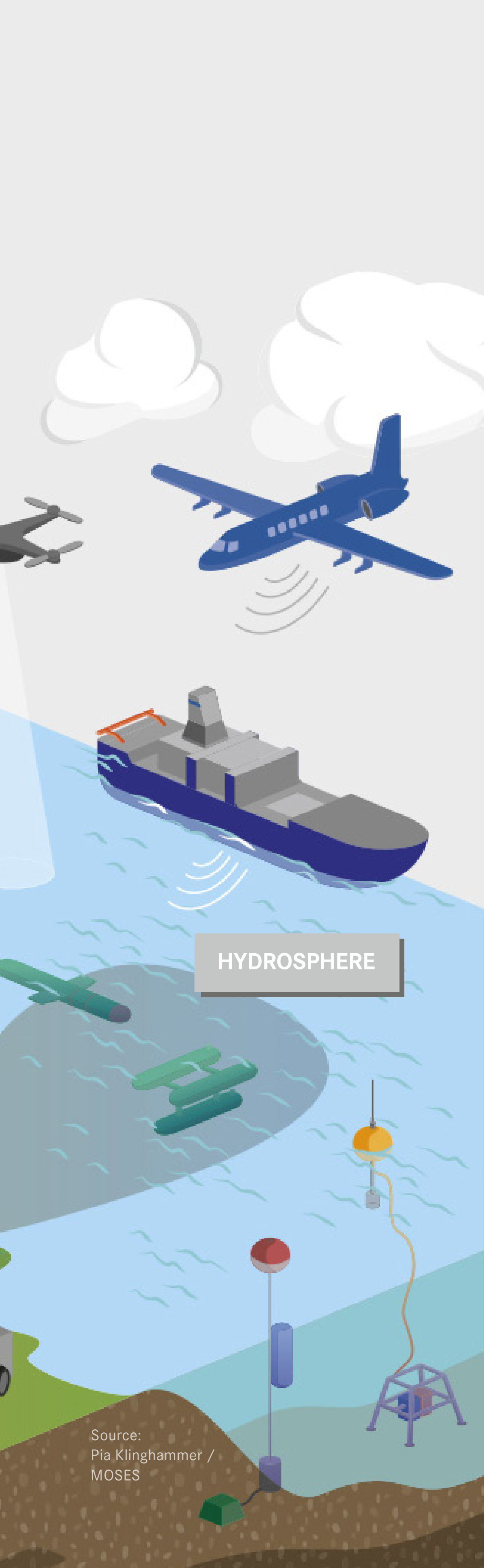
MOSES – IN THE RIGHT PLACE AT THE RIGHT TIME

Climate change is affecting our environment – and that will have consequences. Permafrost soils are thawing and releasing greenhouse gases, while extreme weather situations like heat waves, droughts and heavy rain are on the increase. These highly dynamic events are impacting our planet and environment, permanently and over large areas. But where exactly, to what extent and with what consequences? Helmholtz researchers intend to close gaps in our knowledge with the MOSES observation system. It consists of flexible and mobile modules designed to investigate the interaction of short-term events and long-term trends in earth and environmental systems. Still under construction, it is being prepared for operational deployment. The plan is for MOSES to go online by 2022.



In mid-May 2019, Storm Axel brought continuous rain and storms to southern Germany. In some areas of Upper Bavaria, there was the same amount of precipitation as there would normally be in one month. In Weilheim-Schongau district, the river Ammer broke its banks and fields were flooded. It was just at this time that researchers from several German research institutions had come together for a joint observation right at the heart of the affected area, in Fendt near Peißenberg. Their plans were to test how they could analyse the land-atmosphere exchange processes in the soil, vegetation and air caused by heat waves and drought. In this context, they were in particular testing the interaction between mobile sensor systems that can be used to identify decisive indicators for these processes, such as the greenhouse gas balance, soil moisture, biomass and air quality. But instead of sunshine and spring-like temperatures, it was suddenly "mind the floods" along the Ammer. The observation concept was adapted to the new situation within a few hours. The measuring systems that had actually been set up to test their deployment in heat and drought were recording the impact of a different kind of extreme weather instead: heavy precipitation. Such flexibility is one of the main hallmarks of the MOSES (Modular Observation Solutions for Earth Systems) observation system.

MOSES brings together the skills and expertise of the Helmholtz Centres

Nine research centres of the Helmholtz Association have been working together since 2017 to build up the MOSES research infrastructure, coordinated by the UFZ in Leipzig. By 2022, Germany's largest non-university research foundation will have invested 30 million euros into providing answers to urgent questions on the long-term development of earth and environmental systems: What is the impact of short-term dynamic events such as heat waves, heavy rain or droughts? What happens when extreme weather conditions become more frequent due to climate change and ecosystems lack the time to recover? How do ocean eddies influence marine energy transport and food chains? What amount of atmospheric greenhouse gases is released during the thawing of Arctic permafrost soils?

MOSES focuses on four types of event selected on the basis of their relevance to climate and environmental changes and their socio-economic impact: heat and drought, extreme hydrological events, ocean eddies and the abrupt thawing of permafrost. The objective is to build up an infrastructure that

Modular Observation Solutions for Earth Systems

With MOSES (Modular Observation Solutions for Earth Systems), the Helmholtz Association is building up a flexible and mobile measuring system for Earth and environmental observation, scheduled for completion by 2022. Germany's largest non-university research organisation is investing approx. 30 million euros from federal and state funding in the creation of MOSES, reinforcing its leading role and visibility in international Earth system research.

Nine research centres are involved in building up MOSES:

- Helmholtz Centre for Environmental Research – UFZ (Coordination)
- Karlsruhe Institute of Technology (KIT)
- Forschungszentrum Jülich (FZJ)
- Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences
- GEOMAR Helmholtz Centre for Ocean Research Kiel
- Helmholtz-Zentrum Geesthacht Centre for Material and Coastal Research (HZG)
- Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI)
- Helmholtz Zentrum München – German Research Center for Environmental Health (HMGU)
- German Aerospace Center (DLR)

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captures as fully as possible the direct impact of such events on earth and environmental systems. In concrete terms, this would mean, for example, recording the course of heavy rain as a potential extreme hydrological event and investigating the conditions that lead to flooding in the region affected. The vision is for researchers to be able to track the event with all its effects on the river right down to the sea – from its origins in the atmosphere through to the reactions of the biosystems.

> "To be able to assess what an extreme situation is, we have to know what normal is," says project coordinator Ute Weber.

To succeed in doing so, the MOSES researchers need sensor and measuring systems that meet the specific requirements. These are, however, not available for purchase "off the shelf". For this reason, the researchers intend to put together their own modular system consisting of existing measuring systems from the Helmholtz centres and newly developed technologies and stand-alone devices. Refining the equipment for mobile, flexible and rapid deployment and interlinking the individual units is one of the central tasks over the development phase for MOSES that runs until 2022. "This 'system of systems' will put us in a position to capture highly dynamic events at the right time and in the right place in a previously unknown spatial and temporal resolution," says MOSES project coordinator Dr Ute Weber, summarising the objective of the project. However, not only coordinated development and systematisation of both content and technologies are required; cooperation with observation platforms and networks focusing on long-term environmental observations and that already have collections of data series, gathered continually over many years and decades, is also necessary. "To identify an extreme, we have to know what normal is," she says. Expressed in scientific terms, this means that you need to know how the system behaves over a long timeframe. The long-term observatories cooperating with MOSES include the TERENO network of Helmholtz observatories that examine the long-term impact of global change on terrestrial environmental systems in four very different regions in Germany, the COSYNA coastal observatory, ICOS, the European research infrastructure for quantifying the greenhouse gas balance, and the worldwide LTER network, which focuses on long-term ecosystem research.

Modular MOSES system

The measuring and sensor equipment is provided on the basis of a modular system, involving a total of eleven specialist modules. They cover all compartments – from the sea (blue) via the land (green) through to the atmosphere (grey) and can be flexibly deployed for a range of different events in a range of different regions. They are supplemented by an aircraft-based Tandem-L system from the German Aerospace Center (DLR).

MOSES Modules	Helmholtz centres involved	heat and drought	hydro-logical extremes	ocean eddies	perma-frost
Ocean	GEOMAR, HZG		o	o	o
Underwater observation nodes	AWI, GEOMAR, HZG		o	o	o
Coast	AWI, GEOMAR, HZG		o	o	o
Permafrost	AWI, GEOMAR, GFZ	o	o		o
Current and sediment dynamics	AWI, GFZ, UFZ	o	o		o
Water quality	UFZ, GFZ	o	o		
Water resources	GFZ, FZJ, UFZ	o	o		o
Vegetation	UFZ, KIT, FZJ, HMGU	o	o		
Land-atmosphere exchange	KIT, FZJ, UFZ, GFZ	o	o		o
Atmospheric dynamics	KIT, FZJ	o	o		
Atmospheric chemistry	KIT, FZJ	o	o		o

Elaborated logistics and organisation, worked out in every detail, are of no less importance: information chains need to be established, a wide range of measuring devices need to be transported from the research centres to where they are needed and be set up, data communications have to be organised, authorities informed, human resources made available. There is not much time for all this when an event is already happening: the early warning times for deployment in the event of heat and drought amount to a few weeks, in the case of heavy rain and flooding as little as only a few days. “This means that it is vital for planning to run like clockwork,” says Ute Weber, emphasising the challenges. The necessary teamwork and interaction does not run smoothly from one day to the next and certainly cannot be solved in a purely theoretical approach. For this reason, around ten test campaigns are planned for the development phase. These will become increasingly refined over time until all processes involved in the four types of event are fully covered.

Heavy rain in the Ore Mountains and the Alpine Foreland

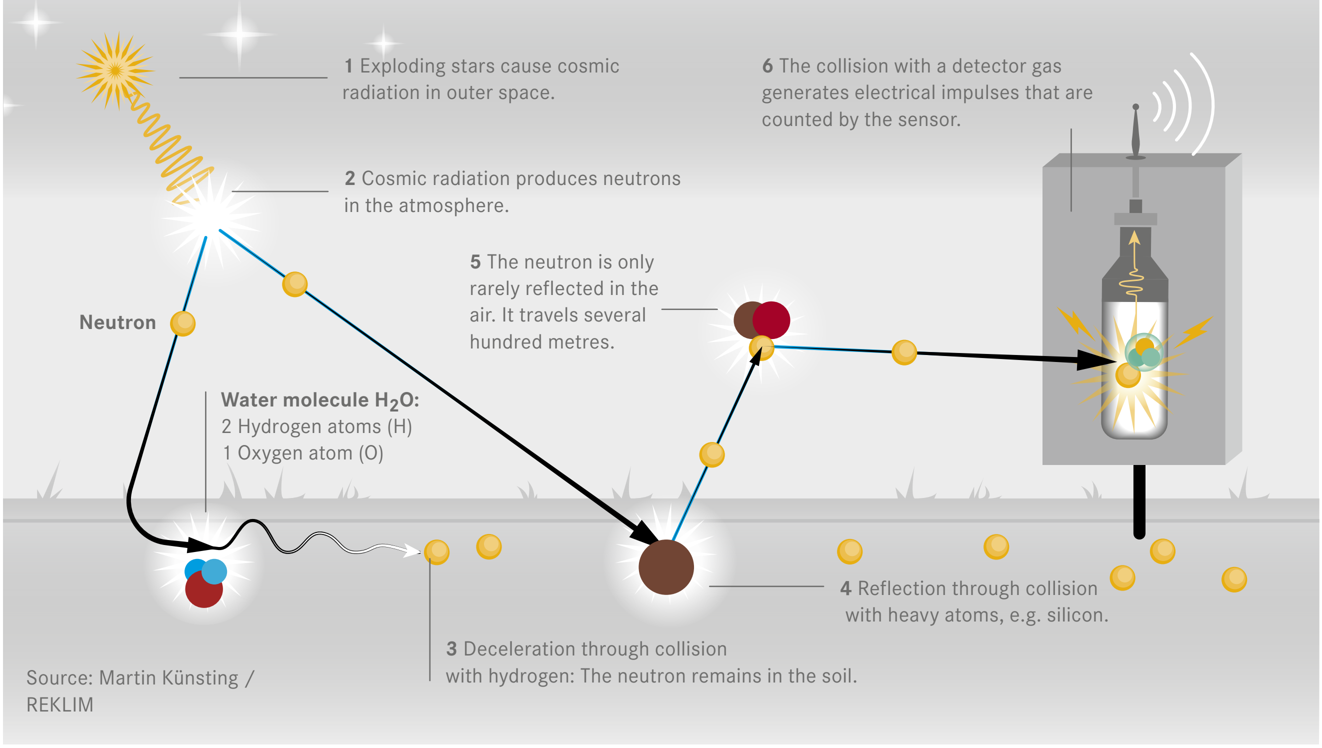
Heavy rain has consequences – not only for the region in which it falls and possibly causes flooding, but for the entire length of the river, the soil, the groundwater and the coastal region in which the river ultimately flows into the sea. This is one of the four chains of effects that the MOSES consortium intends to investigate. The chain begins with the development of heavy rain and the formation of

run-off through to flooding. In spring 2019, the Helmholtz researchers set up their mobile measuring devices in Müglitztal in the Ore Mountains, where in 2002 the little Müglitz river had swollen into a torrent, for this very reason. The researchers registered six instances of heavy rain over their three-month deployment, using various measuring techniques to investigate these events.

The meteorologists headed by Prof Christoph Kottmeier of the Karlsruhe Institute of Technology (KIT), for example, were primarily interested in how heavy rain comes about. “With regard to the volume of air above the measuring location, we used our LiDAR and radar technology to record the distribution of precipitation in the troposphere, at an altitude of up to ten kilometres and at a distance of up to 100 kilometres. Balloon probes, which can rise to a height of 35 kilometres, were used to investigate the influence of thunderstorms. Using water vapour, ozone and cloud instruments, researchers analysed in particular the transport of trace gases caused by the thunderstorm into the Earth’s atmosphere. Gravimeters constantly monitored the groundwater reserves, while pressure and flow sensors recorded water levels and flow rates in the Müglitz and its tributaries. In addition, cosmic ray sensors measured soil moisture. “Soil moisture is a central parameter in the run-off of rainwater. If the soil is very wet or very dry, the rainwater runs off directly over the surface of the land and flooding arises more quickly,” Ute Weber explains.

In the case of the test campaign in Fendt in Upper Bavaria triggered by Storm Axel mentioned at the beginning, where the main issue related to the impact of the heavy rain within the area under investigation, soil moisture also played a key role. Three different procedures were tested for their ability to record the development of soil moisture during and after the precipitation. Firstly, the MOSES researchers installed a 100 by 100 metre sensor network capable of measuring global radiation at the Earth’s surface, which is vital for calculating evaporation, as well as soil moisture and temperature at several positions at three different depths at the same time. Secondly, they once again deployed cosmic ray sensors in order to measure the soil moisture in a radius of 150 metres and at a depth of up to 50 centimetres – using a stationary system of 20 small masts spread over a square kilometre and a mobile system based on off-road vehicles to cover a larger area of many square kilometres.

— Alongside equipment for measuring soil moisture, the researchers also tested the deployment of hyperspectral cameras in order to measure the soil temperature and the state of the vegetation among other factors during their time in Fendt in Upper Bavaria. In the next campaigns, these cameras will be installed in aircraft and data collected from the air.



— Cosmic ray technology is essentially based on a detector counting the number of neutrons in the air that are created by the entry of cosmic rays into the Earth's atmosphere. These particles also penetrate into the soil but they are mostly reflected back into the air. If, however, they hit hydrogen atoms, their speed is strongly reduced and they no longer make it back to the Earth's surface. As water contains two hydrogen atoms, a neutron counter can be used to measure the soil moisture.

— It was possible to go for a walk on the Domfelsen, a sandstone formation in the Elbe in Magdeburg that is only visible during low water, right out into the middle of the river – already for the second year in a row.

Low water in the Elbe

Similar to heavy precipitation, too little precipitation and heat waves have consequences not only for the region immediately impacted. These can be tracked along a chain of effects along rivers through to the sea. This was visible in many places last summer, on the river Elbe for example. At the Strombrücke measuring point in Magdeburg, the low water record from 2018 of 46 centimetres was once again reached at the end of July 2019; that is around 40 centimetres less than the mean low water between 2006 and 2015.

But what is the effect of such extreme low water on water quality? This question was at the focal point of the "low water" MOSES test campaign in August 2019. UFZ researchers and technicians travelled down the Elbe on their research vessel, the ALBIS, covering 580 kilometres in nine days – from the Czech border at Schmilka to Geesthacht near Hamburg. They stopped off at 24 locations to take water samples from near the right and left banks and in the middle of the Elbe. More than 800 samples were collected over this period. These are currently undergoing comprehensive analytical procedures at the UFZ's laboratories, primarily with regard to nutrients and pollutants as well as algae and other micro-organisms. Such detailed measurements at a distinct low water lever are unique to date. "This data helps us to understand the mass balance of the running water in an extreme situation and to derive prognoses for the future," explains UFZ water ecologist Prof Markus Weitere. Along the entire route, the researchers used multiparameter probes to measure other important water quality parameters such as the temperature, the oxygen content, the pH value, the phytoplankton concentration and the turbidity of the water.

The high water temperatures of more than 25 degrees, for example, caused problems especially for migratory fish such as the Atlantic salmon. In contrast, other species benefited from the warmer, more algae-rich and slower-moving Elbe: the Asian clam, for example, saw strong proliferation. It is currently impossible to say conclusively whether this invasive species of clam will take on a dominant position and thus compete with native clams for living space, says Markus Weitere. This will also depend on factors such as the frequency at which such periods of heat and drought occur in the future, their duration and the trend in winter temperatures.

It is also possible to draw some conclusions about phytoplankton concentrations along the course of the Elbe. Why is that important? Single-celled algae floating in the water serve as food for many species of animal and, at the same time, they absorb nutrients such as phosphate and nitrate. This means that moderate algae growth can have a positive impact on bodies of water. In contrast, excessive algae growth leads to a decline in the water quality and eutrophication. Therefore, the right balance is essential and that can quickly be destroyed by extremely low water levels. The measurements taken so far in the MOSES campaign now reveal that the phytoplankton concentration continually increased downriver; at the same time, the concentration of dissolved phosphorus decreased to zero. “This means that the phosphorus was completely consumed by the algae, which was consequently the factor limiting their growth,” explains Weitere. This, he adds, is an important finding for the management of river systems. It shows that a reduction in nutrient input can contribute to reducing algal blooms even in low water situations.

Transportation of nutrients into the North Sea

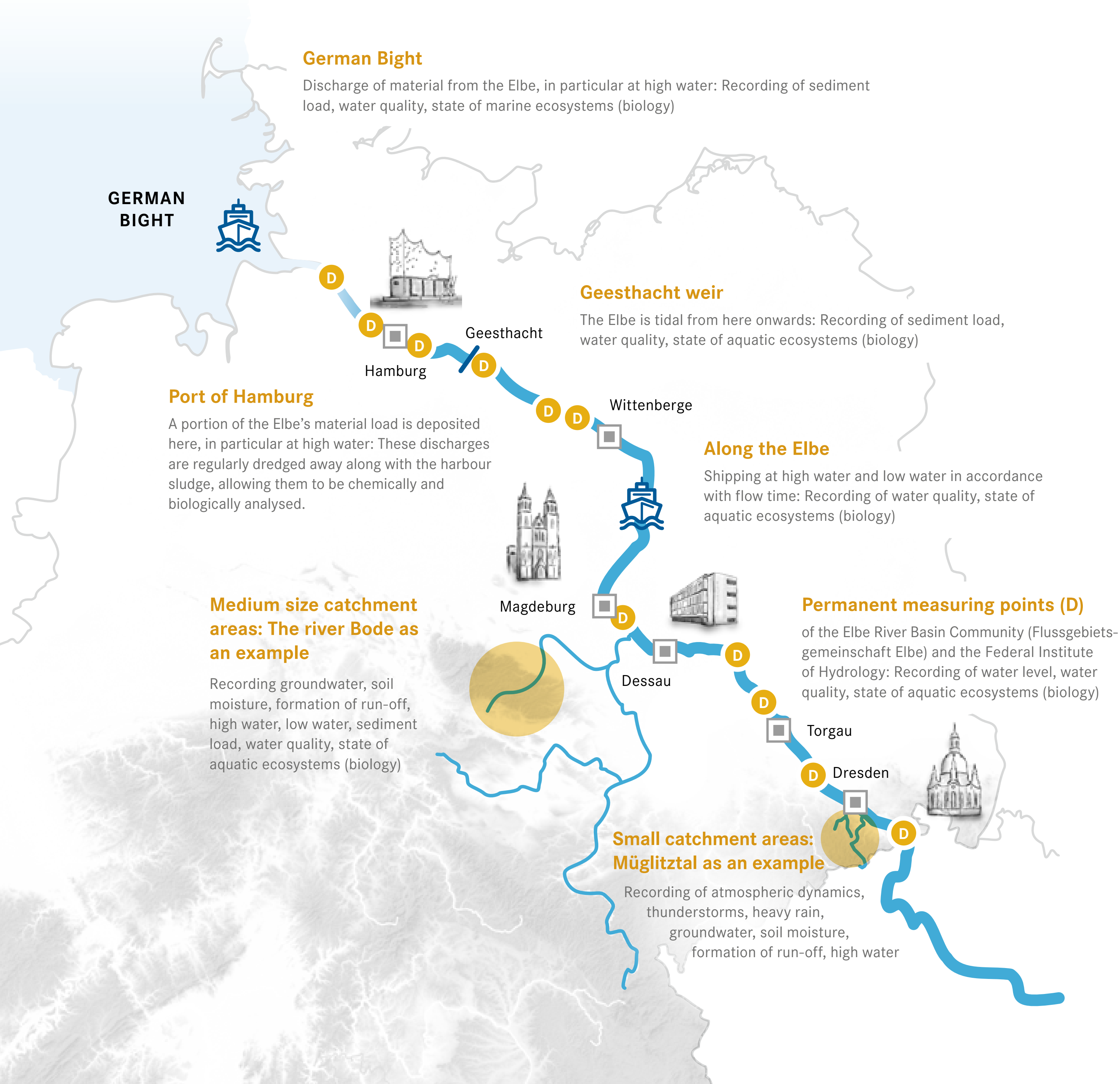
Irrespective of whether the Elbe is carrying small or large amounts of water, it flows into the North Sea, bringing it to the attention of the MOSES coastal researchers. They examine the material load the Elbe sweeps into the sea – at low water and at high water. This load includes nutrients, organic material such as algae and bacteria, pollutants and sediments. Dr Holger Brix of the Helmholtz Centre in Geesthacht can still easily recall the impact of the Elbe floods in the early summer of 2013 when algal blooms arose at several locations near the coast as a consequence of the large nutrient load. “These pulse-like discharges from a flood wave may promote the growth of phytoplankton, which in turn can change the food available to fish,” says Brix, describing an important chain of effects.

Generally speaking, the North Sea, just like the Elbe, is to a certain extent adapted to extremes. “But if changes in climate and land use result in a different environment, for example through more frequent high and low water events, the rise in the sea level or overfishing, the existing system may suffer irreparable damage,” says Brix. “To be able to define such scenarios and compute them in a numerical model, however, we first have to understand how the system works.”

— A great number of the new test devices were tested for the first time in mobile and combined operations as part of the MOSES test campaigns undertaken in 2019. Among other things, mini-balloons tracked heavy rain and thunderstorms into the stratosphere (a); drones were used to measure greenhouse gases (b); at ground level pollen and aerosol measuring devices were deployed (c); multiparameter probes provided information on water quality (d); gravimeters observed the groundwater reserves (e); coastal researchers used autonomous measuring systems such as “gliders” that automatically follow specified routes and are able to measure a wide range of parameters (f).

The Helmholtz coastal researchers have undertaken three test campaigns on their research vessels between the mouth of the Elbe and Heligoland within the framework of MOSES. Just like their UFZ colleagues on the Elbe, they used these trips to measure general water quality parameters and analyse water samples with regard to changes in the load of nutrients and pollutants. The main aspect of the measuring campaigns, however, centred on tracking the path of a potential Elbe high water and optimising the measuring concept to meet this challenge. For this purpose, the researchers used their computer models to generate a forecast of the flow of currents in the German Bight. “This is important because, on the North Sea coast, not only the tides but also the background current

2020 hydrological extremes test campaign



are responsible for the spread of the Elbe's efflux," says Holger Brix. They subsequently went out on two research vessels to discover the Elbe's water body and its extent on the basis of the material load it carries. While the measuring equipment on the ships collected data on a continual basis, the Helmholtz researchers taking part in the campaign on land simultaneously modelled the prevailing flow of currents which they used to guide the vessels into the anticipated destination area of the Elbe's efflux.

To ensure that cooperation between the MOSES researchers does not run into any difficulties in the event of high water on the Elbe, procedures such as these must become routine. For this reason, the three test campaigns were not only used to test the sensor systems and collect scientific data. They were primarily intended to test the mobile taking of measurements and online communications between the vessels and land-based stations and uncover any weak points that in a real scenario might jeopardise measurements that can never be repeated. If there were to be a real-life case of extreme high water on the Elbe, the researchers on the coast might have at least a week's time before the water in the Elbe flows into the North Sea. "But then everything must work perfectly," says Holger Brix.

2020 MOSES dress rehearsal

But what actually happens with the data collected by the MOSES researchers? Along with the long-term data of the observatories and satellite data, it forms the observational basis upon which the researchers can develop scenarios for the future. Here again, the challenge arises from observation of the ongoing processes across systems. For this reason, the researchers couple together the various model approaches. Only by doing so are they able to analyse and better understand the effects of dynamic events and the interactions they trigger between atmospheric, hydrological and terrestrial earth and environmental systems. At the same time, the results of the computer models are required to adjust the deployment and the design of the MOSES observation system to the anticipated events.

To ensure the success of this approach, the data first has to be processed in such a way that it can be made available as easily accessible, long-lasting data products that can be used in a variety of ways (FAIR principle). Consequently, the researchers are currently working on a joint portal for the metadata, the prototype of which is scheduled to go online in the coming year. Interested researchers can use it to search for specific key words; the search result takes the form of a link to the desired data. But MOSES wants to achieve more. In future, the objective is for data collected in an ongoing campaign to be made available virtually in real time to all partners involved. A tool of this kind would also help to adapt and refine the method of measurement-taking on an ad hoc basis. The researchers are currently selecting the variables that might be necessary to manage a campaign in real time. They intend to present solutions to this problem by the end of 2021.

But that is still in the far future, however. In contrast, the "hydrological extremes" test campaign is already on the horizon (see illustration on the left). In the coming year, under the coordination of the UFZ, the seven Helmholtz Centres involved will test the deployment of their measuring and sensor systems, from Müglitztal along the Elbe into the North Sea. The individual activities for this year will then be brought together in one overarching measurement campaign. In terms of organisation and logistics, this means significantly more: more measuring equipment because the majority of new measuring systems will be ready for deployment by that time, more data being collated from the atmosphere, the land surface, the rivers and the coast, and the involvement of more people. The period of deployment will also be extended to six months, from April to September. Over this time frame, there is a realistic chance of being able to rehearse the test deployment under real-life conditions. "This campaign is intended to show how cooperative research can succeed from 2022 onwards thanks to coordinated logistics and functioning measurement systems to allow us to be quickly on the spot during extreme events such as heat and drought, heavy rain or flooding and to be able to investigate the long-term impact on our environmental systems," says Ute Weber. It would be impossible, she adds, for one individual institution to build up or operate such an infrastructure.

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BENJAMIN HAERDLE, SUSANNE HUFE / UFZ

Dr Ute Weber
MOSES project coordinator

ute.weber@ufz.de

IMPRINT

Editor
Helmholtz Centre for Environmental Research – UFZ
Permoserstraße 15 · 04318 Leipzig · Germany

Phone +49/341 / 235 -1269 · info@ufz.de · www.ufz.de

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Susanne Hufe, Benjamin Haerdle and Doris Wolst /
UFZ-Press and Public Relations

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ARTKOLCHOSE GmbH – Die Markenagentur

English Translation
oneword GmbH
Otto-Lilienthal-Str. 36 · 71034 Böblingen

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