Uncharted water conflicts ahead: mapping the scenario space for Germany in the year 2050

Supplements

Supplement A: List of experts

Supplement B: Definition of descriptors and variants in detail

Supplement C: CIB Matrix

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Supplement A: List of experts

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All team members of the ZuWaKo project (n= 9)

Supplement B: Definition of descriptors and variants

Definition of descriptors and variants in detail

Content

Domain Climate

A Change in temperature

This context shows the possible future temperature development in Germany up to the year 2050. Developments in Germany correspond to typical developments in Central Europe. An increase in the annual mean temperature is expected as a result of climate change. A possible increase in temperature extremes in the form of both heat waves and cold spells is to be expected. There may also be increased variability in temperatures, both within a year and from year to year.

A1: Increase in average temperatures

Climate change is significantly advanced in this scenario (RCP 8.5 - DWD). This leads to an increase in mean annual temperatures of up to 4°C as well as an increase in summer days by approx. 12 summer days per year.

A2: Increase in average temperatures (as in A1) plus temperature extremes within years

Climate change is not only leading to an increase in the mean annual temperature (RCP 8.5 - DWD), but also to a general increase in temperature extremes. Summers are (longer) hotter, on the other hand winters are getting colder, which means that water can no longer seep into the ground and groundwater reserves are further reduced in the phase when they are most important (Hyman-Rabeler 2021).

A3: Increase in average temperatures (as in A1) plus alternating hot & cold years

In this climate future, not only have temperatures risen overall (RCP 8.5 - DWD), but the extremes between years have also increased. A very warm year was followed by a below-average cold year.

A4: Future stagnation of temperature increase

Climate change has weakened in this future and there has been no accelerated and stronger global warming. The average annual temperature remains below the 2-degree target and will remain stable from around the middle of the century (RCP 2.6 - DWD).

B Changes in precipitation

In this context, the possible future change in precipitation (rain, snow, hail, dew, etc.) in Germany up to the year 2050 is described. Developments in Germany correspond to typical developments in Central Europe. As climate change progresses, the weather system and thus also precipitation behavior as a whole have changed and will continue to change in the future. Dry months or even years can result in a decline in the supply of water in groundwater and flowing water. Shifts in precipitation patterns can also occur within a year.

B1 Decline in average annual precipitation

As a result of climate change, Germany is experiencing more and more dry months or even dry years. Of the possible predicted decreases in precipitation, the most unfavorable will occur (0 % in winter and up to -60 % in summer, DWD).

B2 Winter shift

As a result of climate change, precipitation will not decrease overall, but will shift to the colder seasons. This means a surplus of water in winter, which under certain circumstances cannot be sufficiently stored or utilized either by nature (cold and therefore partially sealed soils) or by humans (e.g. limited reservoir capacities) (Hyman-Rabeler 2021). On the other hand, hot summers suffer even more from the lack of precipitation.

B3 Alternating dry & wet years

The amount of precipitation varies greatly from year to year. Very wet years are followed by dry years. In addition to the risk of flooding and high water, the excess water cannot be stored as the soil cannot fully absorb the water. As a result, groundwater recharge can decrease despite constant or even increasing precipitation.

B4 Alternating dry & wet years (as in B3) plus high temporal & regional variability

Heavy precipitation and dry periods (block weather conditions) alternate not only between (B3), but also within individual years, which is difficult to predict. In some regions, the total annual amounts increase, in others they decrease. The ability to plan decreases and the adaptability of society and nature is severely challenged.

Domain Land use

C Development of agriculture

This context describes how agriculture could develop in Germany by 2050. It only considers to what extent and what type of crop farming will be practiced in Germany in 2050 (e.g. intensive vs. extensive, annual vs. permanent crops, organic vs. conventional). Livestock farming is not considered. The development of crop cultivation is closely linked to whether and how land utilization, the crops and varieties grown and, ultimately, the water requirements of agriculture will change in the future.

C1 Hardly any changes: production and productivity as in 2020s

In Germany, cereals in particular continue to be grown without irrigation at a high level of productivity and production. Crops that require irrigation, such as potatoes and other speciality crops, remain limited to some regions. The proportion of land used for agriculture and the use of fertilizers and pesticides as well as the water requirements of agriculture and irrigation methods will remain roughly the same as in 2023.

C2 Fruit and vegetable garden of Europe

Germany is increasingly becoming Europe's fruit and vegetable garden (reasons include the loss of usable land in southern Europe due to the effects of climate change and salinization). As far as soils etc. allow, there is a shift in the main crops grown in Germany away from cereals towards potatoes, fruit and vegetables. This leads to a significant increase in water requirements and also to an increase in the use of fertilizers and pesticides. "Water bodies, particularly those in regions with intensive agricultural activity and a high population density, hold poor ecological status and are affected by pollution pressures" (EEA 2019). Incentives for this conversion are provided by corresponding EU subsidies and the higher profit margins of specialized crops.

C3 High-Tech

Overall, agriculture in Germany will rely heavily on precision farming in 2050 (European Parliament 2019). This is supported by a social consensus "in favor of technical progress" (data collection, genetic engineering, especially gene scissors). By using technologies such as GPS, drones, sensors and machine learning methods, farmers can cultivate their fields in a more targeted and efficient manner. Irrigation is more targeted and efficient. The necessary investments for precision agriculture (see Barnes et al. 2019) are made possible by stable global market prices and EU subsidies. The efficiency of water use increases. However, as the intensity of agriculture also increases, rebound effects cancel out the resource-saving effects and water demand remains at around the 2023 level.

C4 Organic farming

Agriculture in Germany will become increasingly less important for food production by 2050. World market prices for food are low, only organic products have profitable profit margins, which is clearly supported by German and EU subsidies. The preservation of the traditional cultural landscape is becoming more important, the proportion of land cultivated with annual crops is decreasing and the proportion of permanent crops such as viticulture, fruit growing etc. is increasing. Of the remaining agriculture, organic farming accounts for around 30% of agricultural production in Germany (Osterburg et al. 2013, Federal Government 2023). This leads to a decrease in the use of fertilizers and pesticides. Organic farming requires more water per tonne of yield due to the higher proportion of fruit and vegetables grown (Wheeler et al. 2015). At the same time, however, the "more diverse crop rotations with perennial forage cultivation and the promotion of soil life also indirectly improve the infiltration capacity of the soil" (Beisecker et al. 2020, p. 59) as well as soil moisture (Schärer et al. 2022). The overall water requirement of agriculture for plant cultivation is falling slightly but varies greatly from region to region.

C5 Loss of importance

Agriculture in Germany will become significantly less important for food production by 2050. World market prices for food are low and the costs for necessary investments are too high. Most family farms will have to give up because they are not economically viable. State subsidies do not compensate for this, farmers are reorienting themselves towards tourism and landscape conservation, among other things, and the area used for agriculture is decreasing significantly. The remaining large and part-time farms have a lower total water requirement for crop cultivation than in 2023.

D Settlement areas: quantity, density, and sealing

In this context, we analyze how settlement areas in Germany could develop up to the year 2050. The focus here is on the quantitative development of land consumption and utilization by settlement areas (i.e. residential, commercial & industrial and transport areas, in terms of the EU land use classes) in both urban and rural areas. Land consumption by settlements occurs primarily at the expense of former agricultural land, and to a lesser extent at the expense of natural areas such as forests and copses. At the same time, it is also considered a) how high the degree of soil sealing of the settlement areas is (currently approx. 46%) and b) how densely or dispersed the land use is. The degree of sealing influences the infiltration of precipitation, the water storage capacity of the soil and thus groundwater recharge and precipitation water runoff. Densification, on the other hand, makes it possible to make large contiguous areas available for other uses (and e.g. to designate them as water protection areas), which is not possible in dispersed populated areas. At the same time, there is a risk of particular heat build-up, especially in densely populated urban areas (Helmholtz Climate Initiative 2023).

D1 Like 2020s

The proportion of settlement areas will remain the same, while the settlement density, the degree of sealing and the rate of urbanization in the cities and municipalities will all remain at around the same level as in 2023.

D2 Slight expansion

The proportion of residential areas is increasing slightly and these are becoming increasingly dense. The degree of sealing is increasing and the infiltration rate in cities and municipalities is falling.

D3 Strong expansion

The proportion of residential areas is increasing considerably. Settlement density, degree of sealing and infiltration rate per hectare remain approximately on their 2023 levels.

Domain Politics

E Water governance (cooperation and coordination)

This context describes how water governance in Germany could fundamentally develop up to the year 2050. We consider the coordination and cooperation of various political, social, economic and, above all, administrative organizations and actors and their relationships with each other, which together form the water governance and management system (see Pahl-Wostl et al. 2020: 25 ff.). The context factor water governance comprises horizontal coordination and cooperation (i.e. between sectors and administrative units) as well as vertical coordination and cooperation (between government and administrative levels, e.g. local, regional, national) (Pahl-Wostl et al. 2020: 25 ff.). We consider formal and informal structures (STEER 2020: 17) as well as cross-border cooperation with neighboring countries (see Baranyai 2020). We assume that water governance is a rather stable context in which transformations tend to take place over decades (Pahl-Wostl et al. 2020). However, various developments are plausible up to the year 2050.

E1 High

Cooperation (based on Dombrowsky et al. 2022) takes place on the basis of common goals of all parties involved. Local, regional and state authorities from the federal state and federal government as well as various social actors are involved in a meaningful way, and synergies are created to minimize damage in the event of conflicting goals (Scharpf 1997). Actors and institutions exchange information where necessary, supported by formal agreements, and cross-border organisations act as promoters of initiatives (Lazurko et al. 2023). Differences over transboundary waters lead not only to new agreements (see Baranyai 2020: 64), but also to actual cooperation at eye level (Zeitoun & Warner 2006).

E2 Limited

Coordination (based on Dombrowsky et al. 2022) between actors and institutions takes place strategically as long as they (temporarily) pursue similar goals; limited to the achievement of these goals (Lazurko et al. 2023). Apart from this, there is no rapprochement between actors or institutionalization of cooperation, not even across borders. Differences over cross-border waters can lead to tensions (slight or stronger verbal hostilities (Zeitoun & Warner 2006/ Yoffe 2001)) (Baranyai 2020).

E3 No effective cooperation, (cross-border) water conflicts

The institutions and actors act largely independently and without consultation. If (early) formal cross-border agreements exist, these are often broken in order to pursue national interests (Lazurko et al. 2023). Differences over transboundary waters result in conflicts (Baranyai 2020), ranging from strong verbal to diplomatic-economic hostilities (Yoffe 2001). There are no de facto powerful or effective cross-border organizations that could act as mediators in these conflicts (Lazurko et al. 2023).

F Political-regulatory framework (regarding water)

The context factor "political (especially regulatory) framework at federal level" describes the politically implemented framework conditions for dealing with water. Although the factor refers to the federal level, sub-national and supranational structures (municipality/federal state/EU) also play a significant role in shaping the framework: sub-national political-administrative units in the actual implementation and control of laws and regulations, as well as in the allocation of certain water rights on the one hand, and supranational regulations as formative (and sometimes mandatory) for national legislation on the other. The interlocking of several political levels is therefore a prerequisite for coherent implementation.

In terms of content, the factor includes regulations relating to water (re)use (Water Reuse Regulation EU 2020/741), strategies relating to the planning and approval of water supply infrastructure and the preservation of water-related ecosystems (WFD, National Water Strategy), possibly also state subsidies in the use of water, as well as administrative processes in the allocation, review and control of water rights. It is assumed that one variant within the descriptor is pursued in the long term/statistically; accordingly, decisions today will characterise development until at least 2050.

F1 EU regulations as of 2023 will be transposed 1:1 into German law (EU regulations implemented)

EU policies and regulations are consistently and uncompromisingly transposed into national law and compliance with them is monitored, if necessary with new administrative units for this purpose and taking into account current water data (e.g. drought monitor, soil moisture maps, weather services, etc.). However, the water balance is still not managed as a system, but on a sector and demand basis. The protection of the environment and water resources is particularly relevant when health, safety (e.g. due to pollutants) or the availability of resources for people are at risk (UN Water 2013, EU Water Framework Directive/WFD 2000/60/EC, Urban Waste Water Directive/UWWTD, Drinking water directive 2020/2184). In accordance with the German Strategy for Adaptation to Climate Change (DAS) (BMUV 2008) and the national water strategy (2023), regular monitoring is carried out and adaptation measures are not only identified but also implemented (Water Action Programme and beyond). Non-compliance is penalized. This is based on the WFD and successor directives as well as the Water Reuse Ordinance. Involvement of the public and various interest groups is explicitly encouraged (De Stefano et al. 2012, Aarhus Convention).

F2 EU regulations implemented and added by systems perspective (Wide-ranging systemic nexus approach WEFE (Water-Energy-Food-Ecosystems))

The political and regulatory actions in Germany go beyond the EU legal situation and is cross-sectoral and systemic; water is considered together with other related topics such as energy, food and ecosystems. The needs of people and the environment are harmonized in the best possible way (WEFE nexus UNECE 2022, "hydropolitical resilience" (Baranyai 2019)), if necessary also beyond administrative system boundaries. Before water rights are granted, a comprehensive structural assessment must be drawn up locally to ensure the preservation of natural systems and regular checks to ensure compliance in practice (active and passive water management: use and preservation/protection against negative impacts; see also Water Resources Act (WHG)). Local authorities are required to adapt their water management to approximate the natural water balance (UBA 2023a/b). Where possible - e.g. in the case of virtual water - regulations also apply beyond the German/European border.

F3 ‘All you can take’ (strong influence of the economy)

Lobby groups/companies/interest groups exert considerable influence on the design of European and national water policy in Germany as well as on corresponding equivalences at state level (Campact on Deutschlandfunk 2023). Thus, strategic interests in resource use (economic efficiency) dominate over the preservation of ecosystems. Water rights are only partially subject to an impact assessment before they are granted, and compliance checks are only carried out sporadically. Water consumption and water quality assurance cannot be comprehensively monitored (polluter pays principle does not apply, Merkur 2023). Price structures are the only way to incentivize the sustainable use of water resources.

F4 Deliberate bypassing of rules

Particularly at local level, there is a widespread, targeted weakening, softening or non-compliance with applicable EU, federal and state regulations in practice. This means, for example, that rising demand can continue to be met in the short term, but ecosystems usually lose out. With the exception of drinking water supply, local administrative units do little to fulfil their task of monitoring water rights and other national regulations.

Domain Economy

G General economic situation

In this context, we analyze how the economic situation in Germany could develop up to 2050. The focus is not only on GDP, but also on the willingness to invest and investment behavior in Germany. The assumption here is that the gross domestic product (GDP) will increase as a result of the direct demand effect of larger investments (Kemmler et al. 2021: 325). In addition to the amount, the direction is decisive. Since water infrastructure is generally used in the long term and requires a lot of capital (Balzer & Schorn 2020: 1), it is important whether investments are made sustainably or whether the focus is on achieving short-term goals.

G1 Moderate growth – Business as usual (BAU)

There are no binding sustainability targets (Kemmler et al. 2021: 4). GDP does grow, but as a result of lower (sustainable) investments (e.g. in the energy transition), growth will be rather moderate until 2050 (Kemmler et al. 2021: 325) (ca. 1%). Investments are made in the short rather than the long term.

G2 Eco-investing

Sustainable investments are gaining ground, which increases the investment volume. The additional investments have a positive effect on GDP. GDP is up to 1.7% (in 2030) higher than in variant 1, in 2050 up to 0.6% growth is possible (Kemmler et al. 2021: 325; Lutz et al. 2021: 9). Investments are mainly made in the long term.

G3 Green liberation

Climate protection is being implemented consistently and at high speed in Germany. Emission- and resource-intensive products and processes are either substituted or completely avoided. Wherever possible, cycles are created (Purr et al. 2019: 405). The use of resources and the associated environmental impact will be decoupled from economic growth (Purr et al. 2019: 46 f.). Economic growth declines to 0 by 2030 and remains at this level until 2050 (Purr et al. 2019: 379). While most sectors and industries are in decline, some are experiencing qualitative growth that compensates for this decline (Purr et al. 2019: 67). From an early stage, investments are made exclusively for the long term.

G4 Recession

The global economy enters a significant crisis before 2050 and per capita economic growth gradually declines before 2050 (Meadows et al. 1972: 124, 127 & 132). In an update of Meadows' study, three of four scenarios show a global economic downturn (Herrington 2021: 617), which this variant is based on. This downturn also applies to Germany, whose economy is in a severe recession from 2040 at the latest. GDP growth is negative and hardly any investment is possible, neither in the long nor short term.

H Structural development of the water-intensive industry (Energy transition)

In this context, we analyze how the structure of the water-intensive industry in Germany could develop by 2050. It is important to differentiate between the terms used here. According to Scheele & Malz (2004: 92), water abstraction refers to all quantities of water extracted from surface and groundwater resources that are utilized anthropogenically. If these withdrawals are no longer returned to the receiving waters, they are referred to as water consumption. The Federal Environment Agency uses the term water utilization congruently with the term water abstraction (UBA 2022a).

Of particular importance is the energy sector, which withdrew 8.8 billion m^3 of water in 2019. This corresponds to 44% of the total withdrawal of 20 billion m^3 of water in 2019. The energy suppliers withdraw most of the water from their own extraction plants, with the share from third parties only amounting to approx. 3% and increasing the volume of water to 9.1 billion m^3 (UBA 2022b). The manufacturing industry (4.1 billion m^3) and mining (1.3 billion m^3) (Destatis 2023) together had a share of approx. 27% in the same year.

Water withdrawals in the mining and manufacturing sectors have been following a downward trend since 1991, while this has been observed in the energy sector since 2013 (UBA 2022a). The declining water consumption in the manufacturing sector was largely made possible by the closing of water cycles, but it is also partly due to the outsourcing of production to other countries, such as in the textile and electrical industry as well as the coking plant and mineral oil industry. In 2016, the chemical industry required around 2.6 billion m^3, or 58%, of the water used in the manufacturing industry, making it its largest water consumer. This is followed by the metal industry, the food and beverage industry and the paper industry, each with a share of around 10% (UBA 2020).

With reference to technological developments described by Ante et al. (2014), the German government assumes that water use in industry will continue to fall until 2050 (Federal Government 2017: 11). In the energy sector, the high demand for water is mainly due to the cooling required for conventional electricity generation; renewable energies require much less water in comparison (Bormann et al. 2019: 73). An Agora study assumes a hydrogen demand in Germany of approx. 270 TWh in 2050, of which Germany will produce around 31% itself (Prognos, Öko-Institut & Wuppertal-Institut 2020: 27). With a water consumption of approx. 300,000 m^3 per TWh of hydrogen produced (Berna-Escriche et al. 2022: 24), this corresponds to a water consumption of just 25.1 million m^3. Water consumption for the production of green hydrogen will therefore not have a significant impact on the water balance in Germany until 2050. From a regional perspective, however, hydrogen production can certainly have a significant impact on the water balance. The reduction of water demand in the energy sector in Germany as a whole is therefore closely linked to the progress of the energy transition and the achievement of climate targets.

H1 Energy transition business as usual (BAU) as in 2020s

Current trends and developments continue, the energy transition is not implemented to the extent that would be required to achieve the climate targets (Bormann et al 2019: 68). Due to the decrease of fossil electricity production, water withdrawal in the energy sector is still reduced by 23% (to approx. 6.8 billion m^3) in 2030 and by 58% (to approx. 3.7 billion m^3) in 2050 (Bormann et al. 2019: 73).

H2 Energy transition succeeds

Germany promotes the energy transition ambitiously. Moreover, technical measures, such as improvements in efficiency and sector coupling, are implemented by the industry to a great extent (Bormann et al. 2019: 68). Water utilization by the industry can thus be reduced on average to 27% of its 2019 value (5.4 billion m³) in 2030 and even to 5% (just under 1 billion m³) in 2050 (Bormann et al. 2019: 73).

H3 Energy transition fails

The German energy transition is not being implemented quickly enough and is being missed. It is failing due to the conflicts and problems arising nationally and internationally, including those resulting from the energy crisis following the war in Ukraine (Reusswig, Lass & Bock 2022: 183). Measures are neither established comprehensively nor early enough, and the far too slow implementation speed makes a timely energy transition impossible (Schill, Roth & Guéret 2022: 379). Accordingly, the energy sector's water use stagnates until 2030 and hardly decreases noticeably until 2050.

Domain Society and Culture

I Water awareness and prioritization

Water awareness describes the social attention and appreciation that water users (industry, agriculture, population) in Germany generally pay to water as a resource, as well as the degree of willingness to limit their own use in the event of scarcity for the benefit of natural water systems. A high level of water awareness goes hand in hand with a high level of acceptance of water-saving measures. The cultural significance of water is reflected at a political level in the fundamental prioritization of various water uses in the event of scarcity and the protection of water-related ecosystems, which are also fundamental to maintaining the water supply for human uses (Cless 2014). It is assumed that the public supply of drinking water is the first priority in all variants.

I1 High. In times of scarcity, water related ecosystems are prioritized (after public sector)

A societal shift towards environmental awareness can be observed at all levels and across all sectors (UBA 2022). In this respect, there is a high level of water awareness in industry, agriculture and the population and an active acceptance of measures that serve to protect and conserve water-related ecosystems (Lehn et al. 1996). Water use that is detached from supply is not socially accepted and is socially sanctioned. Overall, there is a consensus in favor of the high priority of (water-related) ecosystems in the event of scarcity (second priority after - economical - public supply).

I2 Medium. In times of scarcity, public and private sector are prioritized before ecosystems, agriculture last priority

Water awareness is closely linked to society's experience of the water situation (Kluge 2008). In this respect, measures to protect water resources and ecosystems in industry, agriculture and the population are primarily supported when they are directly affected (e.g. risk of drought, heat, heavy rainfall, flooding). Invisible effects such as the drop in GW levels or international links (virtual water) in dealing with water are less reflected and present (Schermuly 2017). There is a clear discrepancy between environmental awareness and environmental action (Schermuly 2017: 325). Overall, water-related ecosystems are given medium priority publicly and politically in the event of scarcity, i.e. they have third priority after public and non-public supply (i.e. industry) but before agriculture, which is in last place.

I3 Low. Priority in times of scarcity is not explicitly clarified. De facto, ecosystems are least prioritized

Water awareness is low in all sectors. Water-intensive industry and agriculture in particular, for which water cannot be substituted and whose economic existence is tied to water (Shiva 2008), are opposed to water-saving measures. A lack of knowledge of the complexity and interrelationships is also a reason for low water awareness. The prioritization of water uses has not been explicitly clarified; de facto, water-bound ecosystems often take last place after public, non-public and agricultural supplies in the event of scarcity (Schermuly 2017).

J Demographic development

In this context, the potential demographic development of the population in Germany up to 2050 is described. The main focus is on the increase, decrease or stagnation of the population as potential water users or consumers of water-intensive products and services.

J1 Population tends to decline

Due to the aging of society and the sharp decline in the birth rate, the population in Germany has shrunk continuously in recent years (variants 1 & 4: Destatis 2022).

J2 Population remains stable

The population has stabilized over the years despite the increase in aging (variant 2: Destatis 2022).

J3 Population tends to increase

Due to a slight rise in the birth rate, increased life expectancy and a positive immigration balance (immigration exceeds emigration), the population has not only recovered, but has actually increased (variants 3 & 5: Destatis 2022).

Domain Nature

K State of ecosystems

This descriptor describes the general future state or health of ecosystems in Germany as a whole. Regional variability is not taken into account. Ecosystems are "plant, animal and microorganism communities [that] live together dynamically with the inanimate environment" (Dickens/McCartney 2021). In addition to the aquatic ecosystems in focus, the descriptor also outlines the state of terrestrial, marine and mixed ecosystems.

According to the EU Biodiversity Strategy (UBA 2021) and the European Water Framework Directive WRR (BMUV/UBA 2022), the following targets are to be achieved by 2030 and 2027 respectively: Peatlands, water bodies, seas and coasts, wilderness and protected areas, as well as forests and soils should be in a good to very good "near-natural" ecological status.

In order to characterize the possible state of ecosystems in Germany up to the year 2050, we consider activity ("vigor of function"), structure ("organizational structure") and resilience under stress (Lu et al. 2015) (or "vigor, organization and resilience" in Constanza's sense).

- *Activity* is measured, for example, by chemosynthetic and photosynthetic production;
- *Structure* comprises the variety and number of interactions between ecosystem elements, with the number and strength of transmission pathways and biodiversity being used as indicators;
- *Resilience* represents the ability of an ecosystem to maintain its activity and structure even under the influence of stress.

K1 Like 2020s

Through the increasing implementation of environmental protection goals, the current state of activity, structure (including biodiversity) and resilience of ecosystems can be kept constant on average until 2050. The improvement of severely endangered ecosystems and the deterioration of moderately endangered ecosystems will balance each other out (UBA 2020).

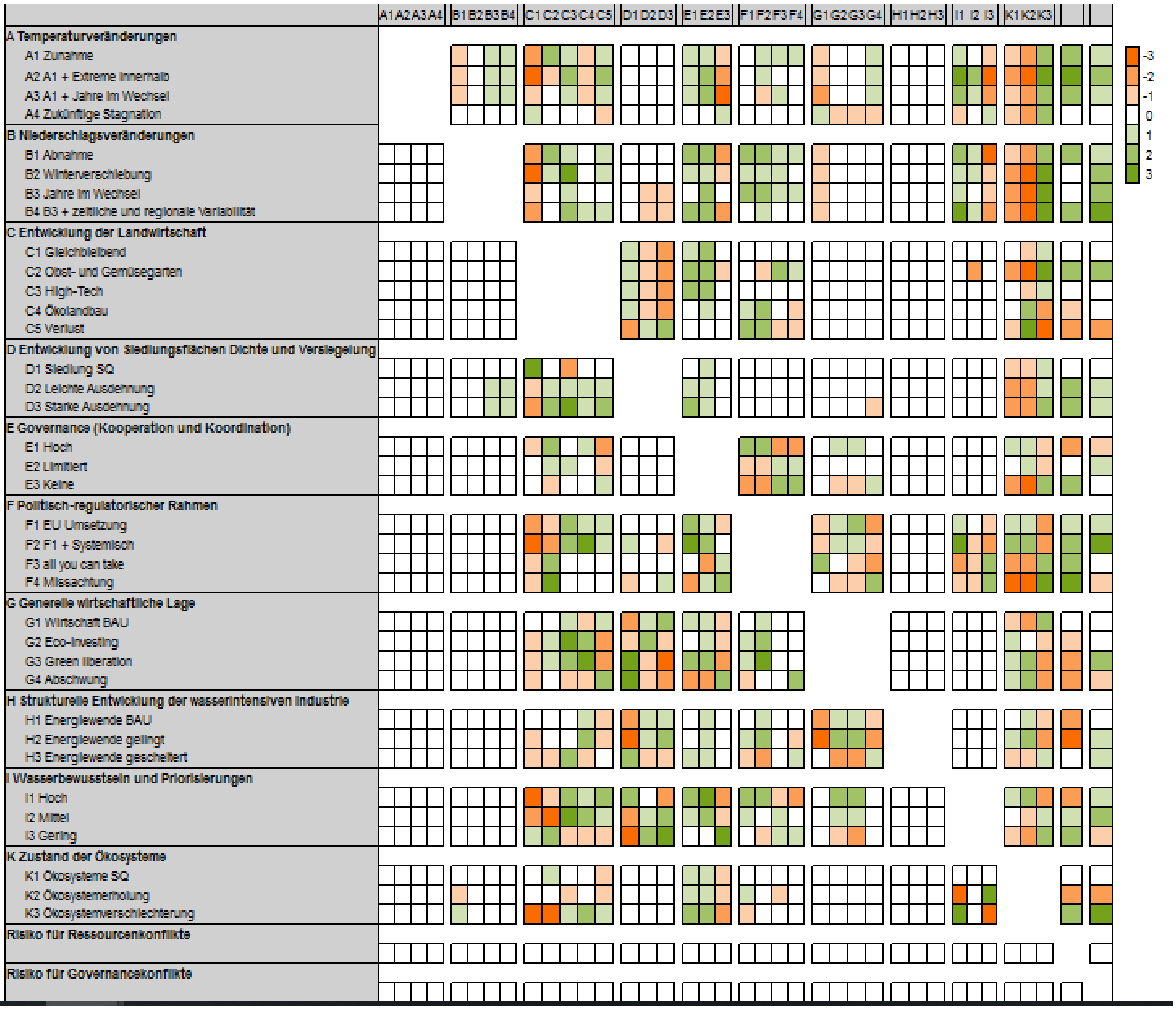
K2 Recovery

By consistently following the EU Biodiversity Strategy and fully implementing the European Water Framework Directive, ecosystems can increase their overall activity and strengthen their structure by 2050 (e.g. through higher biodiversity). In addition, their resilience will become stronger again, i.e. on average they will be able to maintain their activity and structure even after shock events.

K3 Deterioration

The EU Biodiversity Strategy and the WFD are only being pursued and implemented incompletely. As a result, a significant number of ecosystems are losing large parts of their activity and are barely able to maintain their structure, if at all (e.g. high biodiversity loss). The resilience of ecosystems decreases, stress events lead to subsystems being unable to maintain their activity and structure.

Supplement C: CIB Matrix



Please note that the color code of the conflict risk assessments in this matrix (right columns, green cells signify impacts promoting conflict risk) differ from the color code of the heat maps (where green signifies low conflict risk).

Table supplement C: Distribution of impact assessments across 1162 impact cells („ZuWaKo Kontexte 2024_Ewende und Klima autonom.scw")

-3	-2	-1	0	1	2	3
27 cells (2.15%)	76 cells (6.45%)	123 cells (10.59%)	657 cells (56.80%)	155 cells (13.34%)	97 cells (8.35%)	27 cells (2.32%)

Supplement D: Detailed storylines, including key interactions

Storyline of scenario 1: Polycrisis: Climate, politics, and environment in crisis

In this scenario, the climate crisis is significantly advanced by 2050 (RCP 8.5 - DWD).

- This has led to a **rise of average annual temperatures of up to 4°C (A3)** and an increase in summer days of around 12 summer days per year. In addition, the extremes between the years have increased. A warm and dry year is followed by a cold one.
- The overall rising temperatures and their fluctuations also influence precipitation in Germany: **precipitation extremes alternate between years (alternating years) (B3)**. Precipitation amounts fluctuate greatly from year to year. Very wet years are followed by dry years. In addition to the risk of flooding and high water, the excess water cannot be stored as the soil cannot fully absorb the water. As a result, groundwater recharge can decrease despite constant or even increasing precipitation.

In the water sector, there is mainly **temporary and/or goal-specific cooperation between some (not all) actors, with potential tensions** (Limited, E2) Cooperation between actors and institutions takes place strategically as long as they (temporarily) pursue similar goals and are limited to achieving them. Apart from this, there is no rapprochement between the actors and no institutionalization of cooperation, not even across borders. Differences over cross-border waters can lead to tensions (slight or stronger verbal hostilities).

The **implementation of political-regulatory framework conditions is economy-friendly (F3).** There is a European and national water policy in Germany as well as corresponding equivalents at state level, in the design of which lobby groups/companies/interest groups exert considerable influence, so that strategic interests of resource utilization (economic interests) dominate those for the preservation of ecosystems. Water rights are only partially subject to an impact assessment before they are granted, and compliance checks are only carried out sporadically. Water consumption and water quality assurance cannot be comprehensively monitored. Incentives for the sustainable use of water resources are created at most via price structures.

The economy is endeavouring to secure growth and prosperity by 2050 through **green investments (G2).** This will increase the overall investment volume. The additional investment will have a positive effect on GDP. GDP is up to 1.7% (in 2030) higher than in the 2020s, and up to 0.6% more is possible in 2050. Investments are mainly made in the long term. However, this path is made more difficult by the **failure of the energy transition (H3).**

At the same time, we see an intensification of **agriculture with approximately the same use of resources through high-tech (D3)**. Overall, agriculture in Germany in 2050 will rely heavily on precision farming. This is supported by a social consensus "in favor of technical progress" (data collection, genetic engineering, especially gene scissors). The use of technologies such as GPS, drones, sensors and machine learning processes will enable farmers to cultivate their fields in a more targeted and efficient manner. Irrigation is more targeted and efficient. The necessary investments for precision agriculture (see Barnes et al. 2019) are made possible by stable world market prices and EU subsidies. The efficiency of water use increases. However, as the intensity of agriculture also increases, rebound effects cancel out the resource-saving effects and the water requirement remains roughly at the level of 2023. This type of agriculture allows adaptation to the climatically and ecologically difficult production conditions.

Although new land is needed for the eco-investments of the economy, the land-conserving high-tech agriculture, the failure of the energy transition H3, i.e. less land required for solar and wind, and a high level of water awareness lead in total to a **sparing new utilization of settlement areas D1**, which can be maintained at the level of 2023.

At the same time, however, we are experiencing a **deterioration of ecosystems (K3),** which are under pressure from climate change on the one hand and are not adequately protected by weak or business-friendly regulation on the other.

In view of the clearly perceived climate challenges in relation to water and the poor state of ecosystems (see below), there is a high level of water awareness (I1). A rethink in society towards environmental awareness can be observed at all levels and across all sectors (UBA 2022). In this respect, there is a high level of water awareness in industry, agriculture and the population and an active acceptance of measures that serve to protect and preserve water-related ecosystems. Overall, there is a consensus in favor of the high priority of (water-related) ecosystems in the event of scarcity (second priority after - economical - public supply). Water is a social issue and is very present in the media. The high level of water awareness in turn encourages the economy to focus on green investments and the switch to high-tech in agriculture.

Storyline of scenario 2: Growth through adaptation to climate change

In this scenario, the climate crisis is significantly advanced by 2050 (RCP 8.5 - DWD).

- The **annual average temperature rises significantly (increase A1).** Climate change is significantly advanced in this scenario (RCP 8.5 - DWD). This leads to an increase in average annual temperatures of up to 4°C and an increase in summer days of around 12 summer days per year.
- **Precipitation extremes alternate between years** and also within individual years. Very wet years are followed by generally dry years. In addition to the risk of flooding and high water, the excess water cannot be stored as the soil cannot fully absorb the water. As a result, groundwater recharge can decrease despite constant or even increasing precipitation (Hyman-Rabeler 2021). In addition, heavy precipitation and dry periods alternate within individual years, which is difficult to predict. In some regions, the total annual amounts are increasing, in others they are decreasing. The ability to plan decreases and the adaptability of society and nature is greatly challenged (B4: B3 and variability within years).

A societal shift towards environmental awareness can be observed at all levels and across all sectors (UBA 2022). In this respect, there is a **high level of water awareness (I1)** in industry, agriculture and the population and an active acceptance of measures that serve to protect and preserve water-related ecosystems (Lehn et al. 1996). Water use that is detached from availability is not socially accepted and is socially sanctioned. Overall, there is a consensus in favor of the **high priority of (water-related) ecosystems** in the event of scarcity (second priority after - economical - public supply).

Agriculture, the energy industry and the economy in general are succeeding in adapting to the challenges of climate change and continuing to generate prosperity by adapting production:

- The economy favors **green investments** (Eco-investmenting, G2). Sustainable investments are gaining ground, which increases the volume of investment. The additional investments have a positive effect on GDP. GDP is up to 1.7% (in 2030) higher than in the business as usual case, in 2050 up to 0.6% more is possible (Kemmler et al. 2021: 325; Lutz et al. 2021: 9). Investments are mainly made with a long term perspectve.
- Germany is also ambitiously driving forward the energy transition. Furthermore, technical measures such as increasing efficiency and sector coupling are being implemented to a large extent in industry (Bormann et al. 2019: 68). For example, water use in industry can be reduced on average to around 27% (5.4 billion m^3) of the 2019 figure by 2030 and even to around 5% (just under one billion m^3) by 2050 (Bormann et al. 2019: 73). However, the massive expansion of renewable energies such as wind and solar as well as structural change through sustainable investments will lead to a **slight expansion of settlement areas (D2).**
- Parallel to this general trend, agriculture is developing towards intensification with approximately the same use of resources through high-tech (C3). Overall, agriculture in Germany will rely heavily on precision farming in 2050 (European Parliament 2019). This is supported by a continuing social consensus "in favor of technical progress" (data collection, genetic engineering, especially gene scissors). By using technologies such as GPS, drones, sensors and machine learning methods, farmers can cultivate their fields in a more targeted and efficient manner. Irrigation is more targeted and efficient. The necessary investments for precision agriculture (see Barnes et al. 2019) are made possible by stable world market prices and EU subsidies. The efficiency of water use increases. However, as the intensity of agriculture also increases, rebound effects cancel out resource-saving effects and water demand remains at around the 2023 level.

This adaptation of the (land) economy to the consequences of climate change is coherent with the implementation of a **systemic WEFE nexus approach (Water-Energy-Food-Ecosystem) as a political-regulatory framework.** Thus, the political-regulatory framework in Germany in the area of water goes beyond the EU legal situation and is cross-sectoral and systemic; water is considered together with other related topics such as energy, food and ecosystems. The needs of people and the environment are harmonized in the best possible way, if necessary also beyond administrative system boundaries. Before water rights are granted, a comprehensive structural report must be drawn up locally to ensure the preservation of natural systems and on the basis of which regular controls ensure compliance in practice (active and passive water management: utilization and preservation/protection against negative impacts; see also Water Resources Act (WHG)). Municipalities are required to adapt their water management to approximate the natural water balance. Where possible - e.g. in the case of virtual water - regulations also apply beyond the German/European border. The WEFE nexus approach in turn promotes the adaptation of the economy and agriculture in the form of an "angel cycle".

The mutually supportive interplay of climatic, (agricultural) economic and regulatory developments also stabilizes **temporary and/or goal-specific cooperation between some (not all) actors in the water sector**, with **potential tensions (limited) (E2).** Cooperation between actors and institutions takes place strategically as long as they (temporarily) pursue similar goals; limited to the achievement of these goals. Apart from this, there is no rapprochement between the actors and no institutionalization of cooperation, not even across borders. Differences over cross-border waters can lead to tensions (slight or stronger verbal hostilities). The development of a **higher degree of stable cooperation and coordination (E3**) is also possible in this scenario, but is supported by slightly fewer developments.

The overall state of ecosystems is successfully maintained at around the level of the 2020s (Ecosystems as in 2020ies). Through the increasing implementation of environmental protection goals, the current state of activity, structure (including biodiversity) and resilience of ecosystems can be kept constant on average until 2050. The improvement of severely endangered ecosystems and the deterioration of moderately endangered ecosystems will balance each other out (UBA 2020).

Storyline of scenario 3: Agriculture and economy in crisis

As in scenario 2, the consequences of climate change will be clearly felt in Germany by 2050:

- The **annual average temperature rises significantly (rise A1).** Climate change is significantly advanced in this scenario (RCP 8.5 - DWD). This leads to an increase in average annual temperatures of up to 4°C and an increase in summer days of around 12 summer days per year.
- **Precipitation extremes alternate between years** and also within individual years. Very wet years are followed by generally dry years. In addition to the risk of flooding and high water, the excess water cannot be stored as the soil cannot fully absorb the water. As a result, groundwater recharge can decrease despite constant or even increasing precipitation. In addition, heavy precipitation and dry periods alternate within individual years, which is difficult to predict. In some regions, the total annual volumes increase, in others they decrease. The ability to plan decreases and the adaptability of society and nature is severely challenged (B4: B3 and variability within years).

As in scenario 2, a rethink in society towards environmental awareness can be observed at all levels and across all sectors (UBA 2022). In this respect, there is a **high level of water awareness (I1)** in industry, agriculture and the population and an active acceptance of measures that serve to protect and preserve water-related ecosystems (Lehn et al. 1996). Water use that is detached from the available supply is not socially accepted and is socially sanctioned. Overall, there is a **consensus in favor of the high priority of (water-related) ecosystems** in times of scarcity (second priority after - economical - public supply).

However, in this scenario, the economy and agriculture do not succeed in adapting. The reasons for this are as follows:

- The German energy transition is **not being implemented quickly enough and is being missed (H3).** It is failing due to the conflicts and problems arising nationally and internationally, including from the energy crisis following the war in Ukraine (Reusswig, Lass & Bock 2022: 183). Measures are neither established comprehensively nor early enough, and the far too slow implementation speed makes a timely energy transition impossible (Schill, Roth & Guéret 2022: 379). Accordingly, water use in the energy sector will stagnate until 2030 and will hardly decrease noticeably until 2050.
- The failure of the energy transition in turn contributes to the **economic downturn** in Germany (Economic Meltdown, G4). As described in several models in the famous 1972 book "The Limits to Growth" by the Club of Rome, the global economy enters a massive crisis before 2050 and per capita economic growth gradually declines before 2050 (Meadows et al. 1972: 124, 127 & 132). In an update of the study from 2021, three of four scenarios show a global economic downturn (Herrington 2021: 617). This also applies to Germany, whose economy is in a severe recession from 2040 at the latest. GDP growth is negative and hardly any investment is possible, neither in the long nor short term.
- Agriculture in **Germany will also become less important for food production by 2050** (loss, C5). World market prices for food are low and the costs for necessary investments are too high. Most family farms will have to give up because they are not economically viable. State subsidies do not compensate for this, farmers reorient themselves towards tourism and landscape conservation, among other things, and the area of land used for agriculture decreases significantly. The remaining large and part-time farms have a lower total water requirement for crop cultivation than in 2023.

At the same time, **close and stable cooperation and coordination in the water sector (E1)** is taking place in Germany in view of the climate challenges and an ambitious **systemic**

regulatory framework in the form of a WEFE Nexus approach (Water-Energy-Food-Ecosystem, F2) has been implemented in Germany.

- **Cooperation takes place on the basis of common goals of all parties involved**. Municipal, regional and state authorities from the federal state and federal government as well as various social actors are involved in a meaningful way, and synergies are created to mitigate damage in the event of conflicting objectives. Actors and institutions exchange information where necessary, supported by formal agreements, and cross-border organizations act as promoters of initiatives. Differences over cross-border waters not only lead to new agreements, but also to actual co-operation on an equal footing.
- In Germany, a **systemic WEFE nexus approach (Water-Energy-Food-Ecosystem)** will be successfully implemented by 2050. This means that the political and regulatory approach in Germany in the area of water goes beyond the EU legal situation and is cross-sectoral and systemic; water is considered together with other related topics such as energy, food and ecosystems. The needs of people and the environment are harmonized in the best possible way, even beyond administrative system boundaries if necessary. Before water rights are granted, a comprehensive structural assessment must be drawn up locally, which ensures the preservation of natural systems and on the basis of which regular controls ensure compliance in practice (active and passive water management: utilization and preservation/protection against negative impacts; see also Water Resources Management Act (WHG)). Municipalities are required to adapt their water management to approximate the natural water balance. Where possible - e.g. in the case of virtual water - regulations also apply beyond the German/European border

However, political developments in the water sector only have a very limited influence on the crisis-ridden development of the economy and agriculture and can hardly counteract them.

Overall, however, the strict political framework, the high level of water awareness and, above all, the significantly reduced economic and agricultural activities have **positive effects on ecosystems and land consumption:**

- This will lead to the **recovery of ecosystems (K2)** in Germany. Overall, ecosystems can increase their activity and strengthen their structure by 2050 (e.g. through higher biodiversity). In addition, their resilience will become stronger again, i.e. on average they will be able to maintain their activity and structure even after shock events.
- We are experiencing a **sparing utilization of new settlement areas** (D1) that can be maintained at the level of 2023.

Storyline of scenario 4: Sustainable transformation

Climate change has weakened in this scenario and there has been no accelerated and stronger global warming. The average annual **temperature** in Germany remains **below the 2-degree target** and remains stable from around the middle of the century (RPC 2.6 - DWD) (A4: future stagnation).

Although **precipitation** in Germany will not decrease overall by 2050 in this scenario, it will **shift to the colder seasons** (winter shift, B2). This means a surplus of water in winter, which may not be sufficiently stored or utilized either by nature (cold and therefore partially sealed soils) or by humans (e.g. limited reservoir capacities) (Hyman-Rabeler 2021). On the other hand, hot summers suffer even more from the lack of precipitation.

The water sector is responding to this challenge of the winter shift through **close and stable cooperation and coordination** (E1), including across borders. Cooperation takes place on the basis of common goals of all parties involved. Local, regional and state authorities from the federal state and federal government as well as various social actors are involved in a meaningful way, and synergies are created in the event of conflicting objectives in order to minimize damage. Actors and institutions exchange information where necessary, supported by formal agreements, and cross-border organizations act as promoters of initiatives. Differences over cross-border waters not only lead to new agreements, but also to actual co-operation on an equal footing.

The **political framework** for dealing with water is also responding to the precipitation situation and is supported by the high degree of cooperation. In Germany, a **systemic WEFE nexus approach** (Water-Energy-Food-Ecosystem) **will be successfully implemented** by 2050. This means that the political and regulatory approach in Germany in the area of water goes beyond the EU legal situation and is cross-sectoral and systemic; water is considered together with other related topics such as energy, food and ecosystems. The needs of people and the environment are harmonized in the best possible way, if necessary also beyond administrative system boundaries. Before water rights are granted, a comprehensive structural report must be drawn up locally to ensure the preservation of natural systems and on the basis of which regular controls ensure compliance in practice (active and passive water management: utilization and preservation/protection against negative impacts; see also Water Resources Act (WHG)). Local authorities are required to adapt their water management to approximate the natural water balance. Where possible - e.g. in the case of virtual water - regulations also apply beyond the German/European border.

This political framework also promotes the sustainable transformation of the energy sector, agriculture and the economy as a whole:

The **energy transition** is progressing, either

1) **as before** (H2), i.e. previous trends and developments will continue. However, the decline in fossil power generation will reduce water use in the energy sector by 23% by 2030 (to approx. 6.8 billion m^3) and by 58% by 2050 (to approx. 3.7 billion m^3) (Bormann et al. 2019: 73)
2) or is even being **implemented ambitiously** (H1 succeeds), i.e. technical measures such as increasing efficiency and sector coupling will continue to be implemented to a large extent in industry (Bormann et al. 2019: 68). By 2030, water use in industry can be reduced on average to around 27% (5.4 billion m^3) of the 2019 value and by 2050 even to around 5% (just under one billion m^3) (Bormann et al. 2019: 73).

The economy is experiencing a so-called **"green liberation" (G3).** Climate protection is also being implemented consistently and at high speed by the economy in Germany. Emission- and resource-intensive products and processes are either substituted or completely avoided. Wherever possible, cycles are created (Purr et al. 2019: 405). The use of resources and the associated environmental impacts are decoupled from economic growth (Purr et al. 2019: 46 f.). Economic growth declines to 0 by 2030 and remains at this level until 2050 (Purr et al. 2019: 379). While most sectors and industries are in decline, some are experiencing qualitative growth that compensates for this decline (Purr et al. 2019: 67). Early on, investments are made exclusively for the long term.

At the same time, agriculture is **switching to organic farming (C4).** World market prices for food are low and only organic products have worthwhile profit margins, which is clearly supported by German and EU subsidies. The preservation of the traditional cultural landscape is becoming more important, the proportion of land cultivated with annual crops is decreasing and the proportion of permanent crops such as viticulture, fruit growing etc. is increasing. Of the remaining agriculture, organic farming accounts for around 30% of agricultural production (Osterburg et al. 2013, Federal Government 2023). This leads to a decrease in the use of fertilizers and pesticides. Organic farming requires more water per tonne of yield due to the higher proportion of fruit and vegetables grown (Wheeler et al. 2015). At the same time, however, the "more diverse crop rotations with perennial forage cultivation and the promotion of soil life also indirectly improve the infiltration capacity of the soil" (Beisecker et al. 2020: 59) as well as soil moisture (Schärer et al. 2022). The overall water requirement of agriculture for plant cultivation is falling slightly, but varies greatly from region to region and locally.

As a result of the changes in the political framework, the transition in the energy sector, the economy and agriculture and a consistent orientation towards the EU Biodiversity Strategy and the full implementation of the European Water Framework Directive, we are experiencing a **recovery of ecosystems (K2)** in Germany. Overall, ecosystems will be able to increase their activity and strengthen their structure (e.g. through higher biodiversity) by 2050. In addition, their resilience will become stronger again, i.e. on average they will be able to maintain their activity and structure even after shock events.

However, there are two developments in this scenario that could potentially threaten its own sustainability in the long term: Firstly, there is a **slight expansion and densification of settlement areas (D2).** The proportion of settlement areas increases slightly and these become increasingly dense. The degree of sealing is increasing and the infiltration rate in cities and municipalities is falling. This is happening despite the fact that organic farming and green liberation tend to save land, because the energy transition is taking up significant areas for solar and wind power plants and, in addition, because **water awareness** and the prioritization of ecosystems have (again) declined (I3). Paradoxically, the stagnation of the temperature increase (A4) and the improved condition of the ecosystems lead to a reduced water awareness, which cannot be compensated for by the perception of the winter shift in precipitation. This winter shift and the distribution of the water supply are being addressed through a high degree of cooperation in the water sector and the implementation of ambitious political regulations, especially by experts. Water is (once again) less of a general social issue.

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