STATE OF GLOBAL WATER RESOURCES 2021

WEATHER CLIMATE WATER

WORLD METEOROLOGICAL ORGANIZATION

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Foreword

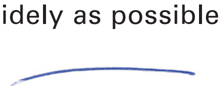
This first WMO annual *State of Global Water Resources* report has been launched in response to calls made, for example during COP 27 in Egypt, for accurate water data and information to guide discussions. It is also an important milestone along the road to the United Nations 2023 Water Conference. This WMO flagship report gives a concise presentation of the status of water resources in each basin in comparison to the 30-year hydrological average of that basin.

Managers, decision makers and policymakers at all levels of government make regular use of accurate and reliable georeferenced data to guide and support their work. However, a concise overview of water availability in the various compartments of the hydrological cycle is missing from their arsenal of decision-making support tools. While several universal water-related information reports exist, the annual WMO *State of Global Water Resources* report is unique in that it summarizes the extent of water resources available globally.

The annual WMO *State of Global Water Resources* report provides important insights for water resource management, at the basin, continental and global scale. This has significant relevance, particularly for large-scale decision-making and policymaking, but also for informing and guiding intergovernmental discussions related to water resources. Moreover, producing annual summaries using consistent methods and formats will enable interannual comparisons that facilitate the differentiation of shorter-term variable effects on water from longer-term trends driving water distribution patterns.

As a first, 'pilot' edition, the present WMO *State of Global Water Resources 2021* report is limited to the conditions of streamflow, terrestrial water storage and selected cryosphere parameters. Global Hydrological Modelling Systems and remotely sensed data were largely used in preparing the 2021 report, and the indicators obtained from these were compared and validated against observational data (where available). Despite a good correlation between modelled and observed results, the validation process would benefit substantially from utilizing further hydrological information. Therefore, I would like to take the opportunity to invite Members to share hydrological information in accordance with the WMO Unified Data Policy to help augment the validation process. Furthermore, WMO is committed to extending the variables in future editions of the report to include groundwater, soil moisture and water quality. Once the WMO Hydrological Status and Outlook System (HydroSOS) is operational, the annual *State of Global Water Resources* report can be produced as a direct output of this system.

I warmly congratulate the experts, lead authors and all contributors who compiled this report using observed and modelled streamflow data, remotely sensed terrestrial water storage data, other observations collected from various sources, and information on cryosphere and major hydrological disasters. Likewise, I thank all the contributors, particularly WMO Member National Hydrological and Meteorological Services, WMO Global Data Centres, members of the global hydrological modelling community (established under the Water and Climate Coalition) and supporting organizations, National Aeronautics and Space Administration (NASA) and the German Research Centre for Geosciences (GFZ). The 2021 report demonstrates the practical utility of an annual global water resources summary. Our mission is to inform world leaders, policymakers and citizens about the state of water resources in 2021 compared with previous years, and the impacts of weather and climate events. Therefore, this report is also an integral step towards the United Nations Secretary-General's call for an early warning system for all in the next five years. WMO remains committed to supporting this publication and communicating it as widely as possible to ensure it provides value to a diversity of end users globally.



Prof. Petteri Taalas
Secretary-General, WMO

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WMO Members who assigned *State of Global Water Resources* report focal points (at the time of writing)

Armenia; Belgium; Belize; Bhutan; Brazil; Bulgaria; China; Czechia; Egypt; Ghana; Hungary; Hong Kong, China; India; Kazakhstan; Latvia; Montenegro; Myanmar; Norway; Paraguay; Peru; Philippines; Poland; Republic of Korea; Republic of Moldova; Singapore; Slovenia; South Africa; Sweden; Tajikistan; Thailand; United Kingdom of Great Britain and Northern Ireland; and the United Republic of Tanzania, who contributed to and supported the preparation of the present report by providing observational data, information about major hydrological events that occurred in 2021 and other information, and participated in the review and validation process.

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Executive summary

Impacts of climate variability and change are often felt through water. The dynamics of the water cycle and its interactions with human society result in varying spatio-temporal patterns of water resource availability and impacts of water-related extremes affecting life, development, and sustainability of ecosystems, societies and individuals.

Despite prevailing La Niña conditions, the year 2021 was ranked as the fifth to seventh warmest on record, with the global annual mean temperature of 1.11 ± 0.13 °C above the 1850–1900 pre-industrial average. Precipitation patterns were characterized by high spatial and temporal variability.

Large areas of the globe recorded dryer-than-normal conditions in 2021 (comparisons based on the 30 years of historical modelled and observed discharge data). These areas included the La Plata River area, where a persistent drought has affected the region since 2019, the South and South-East Amazon, and basins in North America including the Colorado, Missouri and Mississippi river basins. In Africa, rivers such as the Niger, Volta, Nile and Congo had less-than-normal discharge in 2021. Similarly, rivers in parts of the Russian Federation, West Siberia and in Central Asia had less-than-average discharge in 2021.

Above- to much above-normal discharge was exhibited in North American basins and the northern Amazon with extreme flood events, and in the southern African river basins of Zambezi and Orange. Southern and northern China (the Amur river basin) were characterized by above-average discharge, similar to some basins in northern India.

Significant flood events with numerous casualties were reported, among others, in China (Henan province), northern India, western Europe, and countries impacted by tropical cyclones, such as Mozambique, the Philippines and Indonesia.

The present report provides the first overview of the state of global water resources for 2021. WMO aims to produce this kind of report on an annual basis in the coming years.

The results of this report were obtained mainly from the modelled streamflow data and satellite observations of terrestrial water storage. The 2021 report therefore also highlights **the lack of timely accessibility and availability of verified hydrological data**, which is crucial for the preparation of such a global report. In this context, care must be exercised in the interpretation of the findings. WMO urges National Hydrological and Meteorological Services to accelerate the availability and sharing of hydrological data, including discharge information, under the WMO Unified Data Policy. Most importantly, such data is a vital resource for regions, nations and communities for decision-making, for building resilience to the impacts of climate change, for sustainable development, and for integrated water resources management at the scale of whole basins. However, based on the WMO Global Hydrological Survey conducted by WMO in 2020, only 84% of countries (based on input from 75 WMO Member States and Territories) collect discharge information.

Based on its findings, the present report makes the following recommendations:

- Invest in filling the capacity gap in collecting data for basic hydrological variables and assessment of hydrological status, at the country level;
- Increase sharing of hydrological data at the international level;
- Accelerate development of end-to-end drought and flood early warning systems for reducing the impact of hydrological extremes on people, lives and livelihoods, ecosystems, and the economy at large in all parts of the world;
- Continue working together as a global hydrological community on developing the annual *State of Global Water Resources* report to support global understanding, policymaking and planning towards implementing the WMO Vision and Strategy for Hydrology as a support to achieving the Sustainable Development Goals.

Introduction

Threats such as floods, droughts and others associated with water resources are the most consequential of all the potential threats posed by climate change (and variability) for both society and the environment. Water-related climate impacts affect all aspects of societies including agriculture, health, energy, all economic sectors and ecosystems. Understanding changes in the demand for freshwater, and changes in its spatial and temporal distribution, quantity, and quality, in response to climate variability and change is essential to planning for and adapting to future climatic conditions, and to implementing the most effective climate mitigation strategies. The annual *State of Global Water Resources* report aims to detect the effects of climate, environmental and societal changes on the hydrological state of the Earth. This annual stocktake of global freshwater resources aims at achieving a better understanding of the changes that are occurring.

Although hydrological data are collected in nearly all major river basins around the world, their quality, distribution, availability and accessibility are highly variable, as well as the variables monitored. According to the WMO Global Hydrological Survey conducted in 2020, 91% (of 75 Members) collect information on water levels in rivers, yet only 84% monitor discharge.[1] Furthermore, only 60% and 20% of responding Members indicated that they measure groundwater and soil moisture levels, respectively. High variability in the survey results was also observed among the various WMO regions. For example, in WMO Region I (Africa), 57% (8 of 14) of responding Members monitor river discharge, compared to 66% (4 of 6) of responding Members in Region IV (North America, Central America and the Caribbean). WMO has recently made significant advances in facilitating the accessibility of water data, particularly streamflow, with the development of the Hydrological Status and Outlook System (HydroSOS) and the WMO Hydrological Observing System (WHOS).

While accessing data is an essential capability, evaluating the characteristics of these data sets on a regular basis is critical for understanding patterns and trends in water resources and the hazards associated with extreme events. Although periodic hydrological assessments are produced for some countries and regions of the world, there is currently no worldwide synthesis of the status of water resources which is published annually. However, an annual summary is a major contribution to understanding water resource patterns and trends, and to guiding their development needs for the longer term. This first edition of the WMO annual *State of Global Water Resources* report comprises a presentation of the previous calendar year's observed and modelled discharge utilizing maps and graphs.

The present report also includes remotely sensed information with a reasonable global coverage, such as total terrestrial water storage (TWS). The report aims to include data on additional variables in the future, such as groundwater and soil moisture. The report presents crucial hydrological indicators at a global scale, such as the change in the number of extreme events, or change in streamflow (in the current year in comparison to the hydrological normal), which will help in identifying patterns and hydrological hotspots, both annually and over longer time periods.

While there are other global reports on water and related issues, such as the annual *United Nations World Water Development Report* (based on an annual theme defined by UN-Water), none of the reports provide an overview summary of the state of water resources: that is, no global product exists that depicts hydrological conditions at the basin scale. Given that the capability now exists to provide such a product annually, its absence is an unjustified deficiency. Therefore, the WMO annual *State of Global Water Resources* report will fill a niche by providing annual summaries of hydrological variables, such as discharge, TWS and others (in future editions) such as groundwater storage and soil moisture. The report will feed economic, social and environmental policy development and decision-making around the world.

National level streamflow summaries have demonstrated their value to a variety of users, including water resource planners and decision makers, organizations with responsibilities related to agricultural, environmental, energy, and industrial sectors of the economy, policymakers, and researchers in numerous disciplines, among others. Similarly, at the regional scale, this type of summary provides valuable data, not only for assessing the water resources for the past year, but in guiding decision-making related to future resource availability and related investments. This is particularly true for transboundary river basin assessments and management. At the global scale, a consistent and easily updatable map provides an unbiased assessment of recent water conditions for organizations with an international or intergovernmental mission. Such a map can also highlight places where water issues could arise and require the assistance of international humanitarian and development organizations.

The present *State of Global Water Resources 2021* report is a first edition, and as such, does not seek to provide formal statements on the status of water at basin or national scales. As a 'pilot' edition of sorts, it does not yet cover information from a broad range of variables: in subsequent editions the report will be extended and expanded. This first report shows how maps and a graphical summary of streamflow and TWS in river basins worldwide could look in regular reports on global water resources. These maps are based on modelled data (and validated with observed data to the extent possible) and remotely sensed information from the NASA GRACE mission for TWS. Modelled data was used to achieve maximum geographical coverage. Although the present report includes a brief overview of the cryosphere changes as they relate to water resources, future reports will expand on this to provide a more accurate report of the contribution of the cryosphere to water resources.

In the present report, the principal data are presented in the two sections Streamflow and Terrestrial water storage, from both a global and regional perspective. The following section, High-impact events, provides a global overview of the major hydrological events that occurred in 2021, featuring contributions from national authorities. The section on Cryosphere water resources aims to capture and highlight the effect of melting glaciers on water resources, with regional examples contributed from two Central Asian countries. The Conclusions summarize the main findings of the *State of Global Water Resources 2021* report and the scope of future reports. Annex 1 documents details of the methods (including a concise overview of the data sources) and Global Hydrological Modelling Systems (GHMSs) used in the analysis, as well as definitions of the indicators used in the report and any additional results . Annex 2 provides examples of extreme event assessments from National Hydrological and Meteorological Services.

Streamflow

Discharge 2021: Global and regional perspectives

This first edition of the annual *State of Global Water Resources* report focuses on 515 main hydrological basins (referred to as 'basins' in the present report) that cover the entire globe, according to the WMO classification of basins (presented in Figure 1 of Annex 1).[2] For this first edition in 2021, the availability of observed discharge data was limited to only 7% (of 515 basins) (see Figure 2 and Figure 3 of Annex 1 showing WMO basins where observed data for 2021 and historical discharge data were accessible for at least one gauge at each basin outlet). Another source of discharge information was required, in order to ensure global coverage of the analysis. Therefore, this first report is largely based on the outputs of Global Hydrological Modelling Systems (GHMS), obtained under the cooperative framework of the Operational Global and Regional Hydrological Modelling Community.[3] The simulated discharges from those GHMS were analysed at the basin level.

Global Hydrological Modelling Systems used

In total, seven different GHMSs were used in the modelling exercise. These included CaMa-Flood and Dam, CSSP, ECLand, mHM, GeoGlows, GloFAS and TEJRA 55. Annex 1 provides details on each of the GHMSs applied, together with information on how they were set up with historical data and how predictions for 2021 were obtained. The information in Annex 1 also outlines potential sources of uncertainty associated with the modelling framework applied.

Sharing of hydrological data is steadily increasing, especially in the case of operational data at the international basin scale. Similarly, processes for sharing quality-controlled data for long-term water resources assessment have been established for many international rivers. However, sharing quality-controlled data at the global level in a timely manner for the purposes of developing continental or global reports remains a challenge (see the WMO Global Hydrological Survey 2020 for the share of WMO Members that collect observed data).[4]

The present section presents the results of the analysis of discharge data from the Global Hydrological Models that was verified with observed data where possible.

The global perspective

The **modelled discharge** was obtained from an ensemble of Global Hydrological Modelling Systems (GHMS) (see Annex 2 for further details on the models) for each of the selected basins for the year 2021. The obtained average discharge for 2021 was compared with the historical values over the years 1991–2020 and then ranked as either normal, above normal, much above normal, below normal or much below normal with reference to historical values (see Annex 1 for more details on the methodology). Figure 1 presents the average 2021 discharge ranking with respect to the selected historical period. Wherever observations were available, the modelled results were validated.

As can be seen in Figure 1, discharge in the year 2021 was in the range of much below to below normal in many parts of the globe. According to the analysis performed based on the modelled data, the area with below- and much below-discharge conditions was approximately two times larger than that with above- and much above-discharge conditions. Approximately one third of the areas analysed exhibited normal discharge conditions.

Discharge was assessed as below and much below normal in the southern part of the South American continent, especially in the La Plata river basin, the southern part of the Amazon river basin and the Saõ Francisco river basin. In fact, La Plata River has been suffering from

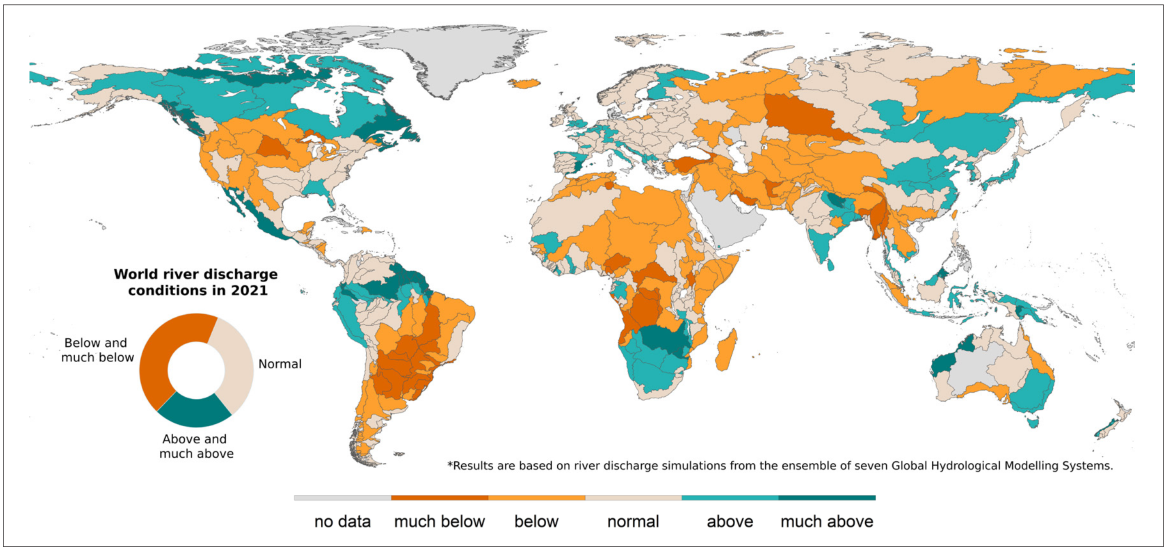


Figure 1. World river discharge conditions in 2021, ranked with reference to the historical period of 1991–2020. The results presented here were derived from the modelled discharge data, which were obtained from an ensemble of Global Hydrological Modelling System simulations (see Methods in **Annex 1**). Grey areas indicate missing discharge data. Note that the results were validated against hydrological observations wherever available (see Examples of basin-scale assessments based on observations for the detailed validations). Inset (bottom left) shows the distribution of the area under the given conditions.

a persistent drought since the year 2019.[5] In contrast, river basins of coastal areas of Peru experienced above-normal annual discharge. The Amazon basin area suffered from both flood and drought in 2021: extreme flood events were reported for the northern Amazon and drought conditions occurred in the southern and south-eastern Amazon. These events were associated with the La Niña conditions and intensification of Walker circulations, in the case of floods, and with the Hadley continental circulation, in the case of droughts.[6] During the flood, the water level at the Manaus station in Brazil was above 29 m (the emergency threshold), breaking the record of the previous flood of 2012.[7]

In North America, specifically in the Canadian province of British Columbia and in the Mackenzie, Yukon and Churchill river basins in the northern part of the continent, discharge was assessed as above and much above normal in 2021. Drought in the western, mid-western and north-eastern United States of America, which started in 2020, persisted also in 2021 and worsened in the western part of the USA in June 2021, when almost the entire region was affected by drought.[8] For the Colorado, Missouri and Mississippi Rivers, the discharge in 2021 was below and much below normal.

Ranking and classification of discharge

Annual mean discharge (Q in m^3 per second) over the last 30 years of modelled data of each of the GHMS or observations (where available) was calculated for each basin. The resulting array was ranked. Annual mean discharge for the year 2021 for each model or observed data was then compared to this ranked array and classified according to the following definition (note that, in the case of the modelled data, an additional step was taken, to aggregate modelled results across all models. Refer to Annex 1 for more details on ranking and aggregation of modelled results).

much below normal:	$Q_{2021} < 0.05$ percentile
below normal:	$0.05 < Q_{2021} < 0.25$ percentile
normal:	$0.25 < Q_{2021} < 0.75$ percentile
above normal:	$0.75 < Q_{2021} < 0.95$ percentile
much above normal:	$Q_{2021} > 0.95$ percentile

In Europe, rivers on the Spanish Mediterranean coast, Ligurian coast, in the south of the United Kingdom, and in central and western Europe exhibited above-normal mean discharge in 2021. In fact, in July 2021 a catastrophic flood took place in Germany, Belgium and the Netherlands, causing a high number of casualties across Europe.[9] In October 2021, above-normal rainfall caused floods and landslides in the Liguria and Piedmont regions. Liguria's environment agency reported a record 181 mm of rainfall in just one hour and over 900 mm in 24 hours.[10] These areas also exhibit above-normal discharge in 2021 when compared to the average annual values.

Eastern and northern China (Amur river basin) were characterized by above-average discharge values. In central-eastern China, record rainfall affected more than 350 000 people, who were evacuated in July 2021 in the Henan Province. In India, headwaters of the Ganges River were characterized by above- to much above-normal discharge. Rivers in the European part of the Russian Federation, in West Siberia as well as in Central Asia had less-than average discharge in 2021, while far eastern Siberian river basins, including the Amur river basin, experienced run-off above the average.

The south-eastern and western Australian coasts exhibited above-normal annual discharge. In Africa, there were severe drought conditions in the Horn of Africa, affecting Ethiopia, Kenya and Somalia.[11]

Examples of basin-scale assessments based on observations

The present section provides insights into basin-scale discharge during the year 2021, based on observed discharge data. It focuses on a few selected areas, where such data were available, to demonstrate the possibilities of detailed hydrological assessments. The discharge in the year 2021 was ranked against the average discharge in the selected historical period in a similar manner as for the global analysis (see The global perspective). The results from the Global Hydrological Modelling Systems (GHMSs) and from observations were compared, and the areas showing an agreement in the results are indicated in Figures 2 to 12 except Figures 3, 6 and 11, with hatching.

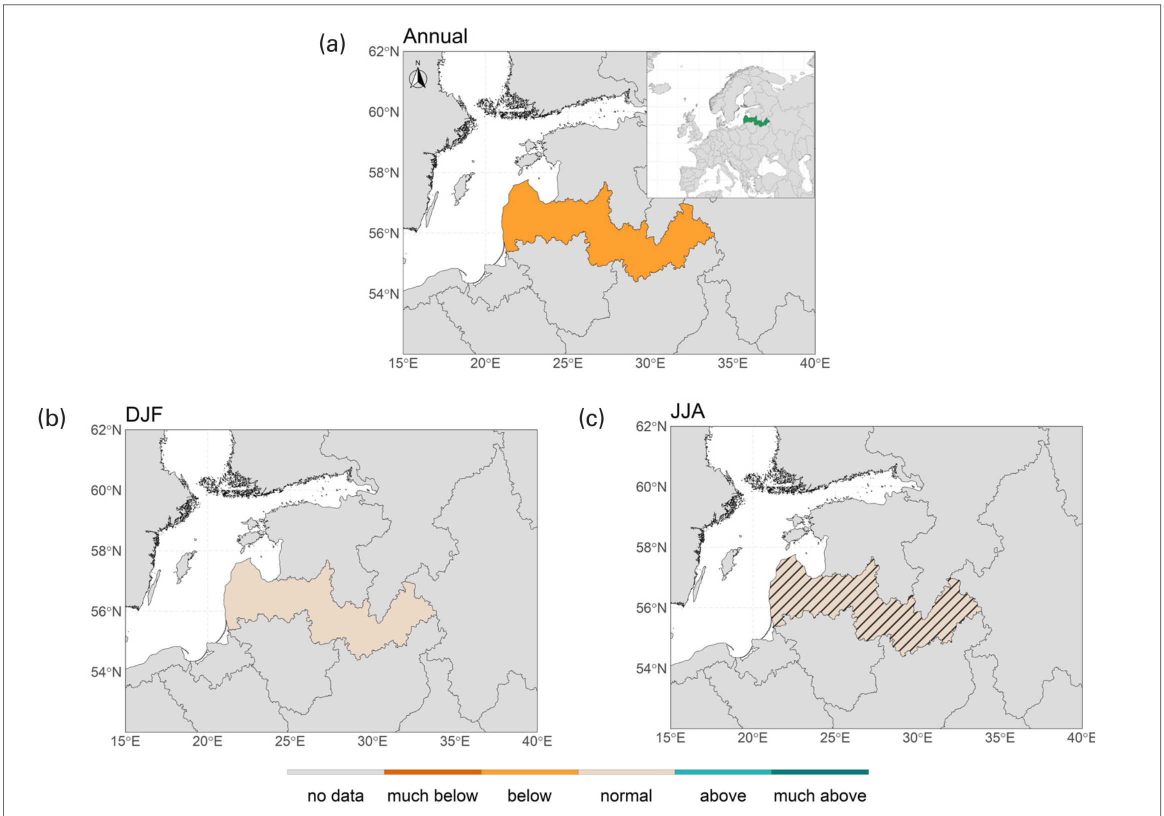


Figure 2. Discharge ranking for 2021 with reference to the historical period (1991–2020) for Daugava River: (a) Mean annual normal; (b) December–January–February (DJF); (c) June–July–August (JJA). Hatching indicates agreement between the discharge characteristics obtained from observed flow data and GHMS simulations. Here and in the captions of Figures 4, 5, 7, 9, 10 and 12, "discharge characteristic" refers to annual mean discharge for 2021 being "normal", "above normal" or "below normal", with reference to the historical period. Refer to Annex 1 for more details on the validation process.

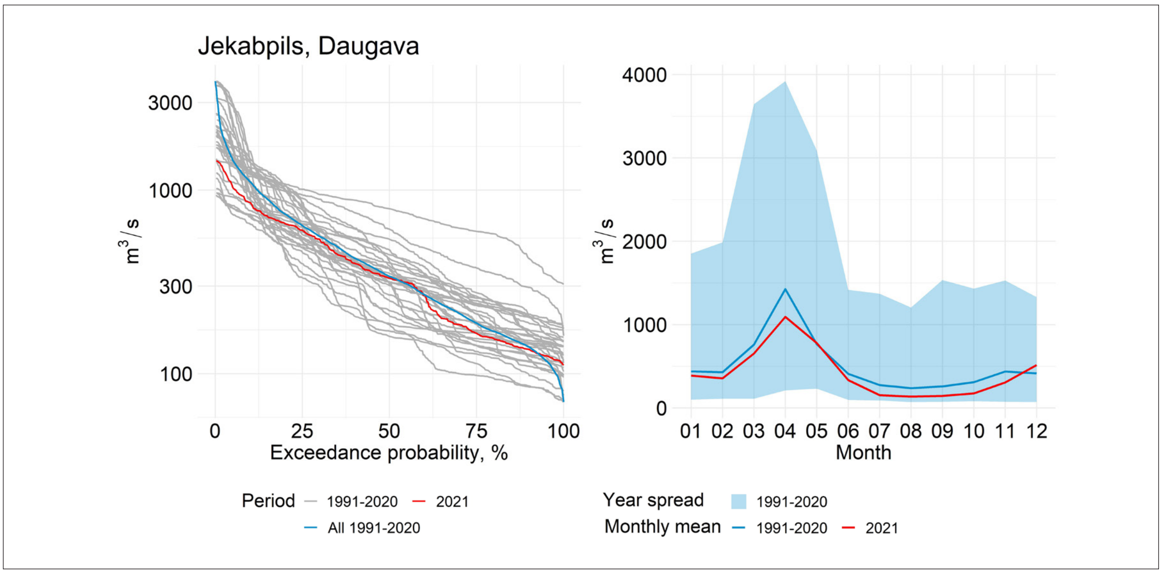


Figure 3. Comparison of 2021 streamflow observation data with reference to the historical period (1991–2020) for the Daugava River, Latvia: exceedance probability (left), mean monthly discharge (right)

Latvia

The discharge data for the Daugava River were provided by the Latvian Environment, Geology and Meteorology Centre (LEGMC). The mean annual river discharge in the Daugava River (Jekabpils station) is characterized as below normal for 2021 in comparison to 1991–2020. Nevertheless, discharge in the boreal winter and summer months plot within the normal. The results obtained during the summer months from GHMSs were in line with those obtained from observed data (Figure 2). Figure 3 presents exceedance probability curves based on observations for historical years and the year 2021, and mean monthly discharge in 2021 against years of the selected historical period.

Guatemala

The discharge data for the Cabuz and Guacalate Rivers were provided by the Guatemalan Instituto Nacional de Sismología, Vulcanología, Meteorologiá e Hidrología (INSIVUMEH). In Guatemala, discharge from the Cabuz River (Malacatan station) and Guacalate River (Alotenango station) (Figure 4) did not vary from the average conditions when compared to the mean yearly discharge, as well as discharge during the months of June-July-August. However, discharge during December–January–February was much above normal, as indicated by both observed and modelled data.

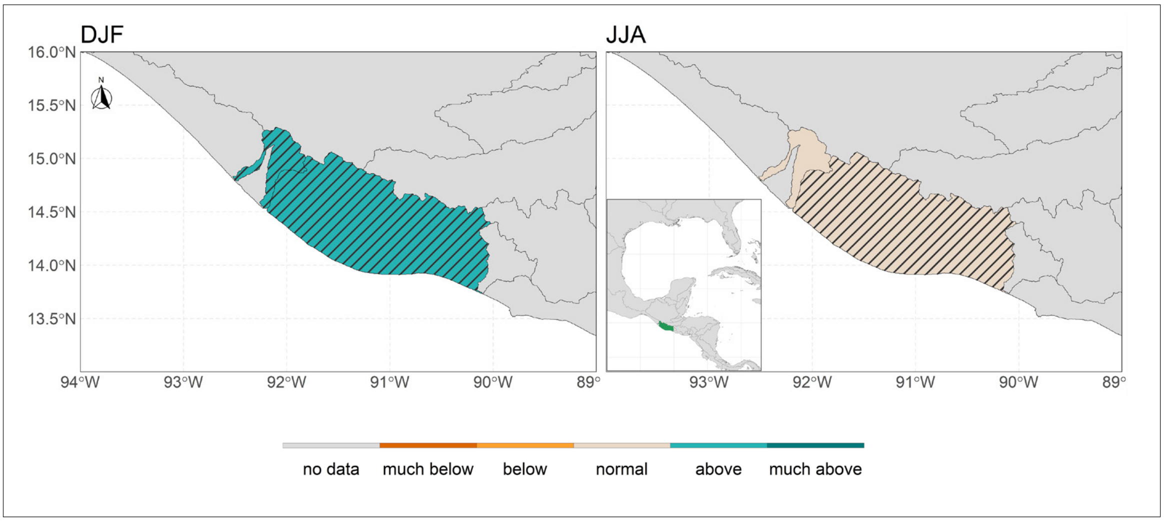


Figure 4. Discharge ranking for 2021 with reference to the historical period for Cabuz and Guacalate Rivers (Guatemala): December–January–February (left); June–July–August (right). Hatching indicates agreement between the discharge characteristics obtained from observed flow data and GHMS simulations.

Myanmar

The discharge data for the Irrawaddy River were provided by the Myanmar Department of Meteorology and Hydrology. Figure 5 presents the mean December–January–February (left) and June–July–August (right) 2021 discharge ranking with respect to the historical period for the Irrawaddy river basin (Toungoo and Sittaung stations in Pyay). DJF was characterized by lower-than-normal discharge, whereas JJA by much lower-than-normal discharge. These results agree with discharge rankings, simulated by GHMSs. Figure 6 presents exceedance probability curves based on observations for historical years and the year 2021, and mean monthly discharge in 2021 against years of the selected historical period.

Paraguay

The discharge data for the Paraguay River were provided by the Paraguay Dirección de Meteorologia e Hidrología and GRDC database. Figure 7 presents the mean December–January–February 2021 discharge ranking with reference to the historical period for the

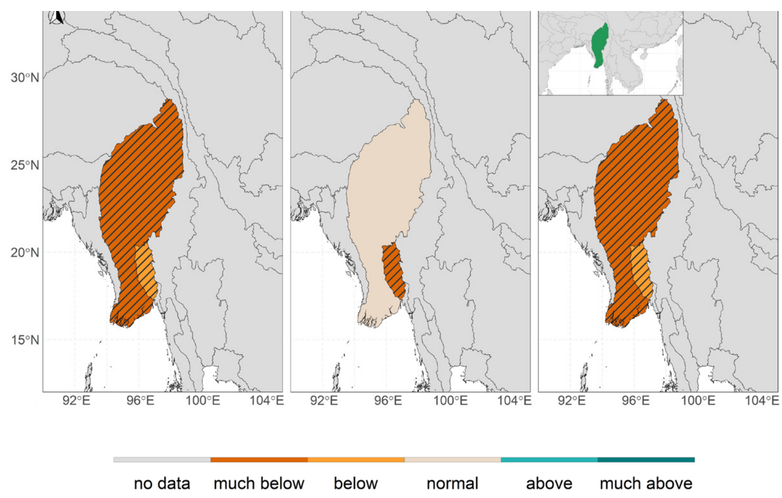


Figure 5. Discharge ranking for 2021 with reference to the historical period (1991–2020) for Myanmar: mean annual (left); December–January–February (middle); and June–July–August (right). Hatching indicates agreement between the discharge characteristics obtained from observed flow data and GHMS simulations.

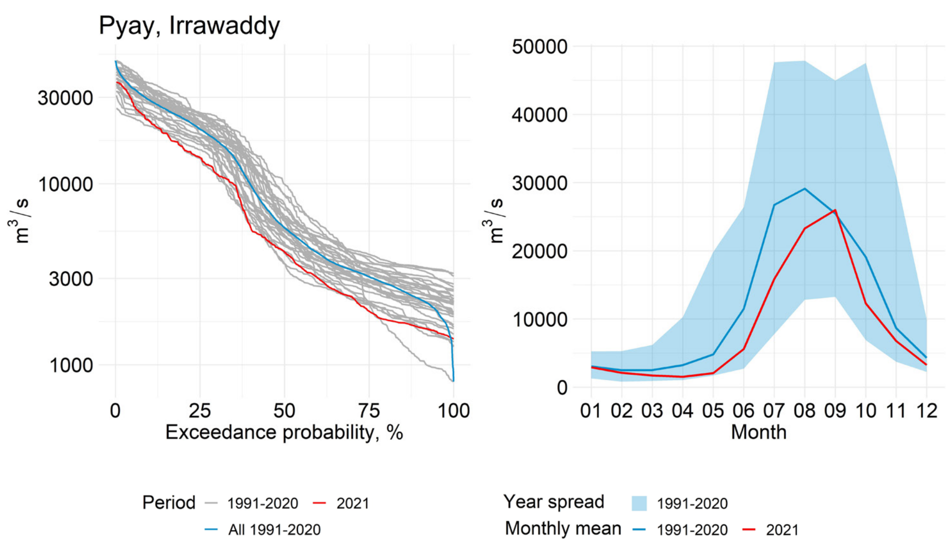


Figure 6. Comparison of 2021 streamflow observation data with reference to the historical period (1991–2020) for the Irrawaddy River, Myanmar: exceedance probability (left); mean monthly discharge (right)

Paraguay River (Asuncion station). The mean DJF discharge was ranked as normal with reference to the historical period, whereas the JJA discharge was much below normal. Simulations obtained from GHMS rank JJA discharge also as much below-normal conditions, and DJF as below normal.

Figure 8 presents exceedance probability curves based on observations for historical years and the year 2021, and mean monthly discharge in 2021 against years of the selected historical period.

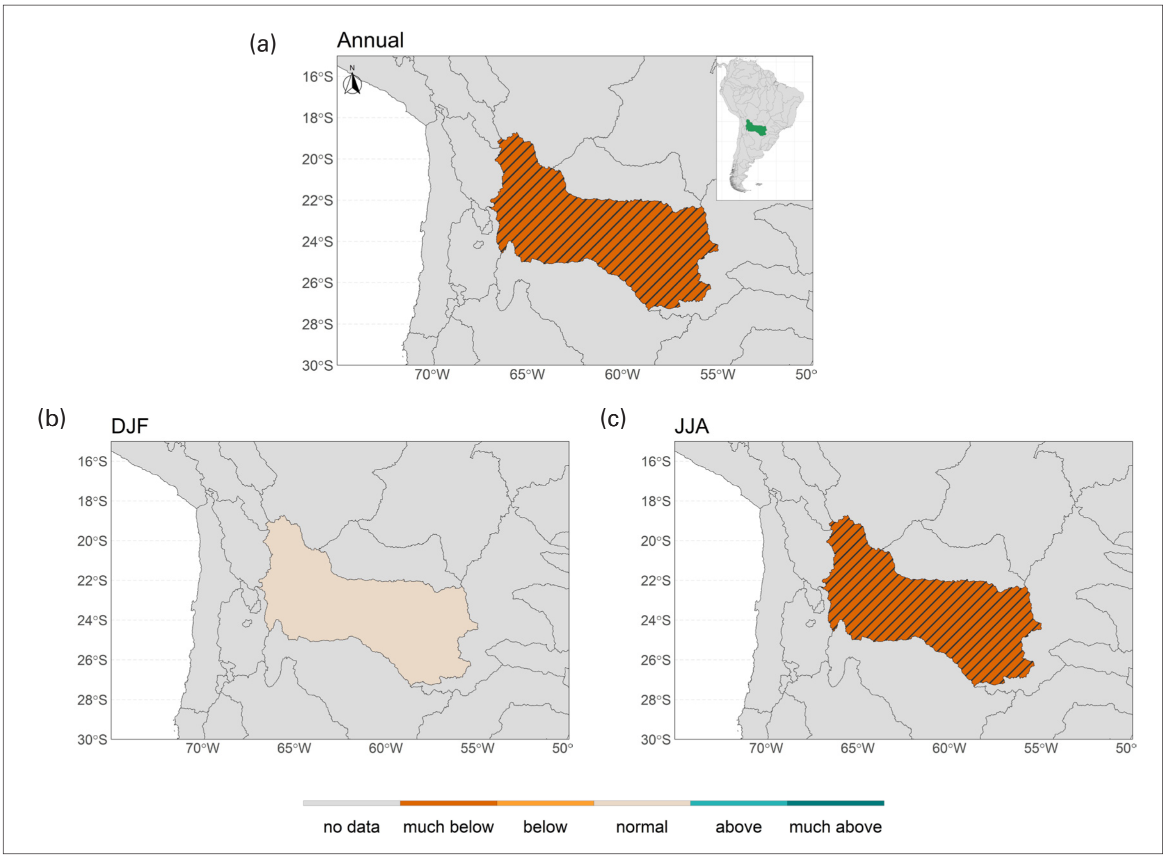


Figure 7. Discharge ranking for 2021 with reference to the historical period (1991–2020) for Paraguay River: (a) Mean annual normal; (b) December–January–February; (c) June–July–August. Hatching indicates agreement between the discharge characteristics obtained from observed flow data and GHMS simulations.

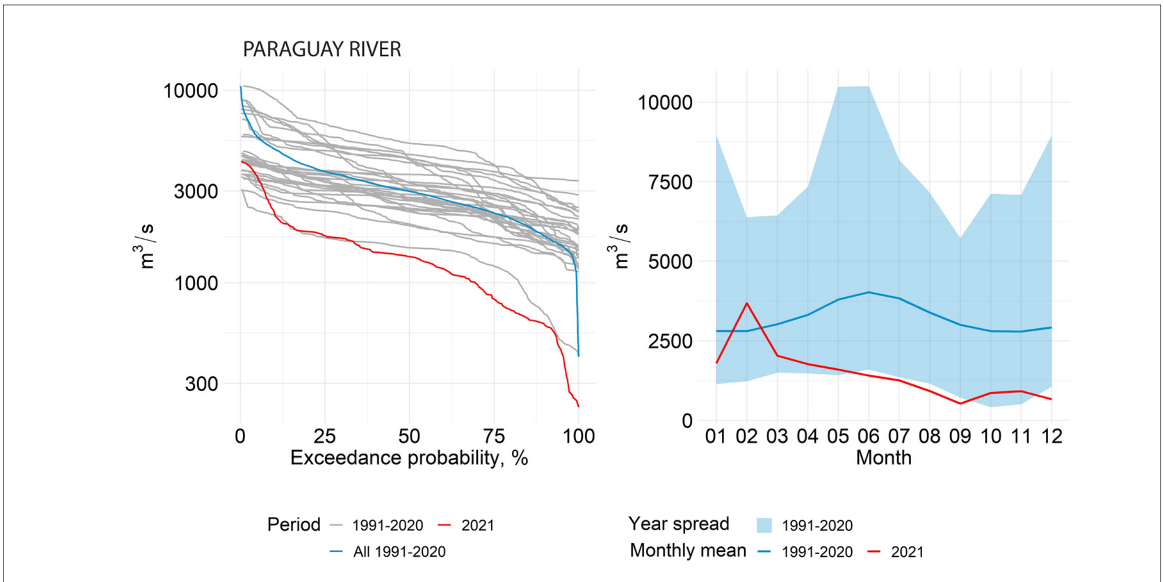


Figure 8. Comparison of 2021 streamflow observation data with reference to the historical period (1991–2020) for the Paraguay River, Paraguay: exceedance probability (left); mean monthly discharge (right)

United States of America

The discharge data for the river basins in central and northern USA were provided by the GRDC database. Figure 9 presents the mean December–January–February 2021 discharge ranking with respect to the historical period and June–July–August 2021 discharge ranking with respect to the historical period as derived from the available stations in the GRDC database. Only seasonal graphs were produced from the data from these stations, as the records did not cover the entire year of 2021.

The central part of the Northern American continent was characterized by below- to much below-normal discharge in both the JJA and DJF periods. The Yukon river basin had much above-average discharge in the boreal winter season (DJF) and normal discharge in the boreal summer (JJA) season.

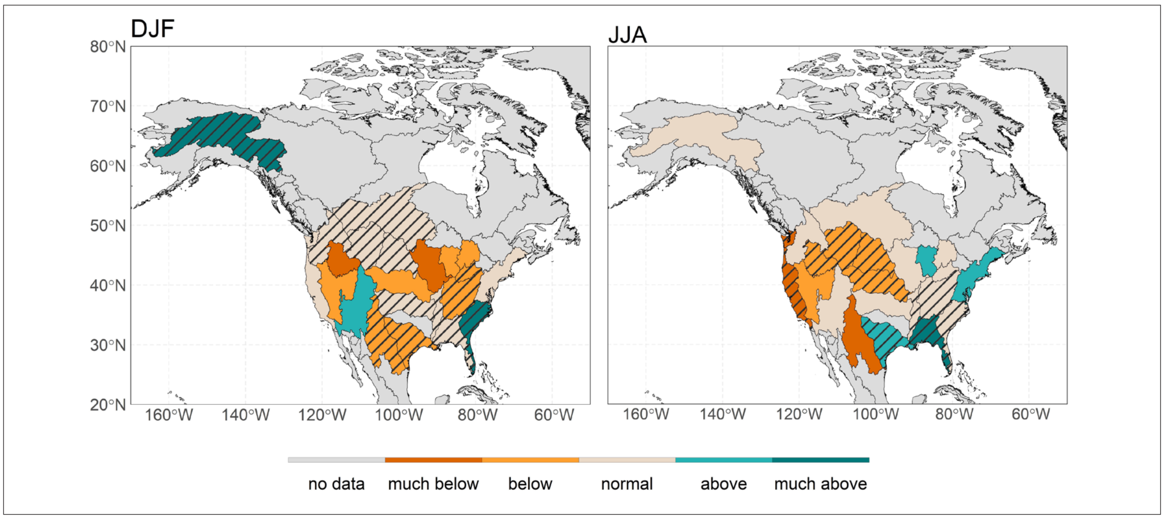


Figure 9. Discharge ranking for 2021 with reference to the historical period for the USA: December–January–February (left); June–July–August (right). Hatching indicates agreement between the discharge characteristics obtained from observed flow data and GHMS simulations.

Norway

The discharge data for the Glomma River, Gammelbollo River and other coastal river basins in Norway were provided by the Norwegian Water Resources and Energy Directorate (NVE). In 2021, the annual river discharge in Norway was characterized as normal and below normal, depending on the region (Figure 10). However, discharge over the boreal winter months of December, January and February was much above normal and below or much below for the boreal summer months of June, July and August of 2021.

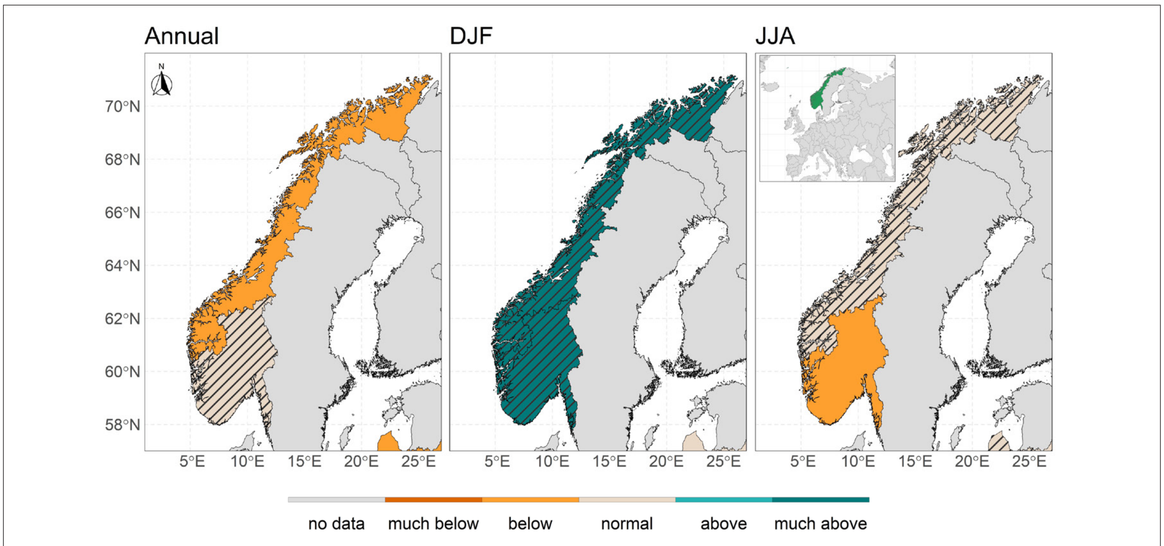


Figure 10. Discharge ranking for 2021 with reference to the historical period (1991–2020) for Norway: mean annual (left); December–January–February (middle); and June–July–August (right). Hatching indicates agreement between the discharge characteristics obtained from observed flow data and GHMS simulations.

Figure 11 presents exceedance probability curves based on observations for historical years and the year 2021, and mean monthly discharge in 2021 against years of the selected historical period for the Glomma River.

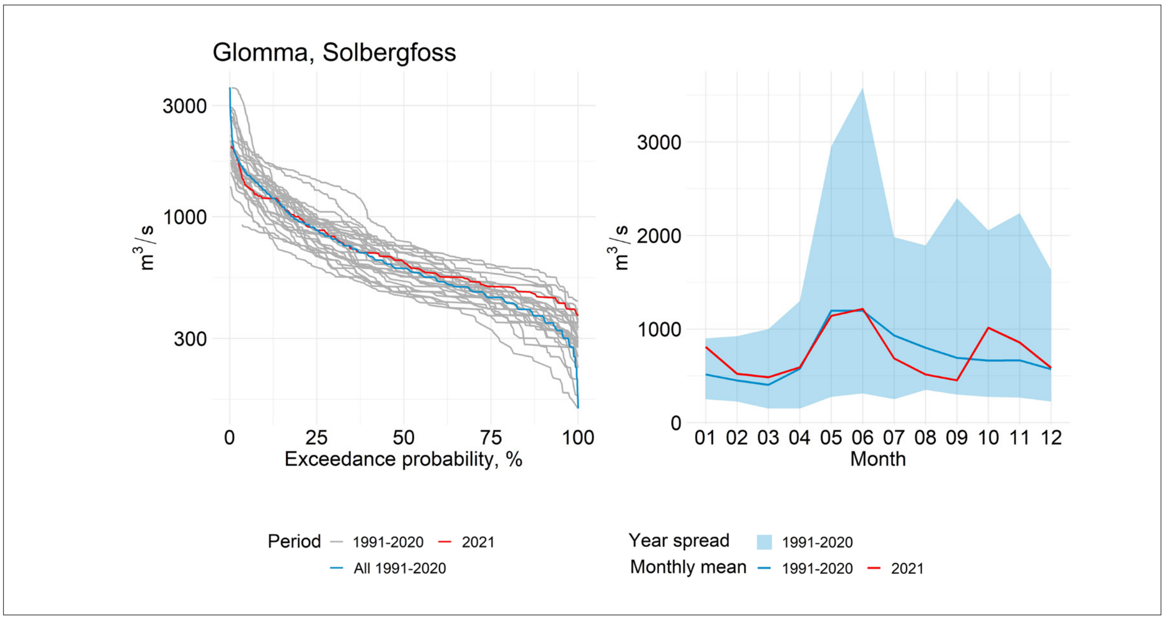


Figure 11. Comparison of 2021 streamflow observation data with reference to the historical period (1991–2020) for the Glomma River, Norway: exceedance probability (left); mean monthly discharge (right)

The United Kingdom of Great Britain and Northern Ireland

The discharge data for the river basins in the United Kingdom were provided by the UK Centre for Ecology & Hydrology (UKCEH). The river discharge across the territory of the United Kingdom in December–January–February was above normal in the majority of basins (Figure 12). During the boreal summer months, the river discharge in 2021 was mainly normal and above normal in the southern part of the United Kingdom.

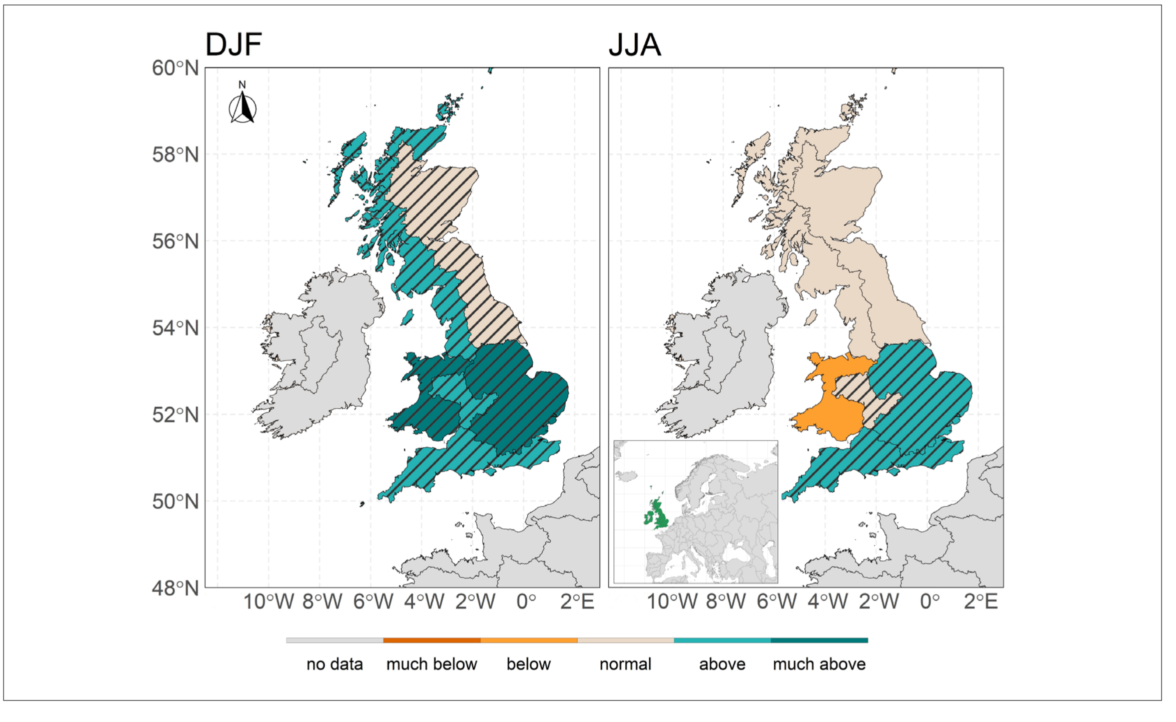


Figure 12. Discharge ranking for 2021 with reference to the historical period (1991–2020) for the United Kingdom: December–January–February (left); and June–July–August (right). Hatching indicates agreement between the discharge characteristics obtained from observed flow data and GHMS simulations.

Terrestrial water storage

Global perspective

Satellite gravimetry is a remote sensing-based method (using data obtained from GRACE satellites)[12] which allows observation of the whole water column, including surface water, soil moisture, groundwater, and snow and ice. Terrestrial water storage (TWS) is expressed in equivalent water heights in centimetres, which is a mean height of the water column over the whole considered area. The section Terrestrial water storage in Annex 1 provides more details on TWS and how TWS anomalies were calculated.

Figure 13 provides linear trend values of TWS anomaly between 2002 and 2021 at a global 1° grid and averaged at the level of the selected WMO basins. Figure 14 provides TWS in the year 2021 compared to 2002–2020 (see Methods in Annex 1 for more detailed information on how the anomaly was calculated).

The map of TWS anomaly in Figure 13 identifies several hotspots with a strong negative TWS deviation, namely in the São Francisco river basin, in Patagonia, in the Ganges and Indus headwaters, and in south-western USA. In contrast, the Great Lakes region exhibits a positive anomaly. The Niger basin, East African Rift and North Amazon basin also show positive anomalies. Overall, the negative trends are stronger than the positive ones. It should be noted that at least some of the strong anomalies (Alaska, Patagonia, Himalayas, and Baffin Island) are also the result of long-term trends caused by the melting of snow and ice. Some of the hotspots of negative trends are mainly induced by over-abstraction of groundwater for irrigation.[13]

For the year 2021, the TWS was much below and below normal on the west coast of the USA, in Patagonia, North Africa and Madagascar, Central Asia and the Middle East, the central part of South America, Pakistan and northern India. TWS was above and much above normal in the central part of Africa, the northern part of South America, specifically the Amazon basin, and the northern part of China. The year 2021 was consistent with the general trends in TWS, as presented in Figure 14.

Continental and regional perspectives

The time series of TWS anomaly for continents (see Figure 15) indicate that the continental trend takes a positive value only for the African continent. However, most of this trend results from an increase in TWS in spatially limited hotspots (for example, in the Lake Victoria region) while the trend in other parts of the continent might show a different direction. In contrast, Asia, Europe and North America show a pronounced decline of TWS.

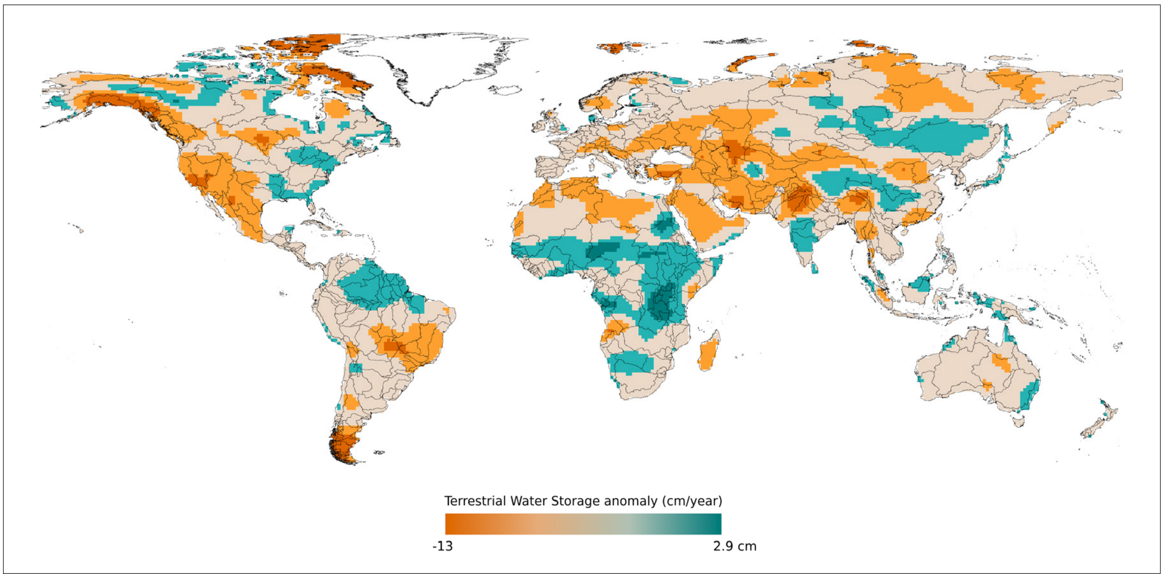


Figure 13. Terrestrial water storage anomaly trends in cm per year over the period 2002 to 2021 on a 1 degree grid. Note: The areas in orange indicate large displacement in fresh water to the oceans during the time period. Note also that Greenland and Antarctica are not included in the maps, as their mass balance trends are large, and therefore overshadow the other continental mass balance trends depicted here.

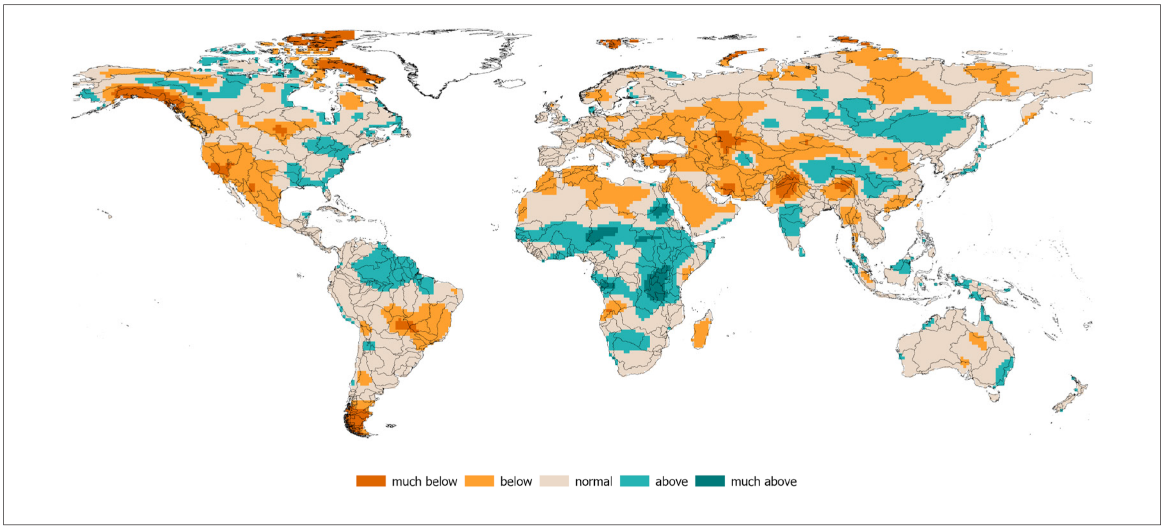


Figure 14. Terrestrial water storage in 2021 ranked in comparison to the historical period (2002–2020). Note: The areas in orange indicate large displacement in fresh water to the oceans during the time period. Note also that Greenland and Antarctica are not included in the maps, as their mass balance trends are large, and therefore overshadow the other continental mass balance trends depicted here.

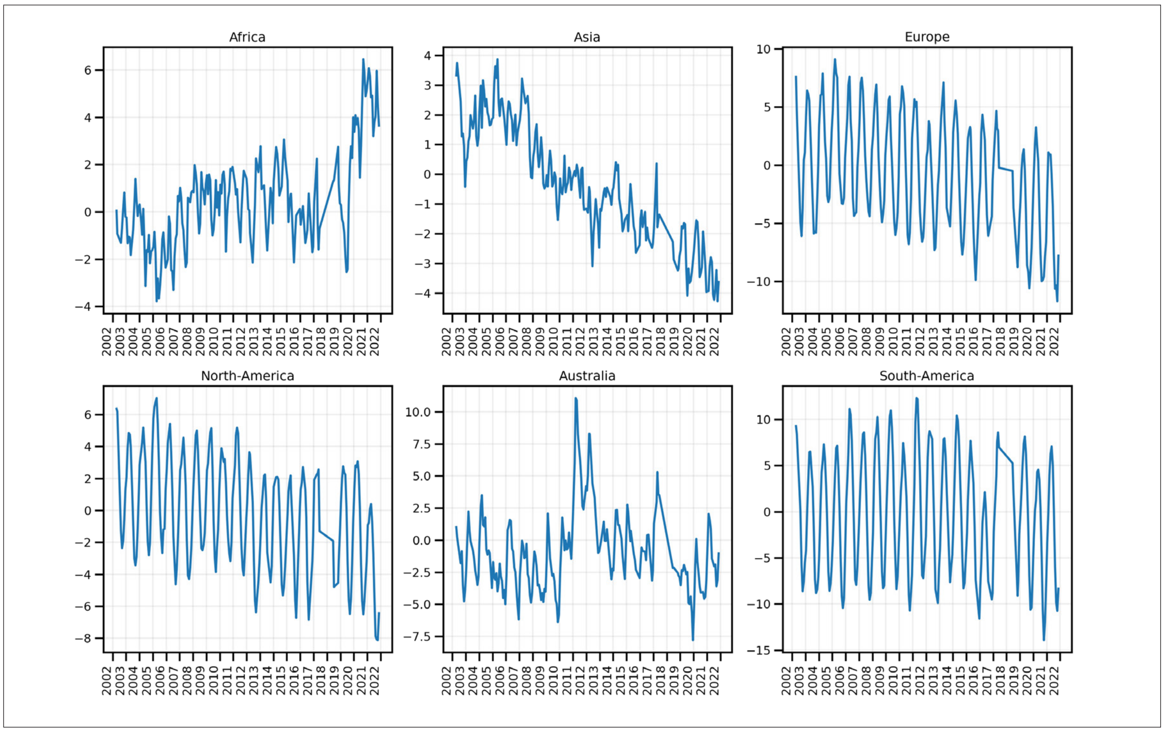


Figure 15. Terrestrial water storage anomaly in cm for the year 2002–2021 for each continent

Figure 16 shows monthly values of terrestrial water storage for the Danube, Vistula, Don and Rhine river basins for the years 2002–2022, year by year. The distance of each point from the centre of the plot represents the centimetres of stored water (surface, groundwater and soil moisture), while the colour is related to the year (dark blue for earlier years, green/ yellow for more recent ones).

Similarly, Figure 17 shows spider plots for the Niger, Volta, Congo, Nile and Zambezi river basins exhibiting a gradual increase in TWS since 2002. The greatest positive change in TWS is observed in the Congo and Nile river basins.

Figure 18 presents TWS for river basins in North and South America. The São Francisco, Colorado and Yukon river basins exhibit a gradual decrease in TWS, with 2021 being the year with the lowest TWS between 2002–2021. The Amazon and Mississippi river basins, in contrast, do not show a particular trend. For the Saint Lawrence river basin, a positive trend in TWS is observed.

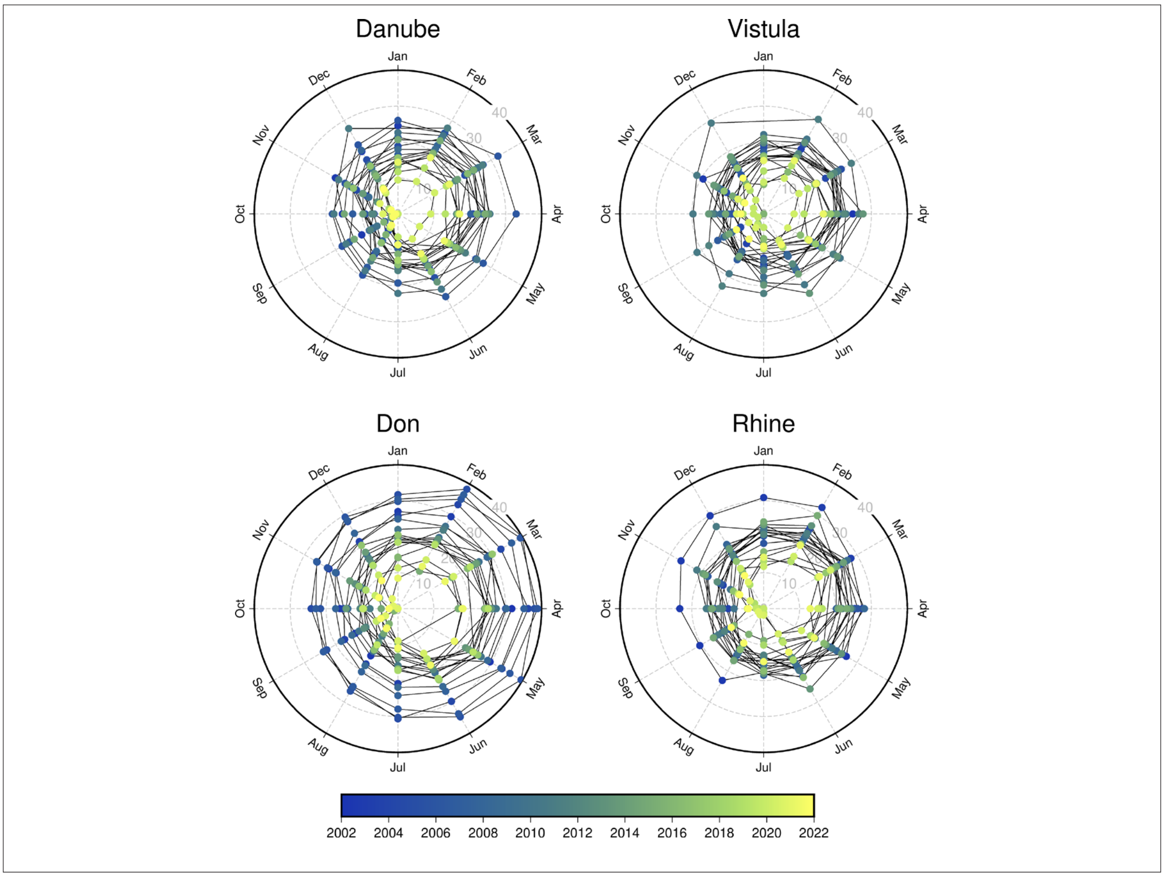


Figure 16. Terrestrial water storage in cm per month for the years 2002–2021 for central and eastern European rivers basins the Danube, Vistula, Don and Rhine

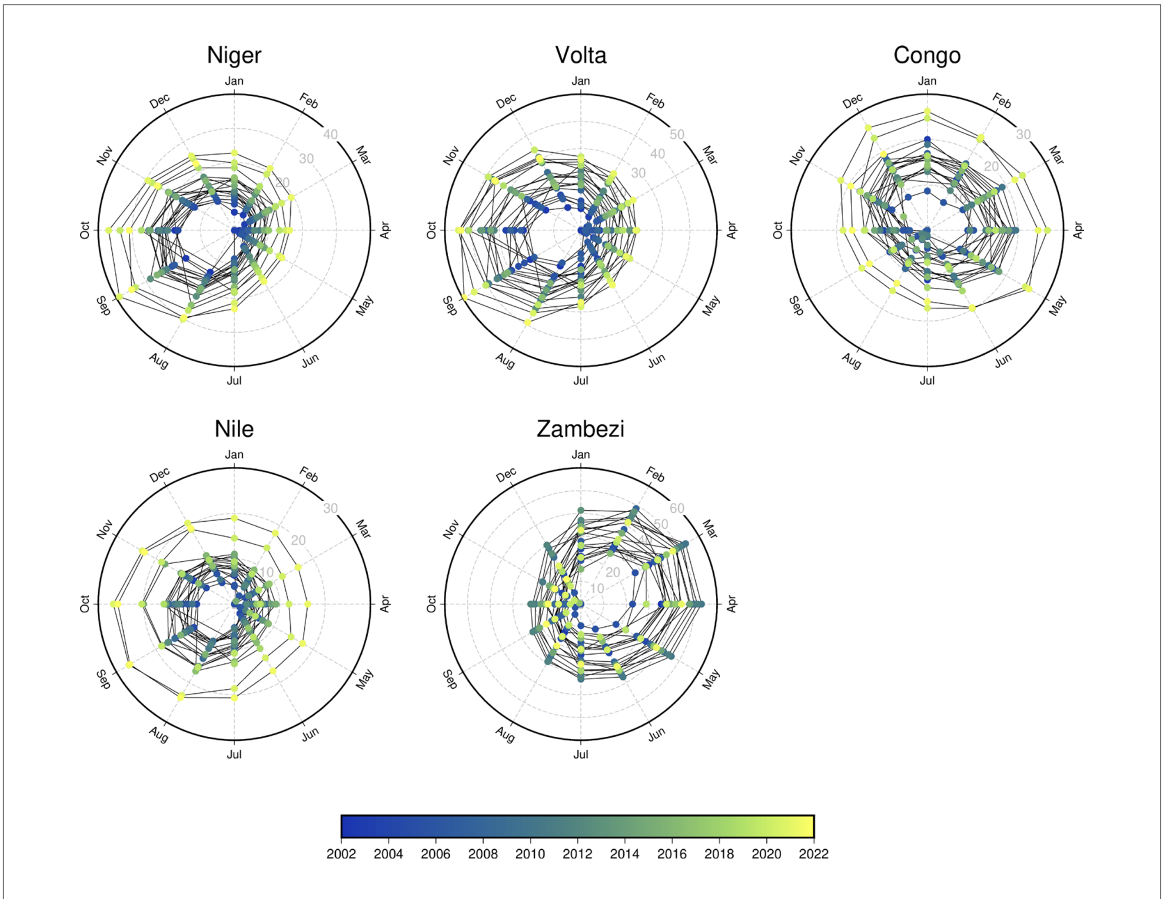


Figure 17. Terrestrial water storage in cm per month for the years 2002–2021 for African river basins the Niger, Volta, Nile, Zambezi and Congo

As depicted in Figure 19, major Indian river basins (the Brahmaputra, Ganges and Indus), as well as other important river basins in Asia (Huang He, also known as Yellow, and Mekong), exhibit a gradual decline in TWS over the period 2002–2021. On the other hand, the Amur river basin shows an increase in TWS.

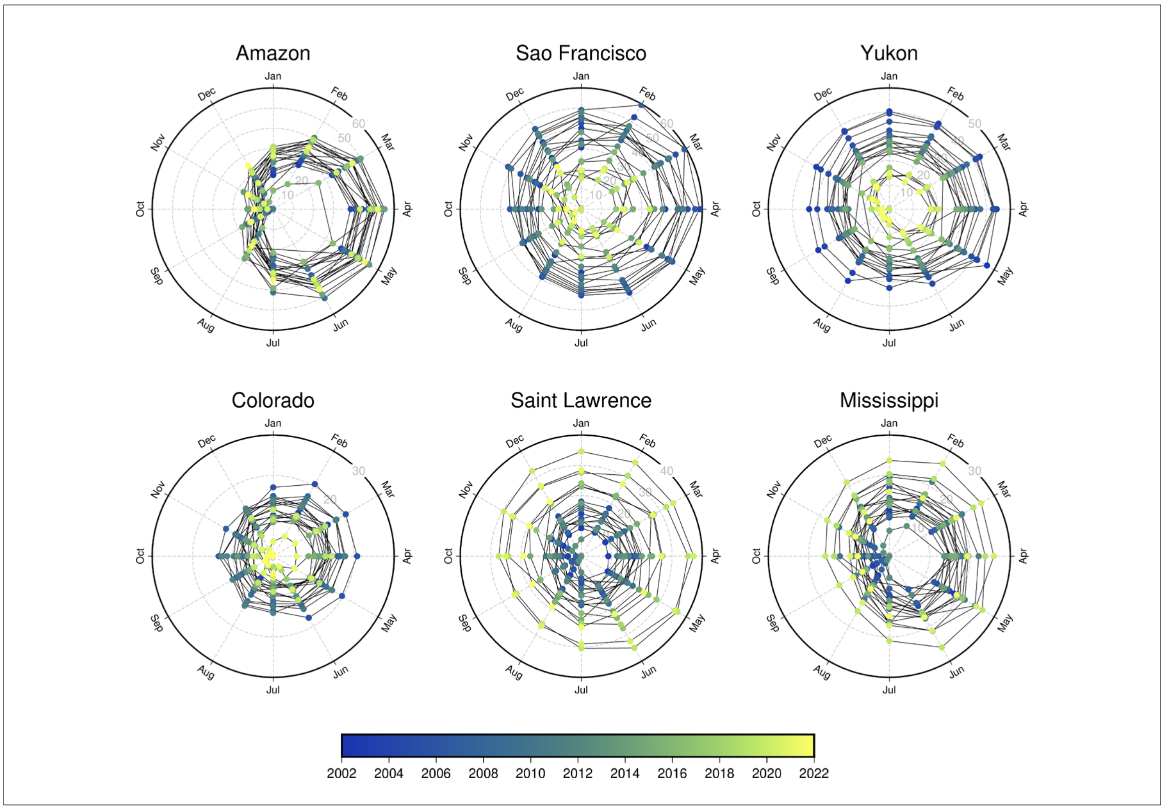


Figure 18. Terrestrial water storage in cm per month for the years 2002–2021 for North and South American river basins the Amazon, São Francisco, Saint Lawrence, Yukon, Colorado and Mississippi

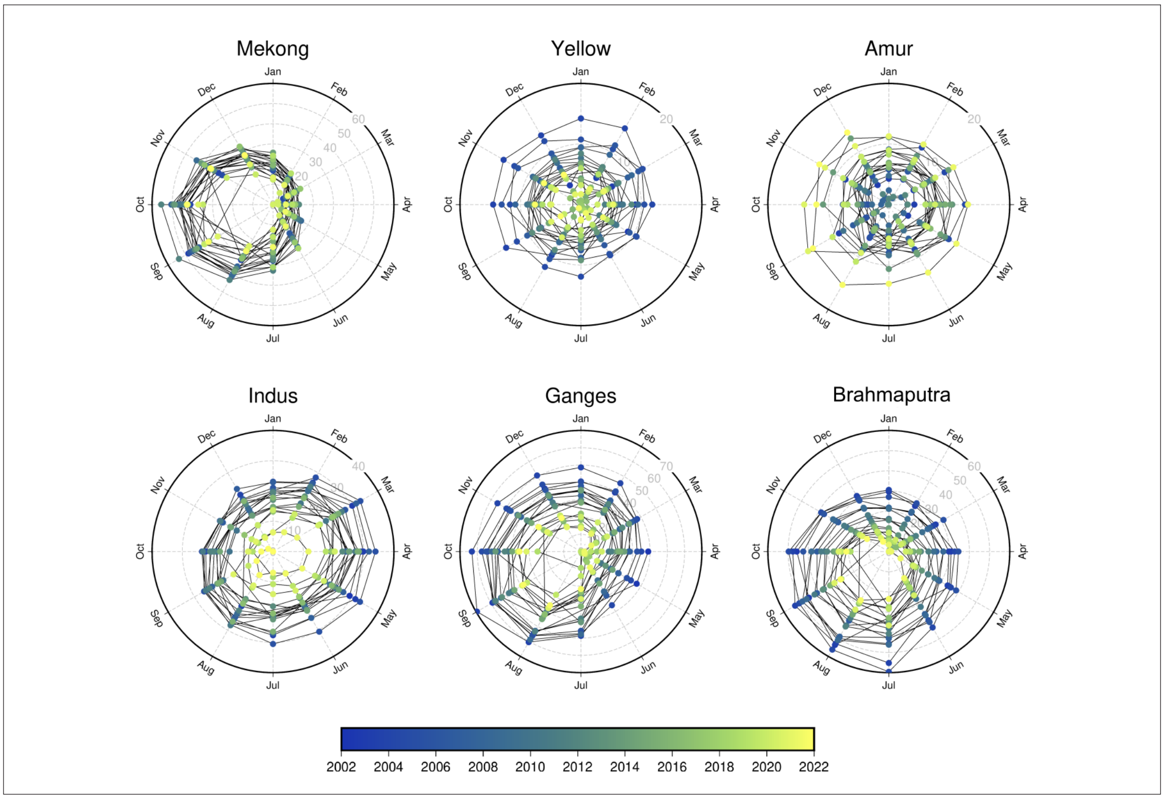


Figure 19. Terrestrial water storage in cm per month for the years 2002–2021 for Asian river basins the Mekong, Huang He (Yellow), Indus, Amur, Ganges and Brahmaputra

High-impact events 2021

Global perspective

The year 2021 was ranked between the fifth and seventh warmest year on record, with the global annual mean temperature of 1.11 ± 0.13 °C above the 1850–1900 pre-industrial average, despite prevailing La Niña conditions. Globally, high spatial and temporal variability in precipitation were observed (*State of the Global Climate 2021* (WMO-No. 1290)). In 2021 there were 432 registered large and medium-scale natural hazard extreme events across the globe.[14] These events caused almost 10 000 deaths, caused more than US$ 250 billion in damage and directly affected more than 100 million people worldwide.[15]

Figure 20 presents a number of notable extreme events in 2021, focusing on floods and droughts, selected from the EM-DAT database[16] and other open sources.

Local perspectives

The present section highlights the high-impact events of 2021. Information on selected events was obtained from resources such as EM-DAT,[17] ReliefWeb and other open data sources, scientific papers, the *State of the Global Climate 2021* (WMO-No. 1290) report, as well as from the NHMSs of Paraguay, Latvia, Myanmar (provided in Annex 2) and India.

Western Europe

In July 2021, several western European countries suffered from floods caused by heavy rain. Especially severe conditions were reported in Belgium and Germany. Extreme rainfall of up to 160 mm in 24 hours resulted in the fast rise of smaller rivers draining the Eiffel highland, such as the Ahr and Erft Rivers (Germany).[18] Hagen (Germany) reported 241 mm of rainfall in 22 hours (*State of the Global Climate 2021* (WMO-No. 1290)). The observed rainfall broke all records registered in this area. In Germany alone, the flood caused 183 deaths and 36 deaths in Belgium (*State of the Global Climate 2021* (WMO-No. 1290)).The damage caused by the flood in Germany was estimated to exceed US$ 20 billion (*State of the Global Climate 2021* (WMO-No. 1290)). Furthermore, Munich Re (2022) estimates that the total damage reached $US 54 billion, of which $US 40 billion was in Germany alone.[19]

China

Several serious floods were recorded in China in 2021, mostly in July 2021. The most impactful event was in Henan province, where in Zhengzhou, the provincial capital, more than 200 mm of rain fell in one hour and 720 mm during the event as a whole (*State of the Global Climate 2021* (WMO-No. 1290)). The event caused the death of more than 380 people

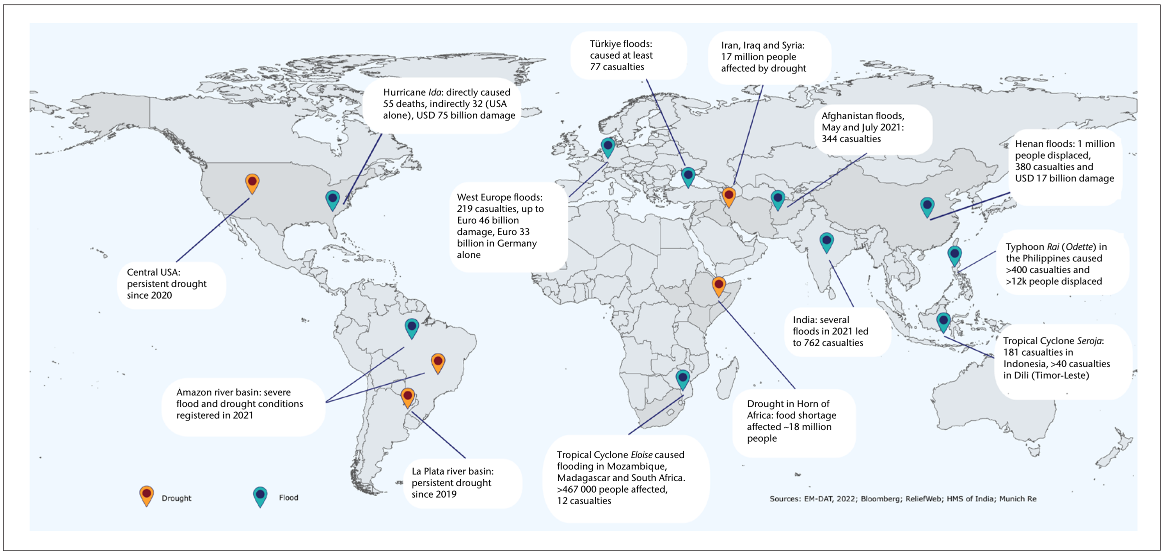


Figure 20. Selected notable hydrological extreme events across the globe in 2021. Pins indicate flood and drought events.

(*State of the Global Climate 2021* (WMO-No. 1290)), displacement of over a million people and more than US$ 17 billion damage.[20]

Afghanistan

A total of six provinces in five regions of Afghanistan were affected by flash flooding caused by heavy rainfall at the beginning of May 2021. These floods caused at least 84 deaths, up to 32 missing people and at least 2 600 residential homes partially or totally destroyed.[21] At the end of July 2021, another flash flood in eastern Afghanistan in the Kamdesh district of the Nuristan province, took the lives of 260 people[22] according to the figures of the Afghan Red Crescent Society, released on 1 August 2021.

Horn of Africa

Ethiopia, Kenya and Somalia have faced several consecutive years with below-average rainfall causing a regional drought. Up to 18 million people were food insecure and more than 7 million children faced acute malnutrition.[23]

Mozambique, Madagascar and South Africa

In January 2021 Tropical Cyclone *Eloise* caused heavy rainfall in Mozambique, Madagascar and South Africa. Subsequent flooding affected more than 467 000 people, and killed up to 12 people.[24]

Amazon

Both flood and drought conditions were reported for the Amazon river basin. The northern Amazon experienced flood conditions in 2021, while the southern and south-eastern Amazon experienced drought conditions. During the flooding, the water level at the Manaus station in Brazil was above 29 m (the emergency threshold), breaking the record of the previous flood of 2012.[25]

La Plata river basin

The severe, prolonged drought experienced in La Plata river basin since 2019 continued over the entire year of 2021. Despite some significant precipitation periods in the region, major rivers like the Paraguay and Paraná Rivers experienced all-time record low water stages in the second half of 2021 (see Annex 2 for further details).

India

Several extreme events, mostly due to heavy rainfalls, were reported in India over the course of 2021. These events led to 762 casualties, with Maharasthra, Karnataka, Andhra Pradesh, Kerala, Madhiya Pradesh, West Bengal and Uttarakand states being the most affected.[26]

USA drought

The western USA experienced a significant, prolonged drought. The period from July 2019 to June 2021 was the driest 24-month period on record.[27]

USA hurricane

Hurricane *Ida* produced widespread rainfall from the Gulf of Mexico along the eastern USA coast to Canada, resulting in major floods in affected areas, including the urban areas of the New York City metropolitan area and New Jersey. *Ida* was the direct cause of death of 55 people and caused $US 75 billion damage in the USA. Another 32 people in the USA alone died as a result of the storm associated with *Ida*.[28]

Philippines

Typhoon *Rai*, also known as Super Typhoon *Odette*, crossed the Philippines in December 2021, ranking among the costliest typhoons there, with significant flooding impacting different parts of the country. *Odette* affected more than 2.3 million people, displaced more than 12 000 individuals,[29] and killed at least 406 people (*State of the Global Climate 2021* (WMO-No. 1290)).

Indonesia and Timor-Leste

Tropical Cyclone *Seroja* hit Timor-Leste and parts of Indonesia in early April 2021, causing flooding in both countries. *Seroja* led to 181 casualties in Indonesia and more than 40 casualties in Dili, the capital of Timor-Leste.[30]

Iran, Iraq, Syria

The water deficit from 2020 in Iran, Iraq and Syria was intensified by a dry and warm boreal winter of 2020/2021, further limiting replenishment of water resources before the summer months. This resulted in a drought affecting large numbers of people: 4.8 million in Iran,[31] and up to 12 million in Iraq and Syria.[32]

Türkiye

On 10–12 August 2021 several provinces in Türkiye on the Black Sea coast experienced one of the deadliest and most impactful floods on record, associated with extreme precipitation. Up to 400 mm of rainfall was recorded within 24 hours in Bozkurt village, causing 77 casualties.[33]

The need for local and global perspectives

The Horn of Africa is mentioned several times in the present report. The mean flow in this region in 2021 was evaluated as below average and drought is listed among the high impact extreme events. On the other hand, winter run-off is ranked as above average. How does that information match up?

The previous year, 2020, was particularly dry in the Horn of Africa, which impacted food production in 2021. December 2020 to February 2021 flows were above average, but this is a typically dry period in the region, with an average of less than 10 mm of precipitation per month. However, the precipitation contributions during these months was inadequate to affect water availability at an annual scale. The rainy season is strongest in April and May over most of the territory, with variable precipitation from June to November, depending on latitude and altitude. In conclusion, all information must be interpreted taking into account the hydrological context/pattern of the specific hydroclimatic region, and the seasonal distribution of rain and flow. Usually, these patterns do not match the calendar year used for global evaluation.

Drought occurrence seems to be in contradiction to the continental TWS increase at the pan-African scale detected via GRACE. This highlights the need for local assessments, as existing large local and sub-regional variability in changes cannot be related to continental trends.

Member NHMSs provide expertise in interpretation and analysis of data for local and regional purposes and a variety of stakeholders.

Cryosphere water resources

General concepts

The cryosphere (glaciers, snow cover, ice caps and, where present, permafrost) is an important natural reservoir of fresh water (the biggest at a global scale), critical for hydroelectric production and operations, for agricultural and industrial water supply, for drinking water for billions of people, and for "sustaining ecosystems and supporting livelihoods in and far beyond the mountain ranges themselves".[34] Mountains are often called natural "water towers" because they provide vital headwaters to many rivers that originate from snow and ice, and other fresh water sources that replenish aquifers. It is estimated that around 1.9 billion people worldwide live in areas where water is supplied by glaciers and snow melt.

Changes to cryosphere water resources have significant impacts on food security, human health, ecosystem integrity and maintenance, and economic and social development. Such changes also cause the emergence of new natural hazards, such as flooding and flash flooding, glacier lake outbursts, droughts, diminished water resources, and ice and land mass flow. On a seasonal to decadal scale, snowmelt and ice melt over land help regulate hydrological run-off (amount, timing and biogeochemical properties) and are critical to regulating water availability and ecosystem services downstream.

Information on current and projected changes in snow and ice, as they relate to water resources, are required at regional and catchment scale, to inform decisions on water management, disaster risk reduction, emergency management, food security and socioeconomic development. At a global level, most major rivers originating from high mountains in mid- to low-latitudes, are snow and glacier fed, as illustrated in Figure 21.

The *Special Report on the Ocean and Cryosphere in a Changing Climate* concluded that "River runoff in snow-dominated or glacier-fed high mountain basins is projected to change regardless of emissions scenario (*very high confidence*), with increases in average winter runoff (*high confidence*) and earlier spring peaks (*very high confidence*)".[35]

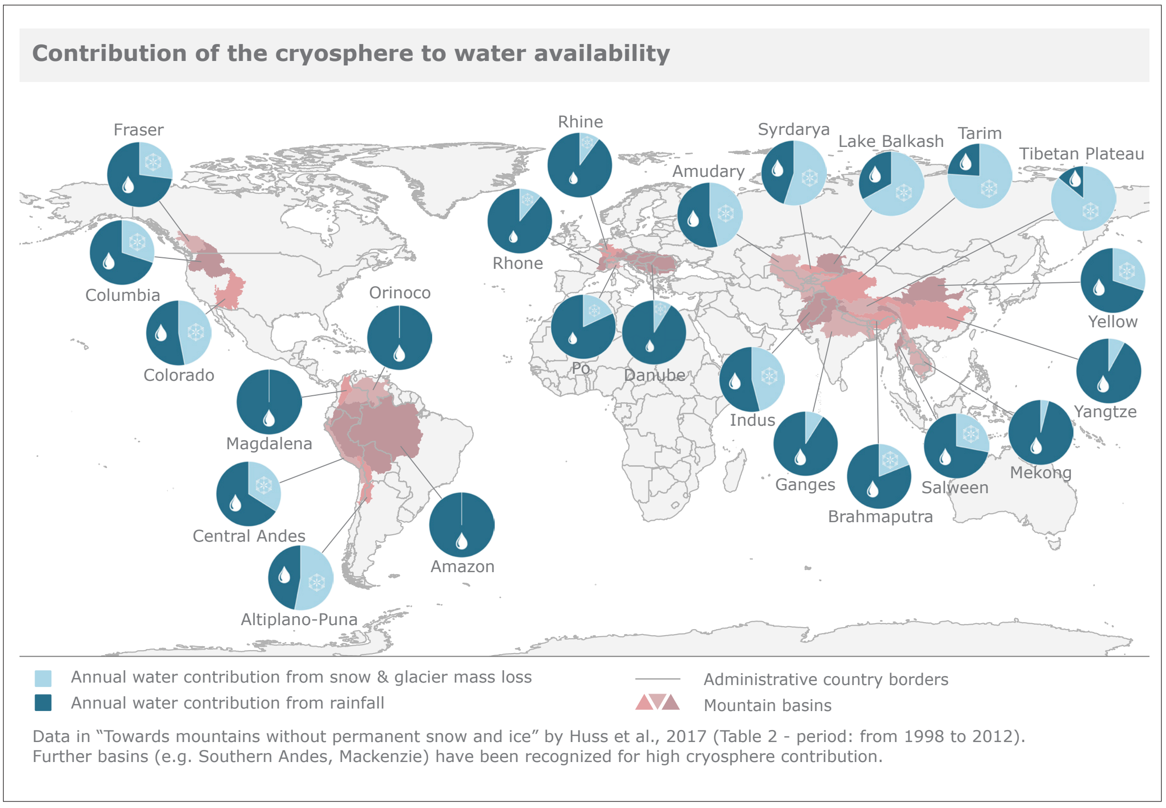


Figure 21. Contribution of the cryosphere to water resources in the basins of major rivers with headwaters in high mountains. ***Source:*** Huss, M.; Bookhagen, B.; Huggel, C. et al. Toward Mountains without Permanent Snow and Ice. *Earth's Future* **2017**, *5* (5), 418–435. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016EF000514, illustration by Nora Krebs (WMO).

The *State of the Global Climate 2021* (WMO-No. 1290) report concluded that in 2021, at a global level, the melting of glaciers continued, with a clear trend towards an acceleration of mass loss on multidecadal timescales (Figure 22).

Factors such as seasonal accumulation of snow, timing of spring snowmelt, long-term evolution of glacier mass balance (accumulation versus loss) under different climate scenarios and their contribution to run-off and groundwater are of interest for understanding cryosphere water resources for snow- and glacier-fed rivers and groundwater resources. With the increased melting of glaciers, the annual glacier run-off typically increases at first, until a turning point, often called "peak water", is reached, upon which run-off declines.[36] The long-term projections of the changes in glacier run-off and the timing of peak water are key inputs to long-term adaptation decisions.

Future assessments in WMO *State of Global Water Resources* reports will provide the incentive to regularly assess changes in the cryosphere and the variability of water resources, at basin and regional level (*State of the Global Climate 2021* (WMO-No. 1290)).

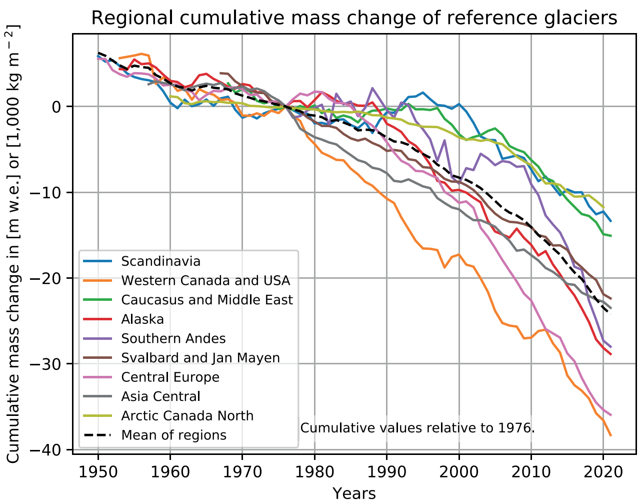


Figure 22. Cumulative glacier mass change relative to 1976 for regional and global means based on data from reference glaciers. Cumulative values are given on the y-axis in the unit meter water equivalent [m w.e.]. ***Source:*** World Glacier Monitoring Service (WGMS). *Global Glacier Change Bulletin No. 4 (2018-2019)*. Zemp, M.; Nussbaumer, S. U.; Gärtner-Roer, I. et al. (Eds.); WGMS: Zurich, 2021. Publication based on database version: doi:10.5904/wgms-fog-2021-05. https://wgms.ch/ggcb/.

Regional examples 2021

Recent snow cover variations in the subtropical Andes

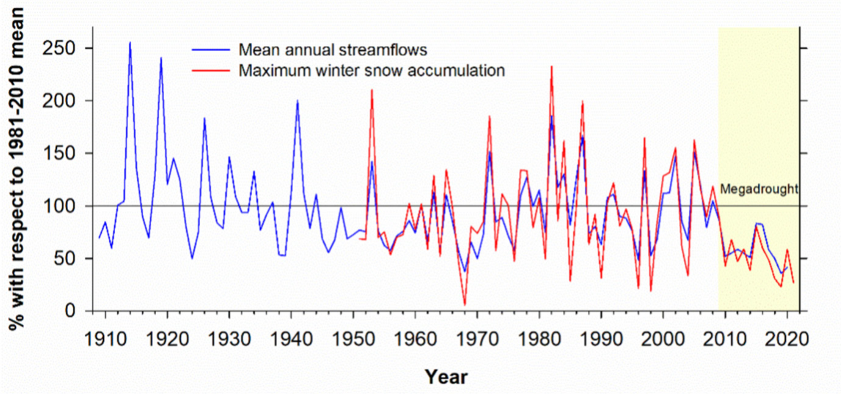
The snow that accumulates each winter in the subtropical Andes represents a crucial water resource for most human activities across central Chile and central-western Argentina. This snow regulates the flows of mountain rivers during the austral spring and summer seasons, and provides the largest volumes of water for recharging the aquifers that are critical for the populated lowland areas on both sides of the Andes.

In Figure 23, a noticeable feature is the sharp decrease in both snowpack and streamflow series starting in 2009–2010, and it has continued since. This persistent dry period has no precedent in the instrumental record. Locally known as the "megadrought", this period has been associated with noticeable water level declines in natural and human-made reservoirs and wells, and with increasing ice thinning rates after 2010.

Glacier changes in Norway

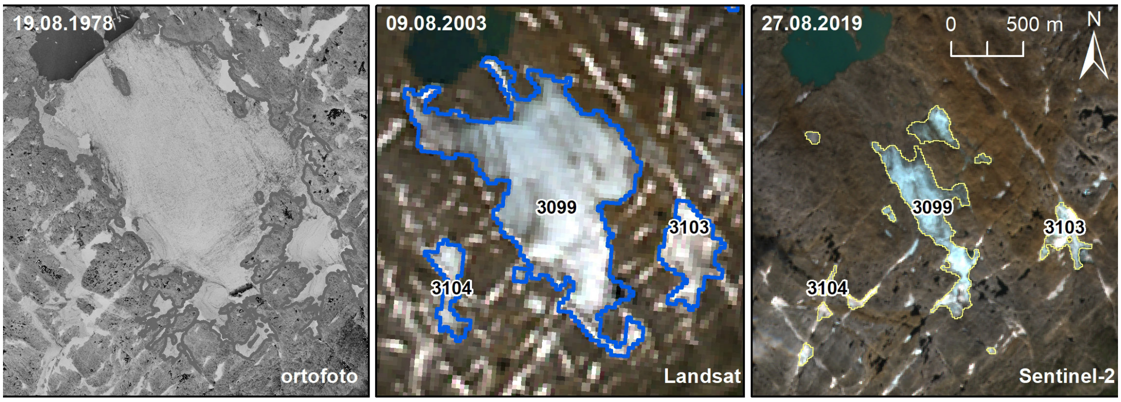
Glacier area in mainland Norway has decreased by 15% from early 2000 to 2018–2019. Breifonn glacier in Rogaland, south-western Norway, is one example of a glacier that has

Figure 23. Regional mean annual time series of maximum snow accumulation in the Andes compared to a regional average of mean annual streamflow records. ***Source:*** Global Cryosphere Watch, updated from Masiokas, M. H.; Christie, D. A.; Le Quesne, C. et al. Reconstructing the Annual Mass Balance of the Echaurren Norte Glacier (Central Andes, 33.5°S) Using Local and Regional Hydroclimatic Data, *The Cryosphere* **2016**, *10* (2), 927–940, https://doi.org/10.5194/tc-10-927-2016, 2016.



shrunk greatly over the last decades (Figure 24).[37] It has disintegrated into several parts and will soon vanish. On the orthophoto from 1978, the glacier had an area of 2.55 km². In 2003 the glacier had disintegrated into three parts, with a total area of 1.65 km², and in 2019 the glacier had disintegrated further with a total area of 0.42 km².

Figure 24. Changes to Breifonn glacier in Rogaland (1978 to 2018–2019). ***Source:*** Andreassen, L.; Nagy, T.; Kjøllmoen, B. et al. An Inventory of Norway's Glaciers and Ice-marginal Lakes from 2018–19 Sentinel-2 Data. *Journal of Glaciology* **2022**, 1–22. https://dro.dur.ac.uk/35938/.



Glaciers in Central Asia

There are around 28 000 glaciers in the Tien Shan and Pamir mountains which are an important source of fresh water for the Central Asian region.[38] Ice melt and snowmelt are principal water resources for the highly populated lowlands of Central Asia, for example, for agricultural, domestic and industrial use.[39]

Tajikistan

The Zeravshan glacier in Tajikistan, with its complex structure and difficult access, is an example of the urgency of monitoring campaigns. Surveys conducted by the Agency for Hydrometeorology of the Republic of Tajikistan for the Zeravshan glacier in 1979, 1991, 2009 and 2019 have shown significant melting and receding of the glacier of around 2.04 km³ of its volume in the last 40 years. A similar declining tendency has been observed for the Kasholayah and Khirson glaciers in Tajikistan (see Figure 25).

Uzbekistan

A survey conducted by the National University of Uzbekistan named after Mirzo Ulugbek (NUU) regarding the Barkrak glacier, western Tien Shan, shows that glacier mass balance in 2020–2021 decreased by 67 cm, which is more than three times higher than the previous year and the largest decrease in at least the last five years (Figures 26 and 27).

Figure 25. The upper part of the Khirson glacier transit area in 2021. ***Source:*** Agency for Hydrometeorology, Committee on Environmental Protection, Government of the Republic of Tajikistan.

Figure 26. The Barkrak glacier in 2021, Pskem river basin, western Tien Shan. ***Source:*** Gulomjon Umirzakov, National University of Uzbekistan named after Mirzo Ulugbek.

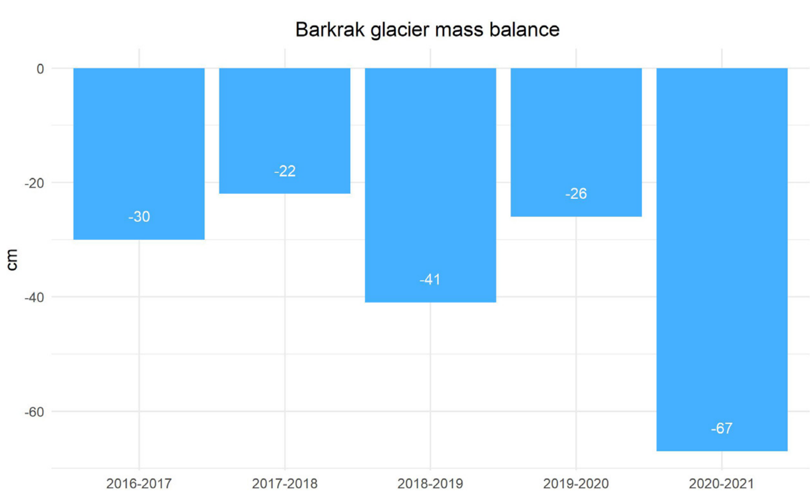


Figure 27. Barkrak glacier mass balance from 2016 to 2021. ***Source:*** Gulomjon Umirzakov, National University of Uzbekistan named after Mirzo Ulugbek.

Conclusions

Despite an increase in hydrological data sharing in recent years, significant challenges remain regarding the availability of verified hydrological data for the assessment of water resources availability on a global scale on a regular (annual) basis.

The present report must be understood as an initial report demonstrating the possibilities for facing this challenge through the successful application of both hydrological models and satellite data for the global overview, and verification with observations whenever possible. At the same time, the report demonstrates the critical role and value of observational data for producing more detailed regional and national water assessments to provide a better understanding of local impacts on nations and communities.

Validation of the modelling results for the year 2021 was only possible in some areas, where the observed discharge data were available. Discharge rankings for the year 2021, obtained from Global Hydrological Modelling Systems (GHMS) and observed data, showed good agreement in some regions (such as Paraguay, Myanmar and Guatemala) and poor agreement in others (such as Latvia). The heterogeneity in the results points out the necessity to improve both the performance of the models, and access to the observed discharge data, in order to achieve better modelling results and validations for the next editions of the report.

It is important to mention that the selection of the historical period of discharge data, 1991–2022, might have influenced the results in this report. This is because water resources might already have been impacted by climate and anthropogenic changes during that period. It is unfortunately not possible to select earlier periods for comparison, as the availability of hydrological data is often scarce.

For 2021, a greater proportion of the Earth's surface belonged to basins that reported below- to much below-normal annual discharge at their outlets than to basins exhibiting above-normal discharge. However, the global overview shows significantly scattered patterns, with neighbouring areas often reporting opposite categories. Case studies from basin-scale assessments demonstrate additional information, which can be obtained from observed discharge data. For example, the Paraguay River experienced an extremely dry year, with its annual exceedance curve dropping below the range of historical data for most of its course and breaking the all-time lowest daily discharge value (compared to values in the last 30 years); the usually high austral winter flow was also absent.

The mapping of terrestrial water storage (TWS) based on GRACE satellite data represents another way to assess water resources at the global and continental scales. Its assessment for 2021 generally agreed with data from GHMSs. TWS time series from 2002 onwards also provide insights into the location of large-area hotspots of increased or decreased water storage; such hotspots include some polar and some high-mountain areas, where melting glaciers likely contribute, among others, to observed trends. Groundwater over-abstraction for irrigation is another possible contributor to hotspots with negative trends in TWS.[40]

The present report includes information about glacier assessments, confirming a need to systematically interpret results of snow cover and glacier change in terms of water resources at the basin level, to support decisions on water management.

In 2021, all regions experienced significant hydrological extremes in the form of floods and droughts, having substantial impacts on communities, including numerous fatalities. Record-breaking floods were observed in western Europe and in the northern Amazon. At the same time, the Paraguay and Paraná Rivers experienced all-time record low water levels.

While providing a general overview of variability in anomalies of the global distribution of terrestrial water resources in 2021, information from this report cannot be used to interpret patterns in the change of water resources at national and local levels. Therefore, detailed insights based on observational data are necessary. Hydrological data are usually gathered and assessed by National Hydrological Services and/or other water resources institutions at the national or subnational scale. Unfortunately, hydrological observation networks in many parts of the world do not receive sufficient finance to ensure their sustainability and guarantee high-data quality for assessments that are critical for society.

WMO is committed to gradually enhancing the annual *State of Global Water Resources* report by encouraging its Members to share quality-controlled data at the global level. Based on the findings of the present report, the following actions are recommended:

- Invest in filling the capacity gap in collecting data for basic hydrological variables and assessment of hydrological status, including cryosphere, at the country level;
- Increase sharing of hydrological data at the international level;
- In line with the UN Secretary General's call for Early Warning Systems for all by 2027, accelerate development of end-to-end drought and flood early warning systems for reducing the impact of hydrological extremes on people, lives and livelihoods, ecosystems, and the economy at large in all parts of the world;
- Continue working together as a global hydrological community on developing the annual *State of Global Water Resources* report to support global understanding, policymaking and planning towards implementing the WMO Vision and Strategy for Hydrology as a support to achieving the Sustainable Development Goals.

Annexes

Annex 1. Technical Brief

Annex 2. Examples of extreme event assessments from NHMSs

List of acronyms

DJF: December–January–February

GHMS: Global Hydrological Modelling Systems

GRACE: Gravity Recovery and Climate Experiment

GRDC: Global Runoff Data Centre

HydroSOS: Hydrological Status and Outlook System

JJA: June–July–August

NHMS: National Hydrological and Meteorological Services

SDG: Sustainable Development Goals

SON: September–October–November

TWS: Terrestrial Water Storage

WHOS: WMO Hydrological Observing System

WMO: World Meteorological Organization

Endnotes

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