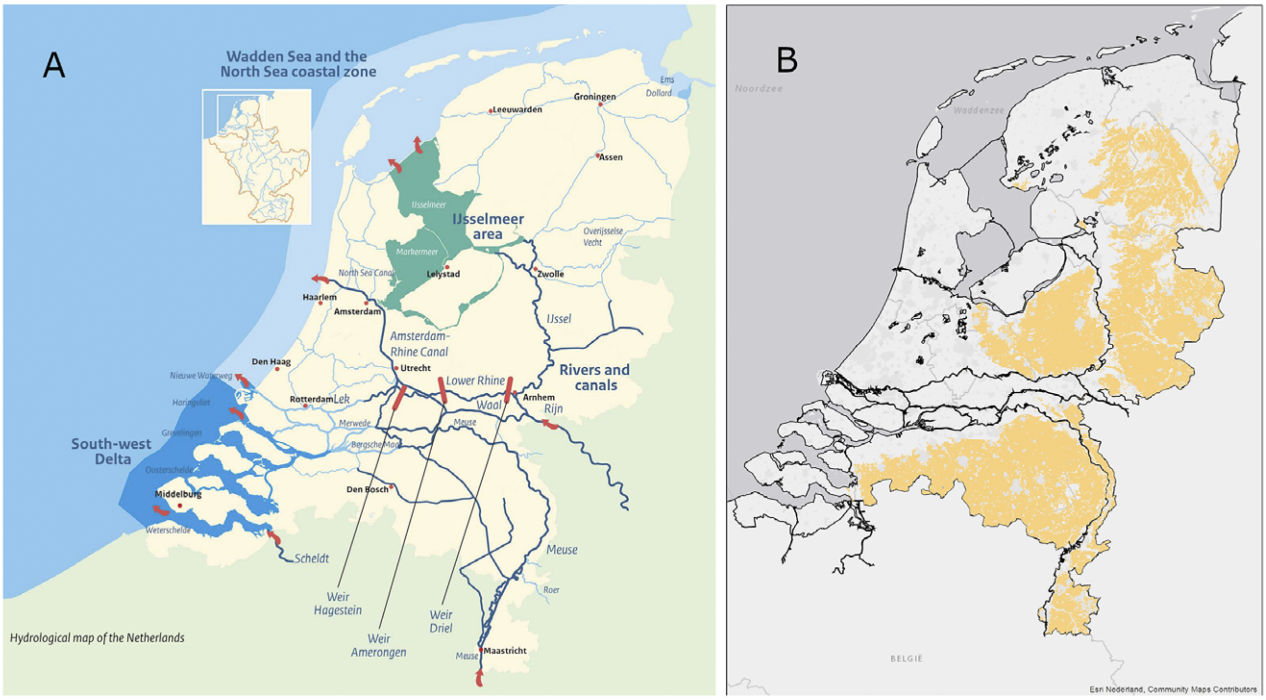

Figure 1. Hydrological map of the Netherlands (adapted from Rijkswaterstaat (2019)), including main rivers Rhine and Meuse (see inset), the IJsselmeer area (green) and the South-west Delta (dark blue). B. Free-draining higher grounds in the east and south (orange) and water-level regulated areas in the western and northern part of the country (adapted from de Wit et al. (2022), CC BY 4.0).

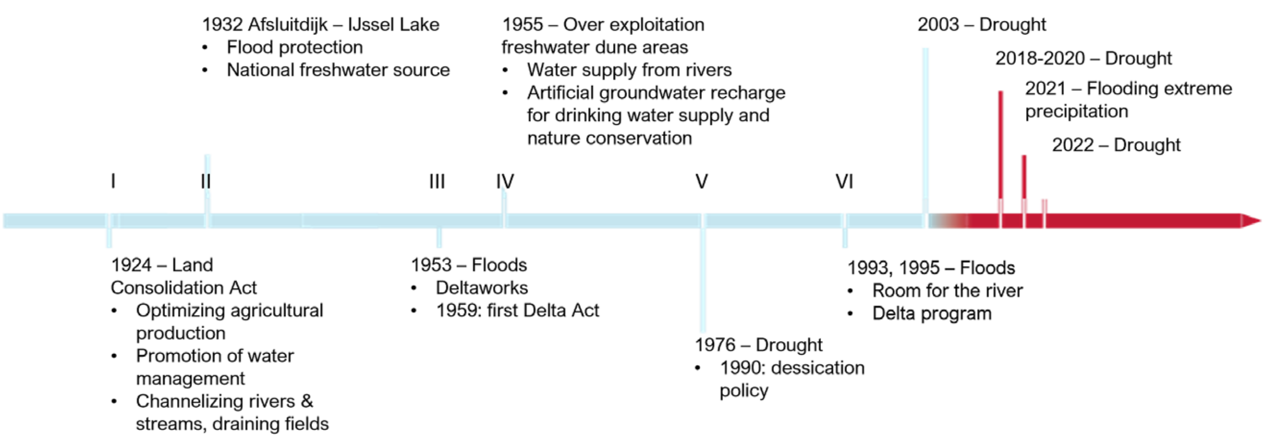

Figure 2. Timeline of selected events of both wet and dry extremes in the Netherlands over the last century and, where applicable, important management or governance changes. The events are further described in Table 1.

Adaptation measures were especially successful in the prevention of floods and to deal with extreme precipitation events. Neither the occurrence of droughts in previous decades nor the measures to deal with droughts led to comparable significant changes in water management. The bias toward adaptation measures on the wet spectrum of the extremes, makes the Netherlands more vulnerable to the amplifying dry extremes experienced from 2018 onwards. As described in the introduction: these might be the benchmark for future conditions.

Amplifying hydrometeorological risks: Hydrological effects, management, and policy actions of recent extreme events

The summers of 2018–2020 were characterized by extreme drought conditions that challenged the Dutch water management. While the events are considered rare in the current climate, it is expected that future climate change will make similar events more frequent and intense (Philip et al., 2020; KNMI, 2021; van der Wiel et al., 2021; Aalbers et al., 2022). In addition, there is an increased probability that drought events will become multi-year events

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Table 1. Description of the events mentioned in Figure 2

Nr	Description	Literature
I	After the First World War, land consolidation was supported to make the economy more self-sufficient (Land Consolidation Act, 1924). Drainage was intensified and land was brought into cultivation (with major reconstructions in 1950s and 1960s), resulting in lower groundwater tables and an increase in crop production. Standard drainage norms were made available in a handbook. Over the past decades, however, excessive drainage contributed to desiccation, impacting groundwater-dependent ecosystems	Cultuurtechnische Vereniging, 1988; van den Bergh, 2004; Knotters and Jansen, 2005; van den Brink and Molema, 2008; Stańczuk-Gałwiaczek et al., 2018; Witte et al., 2019; de Wit et al., 2022
II	In 1932, the former *Zuiderzee* was closed off from the sea by the Afsluitdijk to form the IJssel Lake (IJsselmeer area Figure 1A). This turned this main inland saltwater body into the largest freshwater reservoir of the Netherlands. While the main goal of the lake is to provide flood protection for the surrounding lands (by storing river water during high tide and keeping water levels low), it also acts as a major source for freshwater, supplying water to the North of the Netherlands during summer, especially in times of drought	Lammens et al., 2008
III	In February 1953, the Netherlands was confronted with the largest natural disaster of the twentieth century. Due to the combination of a persistent northwesterly storm and spring tide, the sea level rose to more than three meters above the normal high tide. Many of the low and weak dikes in the Southwest of the Netherlands broke and 1836 people died. To prevent such flood disasters in the future, the Delta Commission was set up and the Delta Works, comprising locks, storm surge barriers, and dams, were constructed (South-west Delta Figure 1A)	Gerritsen, 2005
IV	Freshwater from the coastal sand dunes is used for drinking water production. To prevent overexploitation of the freshwater reservoir, potentially leading to severe salinization due to the decline of groundwater tables, artificial recharge with pretreated water from the rivers Rhine and Meuse started in 1955. Water is transported from the rivers to the dunes across 50–70 km through pipelines. River water is then pretreated to protect the quality of groundwater and nature in the dunes. Next, water is infiltrated through open ponds or ditches and deep well infiltration	Tielemans, 2007; Smeets et al., 2009; Stuyfzand, 2015
V	The droughts in 1976 and 2003 were both characterized by a combination of rainfall deficit, low river flow, and heatwaves increasing sectoral water use. They impacted nature and agriculture, and electricity, navigation, and water supply. These single-year and mostly summer droughts led to some awareness and emergency measures, but led to limited changes in water management. The historic focus on preventing too wet conditions stayed. Decreasing trends in groundwater levels were, however, an increasing problem. In 1990 the 'desiccation policy' was introduced. This policy included measures to prevent groundwater depletion but was deemed unsuccessful at its evaluation in 2006 because of unclear goals, many stakeholders, unstable funding, and lack of monitoring. In 2003, only 3% of the affected area had recovered, while the goal was 25%. Since 2003, farmers implemented irrigation infrastructure to reduce drought impacts, which worked well during the 2018 drought, but also aggravated ecological drought impacts. After the 2003 drought, the '*verdringingsreeks*' (prioritization list for surface water supply) was developed which determines the order of priority of different water users in case of water shortage	Witte et al., 2019; Kreibich et al., 2022 https://www.clo.nl/indicatoren/nl027904-verdroging-en-beleid
VI	The Netherlands was confronted with two significant flood events in the 1990s. In 1993 the Meuse River overflowed its banks after a period of persistent rain. During this event 12,000 people were evacuated, an area of over 17,000 ha was flooded with damage to 5,580 private homes. In 1995, 250,000 people were evacuated and although the flooded area of 15,500 ha was similar to the flood of 1993, the damage was less (165 compared to 253 million Dutch guilders). The floods led to the start of the '*Ruimte voor de Rivier*' ('Room for the River') program. Based on extensive modeling the program implemented measures for deepening and widening rivers and created predesignated spillover basin areas. Stewardship of the approach was organized in the new Delta program that was focused on creating a safe Dutch Delta and on sufficient freshwater. The program was institutionalized with a Delta Act in 2012, led by a Delta Commissioner that is appointed for 7 years and has an annual investment budget of over 1 billion euros. The Delta program has a solid knowledge component. Every 6 years, the key Delta Decisions for freshwater, flood risk management, spatial adaptation, the Rhine–Meuse Delta, and the IJssel Lake area are evaluated and revised if needed	Wind et al., 1999; Zevenbergen et al., 2015; Bloemen et al., 2019

(van der Wiel et al., 2022). Following these events, there was an increase in drought-related policy actions with several committees and reports focused on combating drought impacts. Most noticeable is the 'Drought Policy Table', which evaluated drought impacts and formulated knowledge questions and policy actions following the 2018 event (Ministry of Infrastructure and Environment and Ministry of Economic Affairs and Climate Policy, 2019).

In July 2021, an extreme river flood event occurred in the regions Ardennes, Eifel, and Limburg at the border of the Netherlands, Germany, and Belgium when the Ahr, Erft, and Meuse rivers and several tributaries flooded after a period of intense rainfall. It was extreme because of the large precipitation amounts over a large area, but also because of the timing of the flood, which occurred during the summer low flow season. More than 200 people died and critical infrastructure like roads and electricity transmission network was seriously damaged. Because the event exceeded the (regional) flood protection standards, Dutch citizens became more aware of their vulnerability to extreme events. A governmental evaluation committee (Ministry of Infrastructure and Water Management, 2022) concluded that extreme events cannot be avoided entirely, and measures like land use change is needed to reduce flood impacts. It also led to a debate on which measures could reduce peak flows as well as increase groundwater storage to deal with drought. Vice versa, the question arose whether recent drought measures may have intensified the summer flood. Furthermore, the floods of 2021 called for an improved and better-aligned transnational approach of river flooding and river management (Lehmkuhl et al., 2022) and more focus on regional small rivers that are not protected by dikes. Additionally, it is important to mention that the Meuse river itself did not flood – a success story of the flood policy program 'Room for the River'.

In 2022, Europe was hit again by a severe drought episode with significant impacts across the region, mostly related to low river levels. The low flows during this drought had a significant impact on shipping and the energy sector. Low river levels resulted in insufficient cooling water for (nuclear) power plants in parts of Europe and constraints in the provision of some coal-fired power plants due to low water levels. For most of Europe, climate change will further decrease these low flows (Marx et al., 2018), and as a result, the vulnerable infrastructure will be further under pressure. While this can be partly managed by improved water management, there are limitations to physical water management measures in rainfed rivers where long periods of below-average precipitation will always result in drought. The drought event of 2022 also severely impacted agriculture and ecology and caused an increase in salinity levels of surface water in the western part of the Netherlands. The severity of the impact of this drought was also related to the perception of drought as a risk for society (Blauhut et al., 2022).

In November 2022, the new policy 'Water and soil leading in land use planning' was announced (Ministerie van Infrastructuur en Waterstaat, 2022), an approach to make considerations about soil and water quality and availability more prominent within spatial planning. Instead of adapting land and water management to the preferred uses, the use should be adapted to the (semi-) natural land and water conditions, with the aim of making the country more resilient against hydrological extremes. This means, for example, no water-intensive farming in regions with a limited water supply and no new building activities in areas where flood prevention is too expensive or that are needed for water retention. This is a paradigm shift toward a more nature-based water management. This vision is also supported by the National Delta program that calls for a shift from 'water management follows land use' to 'land use follows natural water availability' and that pushes a 'water transition'. This transition calls for a significant redesign of the land use-water system to provide a higher synergy between land and water in relation to water use: a (semi-)natural water system that can cope with drought and provide sufficient water of good quality. The water transition is further stimulated by ongoing policies like the national program for the Dutch rural areas ('*Nationaal Programma Landelijk Gebied (NPLG)*'). A crucial role in realizing the shift from water follows land use to land use and water demand follows water availability is reserved for local and regional integral spatial planning processes ('*Gebiedsprocessen*'). Because the water transition is intertwined with other sustainability challenges such as nitrogen pollution and biodiversity loss, a regional integrated approach toward these issues is vital for connecting different policy objectives and for building support for rural transitions.

Besides increased focus on 'water and soil leading in land use planning', there is continuous development in technological solutions to increase freshwater availability or reduce freshwater use. Especially in the coastal zone, subsurface technologies are being explored to increase freshwater storage in the brackish subsurface (e.g., Zuurbier et al., 2017). More recently, a pilot study started in which the exploitation of brackish water for drinking water production is being investigated (https://www.dunea.nl/algemeen/life-freshman). In the urban environment, new 'blue–green infrastructure' deals with multiple stresses and contributes to climate adaptation (Voskamp and Van de Ven, 2015). Blue–green roofs, for example, contribute to flood prevention, water storage, and cooling (Cirkel et al., 2018; Busker et al., 2022). Rainwater ordinances are being introduced by multiple municipalities, like in Amsterdam where it builds upon the local climate adaptation network Amsterdam Rainproof (Willems and Giezen, 2022). Additionally, 'water in the circular economy' (Morseletto et al., 2022) and cross-sectoral approaches that integrate the municipal water cycle and natural water system get more and more attention. For example, the exploitation of unconventional water resources, that is, other than groundwater or surface water, like treated wastewater from industrial or domestic origin is currently being explored (Rietveld et al., 2011; Dingemans et al., 2020; Narain-Ford et al., 2020; Pronk et al., 2021; Narain-Ford et al., 2022). Especially for drought management, the Netherlands could build upon experiences in other countries, like Spain and England, which require water boards and water supply companies to have drought management plans (Estrela and Sancho, 2016; Wendt et al., 2021). Current scientific development in the field of drought and flood evaluates these extreme events in a more holistic way. For example, flood and drought impacts are analyzed using a risk framework, considering not only the hazard but also exposure and vulnerability, and impacts are evaluated in a multi-hazard and multi-sector approach (Ward et al., 2022). The dynamic adaptive policy pathways (DAPP) method (Haasnoot et al., 2019) has been developed to support decision-making under uncertain change, mainly regarding sea level rise but also has value for water management in general. And on a higher level, policymakers in the Netherlands are following these scientific developments in dedicated science-policy fora, such as the Expert Network on Freshwater and Drought ('*Expertisenetwerk Zoetwater and Droogte*'), coordinated by the Ministry of Infrastructure and Water, and asked to provide scientific answers to policy questions.

Finally, with regard to water quality the Netherlands will also face an issue: in 2027 it will need to meet the water quality requirements of the EU water framework directive (WFD). It is currently expected

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that the Netherlands will not be able to meet these goals, amongst others due to nitrate pollution by the agricultural sector (Wuijts et al., 2023). The water transition will require more fundamental choices and transformative changes to existing land use and water systems and a change of governmental policies (Wuijts et al., 2023).

Conclusions and future perspective

From the mentioned expected impacts of climate change and increases in hydroclimatic extremes, it becomes clear that a water management transition is needed to better deal with both flood and drought risks. Such a transition will require modifications in water management and governance (Albrecht and Hartmann, 2021).

The selection of historical events shows that both flooding and drought have occurred in the Netherlands and will continue to occur, causing significant impacts and challenges for water management. From looking back in history, we learn that significant changes in policy and measures have been implemented in response to extreme hydrometeorological events, especially with regards to floods. The past shows that the Netherlands has been able to develop transformative responses (Afsluitdijk, Delta Works, Room for the River) to events such as the 1953 disaster and the river floods in 1993 and 1995. Policies to deal with periods of drought were successful in some cases. The IJssel Lake now serves as an important freshwater reservoir for all freshwater users and surface water can be actively transported to large parts of the country. And for specific sectors, such as drinking water supply, large-scale technological measures were taken (e.g., using infiltration), resulting in successful recovery of the freshwater supply. However, where groundwater management is involved and where functions and interests are more closely intertwined, effective management and governance arrangements seemed to be more difficult, especially because specific sectors, for example, agriculture, were served. For example, the structural lowering of groundwater levels led to desiccation of groundwater-dependent ecosystems and increased soil subsidence. This makes multiple sectors more vulnerable to drought, as was visible in the drought of 2018–2020. Only after the extreme drought of 2018–2020 and flood of 2021, the Dutch government developed a vision to stimulate that water and soil become a more dominant factor in spatial planning.

Developing long-term visions for regions to reduce the exposure and vulnerability to floods and droughts can help to rethink the existing water management system. However, such a vision is challenging as droughts and floods act on different time scales: a flood is a typical acute crisis whereas a drought is a creeping hazard (Boin et al., 2020). Besides these different timescales, measures implemented to minimize flood impacts often influence drought risk, and vice versa (Ward et al., 2020). There are still many questions on how this trade-off between flood and drought adaptation plays out in the Netherlands and which measures should be implemented where to be beneficial for both. These research questions should be tackled in collaboration between scientists (from various water-related disciplines) and water managers. Furthermore, as the Netherlands is such a densely populated country, there is a fierce competition for land use and water use functions. The Netherlands will, for example, need to build 1 million houses until 2030, while it also needs more space for water-retention areas, buffer zones around nature areas and the transition to more renewable energy resources. Securing land for flooding and creating space for water storage may require a change of governance (from decentralization to centralization and from short-term responding to long-term preparing and transforming), a change of land use (agricultural land will be used for flood water storage, buffer zones around nature areas, peat growth, houses, or renewable energy or different (salt-tolerant) crops could be planted), and a change of policy instruments and their usage (such as a more dominant and decisive impact analysis of new spatial developments on the water system) (Albrecht and Hartmann, 2021). Visions and policies to be designed should be coproduced and arise from stakeholder dialogs about trade-offs and synergies between multiple challenges and sustainability objectives. An example of multiple connected environmental challenges in rural areas are the nitrogen crisis, groundwater use, water quality, the energy transition and climate change mitigation, and adaptation challenges.

We need to design and manage the system in a way that resilience to both floods and droughts increases integrally. This requires methods and tools to stress-test the system for both extremes, and knowledge of measures that reduce both risks. In regional adaptation strategies, both extremes should be managed in a balanced way, considering the full flood–drought spectrum. Additionally, it has become clear that optimization of the current water system will not be enough. A transformation is needed to deal with future hydrological extremes. In this transformation, trade-offs in effects should be considered to evaluate the effectivity and desirability of policies or measures. Sharp choices will have to be made as to which damage and trade-offs we accept and which we do not. For example, the urgent need to reverse the decline of groundwater levels and limit soil subsidence and greenhouse gas emissions, requires a significant raising of groundwater levels, possibly making current agricultural practices impossible in some areas. And necessary restrictions on irrigation near nature areas will prevent damage to nature, but potentially reduce crop yield. Tools that support a structural evaluation of trade-offs are needed to identify what alternative practices are possible in order to limit cascading of damage to other functions and other policy issues. In addition, transparency about the risk of flooding and limited water availability must provide sectors with information for business decisions on how to adapt to more wet and dry circumstances.

The transformation of the current water management will not be easy and will not everywhere be beneficial for all sectors involved. Additionally, there will be no quick-fix solutions and no blueprint of climate-resilient water management. The future strategy to deal with floods and droughts will, however, need to combine changes in the water system and water management (e.g., to retain and recharge water), technological measures (to recharge, reuse, and discharge water), risk-based solutions (reducing exposure and vulnerability), water use (economical and efficient water use), societal changes (acceptance of damage and spreading of impacts), and supporting governance arrangements (including stronger transboundary cooperation to deal with river floods and low flows, and coordination arrangements for connecting multiple transition challenges). Although the future is uncertain, the principle of so-called 'transformation pathways' (Van der Brugge et al., 2005; Clarke et al., 2014), applied across the full flood–drought spectrum, could provide a valuable framework in the development toward a sustainable management of future water resources, by involving stakeholders for just and equitable transitions and translating long-term visions into concrete pathways for action (Nalau and Cobb, 2022).

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