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IMPROVING PREDICTIONS AND MANAGEMENT OF HYDROLOGICAL EXTREMES

Synthesized results for policy and decision makers

IMPREX has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 641811.

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INTRODUCTION OF BROCHURE

Water is a vital natural resource and, as such, an integral part of our environment and climate system. Excessive water exposure during flood conditions and water scarcity during droughts pose fundamental risks to life and weaken socio-economic resilience. **Present day water management in many sectors has to be able to cope with extreme hydrological conditions.**

In addition, the impacts of global warming on water resources have become a matter of grave concern to water resource managers and decision-makers. Water is the primary medium through which the effects of climate change on people's lives are directly felt. We are experiencing large-scale and gradual changes in climate systems such as rising sea levels or the gradual depletion of hydrological buffers and weather extremes that lead to increasing flood and drought risks. The limited predictability of these extremes at sufficiently long lead times results in considerable social vulnerability, particularly in light of the imminent increase in frequency and severity of extreme events in the future.

Recognising these risks, the European Union (EU) has considerably improved and adapted its water policy instruments over the past few decades. Clear examples are the EU Water Framework Directive (WFD), the Floods Directive (FD) and the EU Water Initiative (EUWI), as well as the policy documents supporting the European Commission's communication on water scarcity and droughts. In addition, in research and innovation budgets, considerable funding has been earmarked for the generation of science-based knowledge and climate services. **The EU Horizon 2020 funded research project IMPREX (IMproving PRedictions and management of hydrological Extremes) provides innovative approaches, tools and practical case studies to help improve our ability to anticipate and respond to future hydrological extreme events. IMPREX demonstrates the successful uptake of innovation in practice, and provides recommendations on decision-making and integration into EU policy frameworks.**

Hydrology and water resources systems are essential for multiple sectors, such as water transport and hydropower, agriculture, urban water supply and other economic fields. Numerous actors working in these fields face the consequences of climate variability and hydrological extremes daily. Improved climate services are of the utmost importance if hydrometeorological phenomena are to be managed effectively. Operational tasks can benefit from improved forecasting and decision support systems that effectively incorporate complex events where many drivers are at play at the same time. Improved climate services are indispensable in order to be able to tailor information on long-term climate change to operational activities such as infrastructure planning in the water sector.

The principle "learn from today to anticipate tomorrow" was one of the true guiding principles behind IMPREX activities. In close cooperation with a wide range of users within the water sector, IMPREX developed approaches and tools that are used today to prepare for hydrological extremes and climate variability. Current state-of-the art forecasting systems and management procedures were analysed and improved. The project took up the challenge of harmonizing the – at times conflicting – requirements for everyday operations and long-term planning, providing evidence-based solutions for improved management support. **IMPREX developed models, tools and approaches that address operational hydrometeorological forecasting and climate outlook systems, and operational system management by practitioners.**

The IMPREX project team has found the management of near-term weather extremes and long-term climate to be strongly interlinked for many applications. The interaction between research and application has significantly improved within the framework of close collaboration between the multi- and transdisciplinary project teams. **The project benefited from existing and new partnerships between the IMPREX consortium members and a large group of scientists, developers, practitioners and policymakers in water related sectors.** Close cooperation with these partners guaranteed relevance and effectiveness of project activities. In the near future this will lead to increased uptake and application of IMPREX approaches, while recognising the diversity of water-related challenges within the EU.

This brochure presents an overview of new meteorological models, hydrological forecasting techniques, management approaches and innovative concepts, developed and applied as part of the IMPREX project. Furthermore, sector-specific factsheets outline innovative solutions developed and applied within different sectors and addressed within the framework of the project: flood management, hydropower, water transport, urban water supply, management of droughts with a focus on the agricultural sector, and global water economy relations. Case studies illustrate how, within the IMPREX project, climate information was customized to meet the different stakeholders' needs, providing guidance on current practices as well as innovative tools. Three policy briefs and one position paper, translating promising tools and relevant topics and approaches to the relevant target groups, are presented here. Selected topics are (1) compound events with regard to the implementation of the EU Flood Directive, (2) probabilistic approaches to improved flood risk assessment and management under consideration of uncertainties and (3) successful implementation of preventive drought risk management in Europe. Additionally, a position paper presents lessons learned with a view to possible steps towards action-oriented outcomes of applied research and climate services for the water sector.

IMPREX INNOVATIONS, TOOLS AND FUTURE DEVELOPMENTS

The development of adequate climate services for the water sector requires an effective combination of a robust scientific approach and a client-oriented focus on the development of innovative and tailor-made tools and approaches.

INNOVATIVE TOOLS AND APPROACHES

- *Inclusion of compound events in risk analysis*
- *Crop yields and flood impacts derived from large scale climate indices*
- *Improvements to the drought risk management toolkit AQUATOOL*
- *Mapping impacts of remote climate extremes on food and manufacturing chains*

INCLUSION OF COMPOUND EVENTS IN RISK ANALYSIS

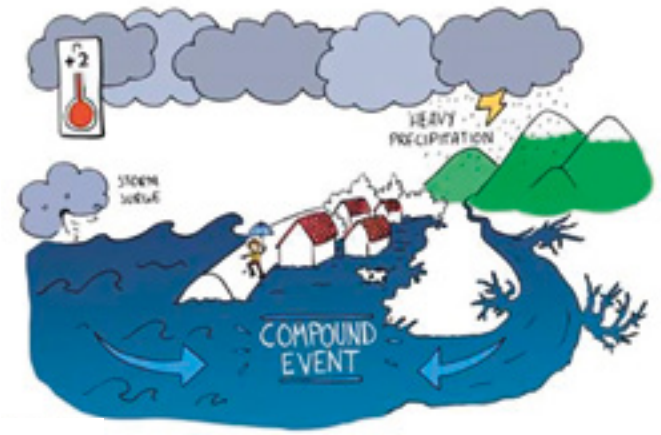


Figure 1: The emergence of compound events.

The scientific analysis of the impact of compound drivers of hazards or impacts has made substantial progress over the past years. The need to consider compound events has been documented in an IMPREX policy brief for European Flood Risk management, and flagged by authoritative publications by IPCC. With help from IMPREX a new European COST action DAMOCLES has been launched to promote awareness and systematic analysis.

In IMPREX work has been carried out including the development of new model data sets and analysis concepts, targeted at studying its relevance for flood risk management in a number of smaller Dutch catchment areas and municipalities. For instance, the city Den Bosch faces risks of flooding by a combination of high water levels in the river Meuse, and high local precipitation with associated flooding from smaller tributaries. Joint occurrence of these events is currently estimated by a rule-of-thumb approach, and this likely leads to a conservative estimate and overprotection of the area. HKV has used IMPREX resources to address this topic in a commercial contract with the city stakeholders, and explored the realism of these assumptions using additional techniques and regional climate model data.

The notion of compound events is well appreciated by many stakeholders involved in IMPREX, and is a component of the commercial portfolio of consultancy firms like HKV. However, the procedure applied for Den Bosch was conceived as too labor-intensive and requires further simplification and operationalization. In order to be absorbed in the stakeholders' decision processes, the advantages of this method need to be clear and convincing. Pilot studies conducted within IMPREX contribute to the identification and demonstration of these advantages. Usage of this method in day-to-day work of companies like HKV will further increase the awareness of this method among stakeholders.

CROP YIELDS AND FLOOD IMPACTS DERIVED FROM LARGE SCALE CLIMATE INDICES

Probabilities of occurrence of high-impact extremes (such as large scale flooding or crop yield failures) are linked to governing large scale climatic patterns. For instance, the North Atlantic Oscillation (NAO) is a pattern governing the large scale Westerly flow and is indicative for anomalously wet or dry conditions in specific European domains and seasons. Advanced machine learning techniques have been used to relate a number of influential climate patterns (e.g. NAO, El Nino and Eastern Atlantic pattern) to the occurrence of both, floods and crop yield anomalies in different European subdomains. The techniques are designed to extract information from past observations that could be used to make a forecast of the probability of major future impacts encompassing a time range of a few months. It was shown for instance that flood occurrence and damage in Southern and Eastern Europe are significantly related to winter and summer NAO. Also prediction of anomalies in sugar beet production can be made, for some regions, up to six months before the start of harvesting season. In these regions approximately 44% of the mean annual sugar beet is produced. This work was carried out in partnership with the European Joint Research Centre.

Some of these results are used in the IMPREX risk outlook, displaying an assessment of risks for hydrological impacts at a lead time of a couple of months, derived from multiple lines of evidence. In a follow-up study carried out by IVM, the method is being extended by including bottom-up local knowledge, which implies an active use of stakeholder information and people's perceptions of risk. The work shifts the focus from forecasting hazards towards impacts, which is a promising approach to generate meaningful outlooks and early warnings for targeted stakeholders.

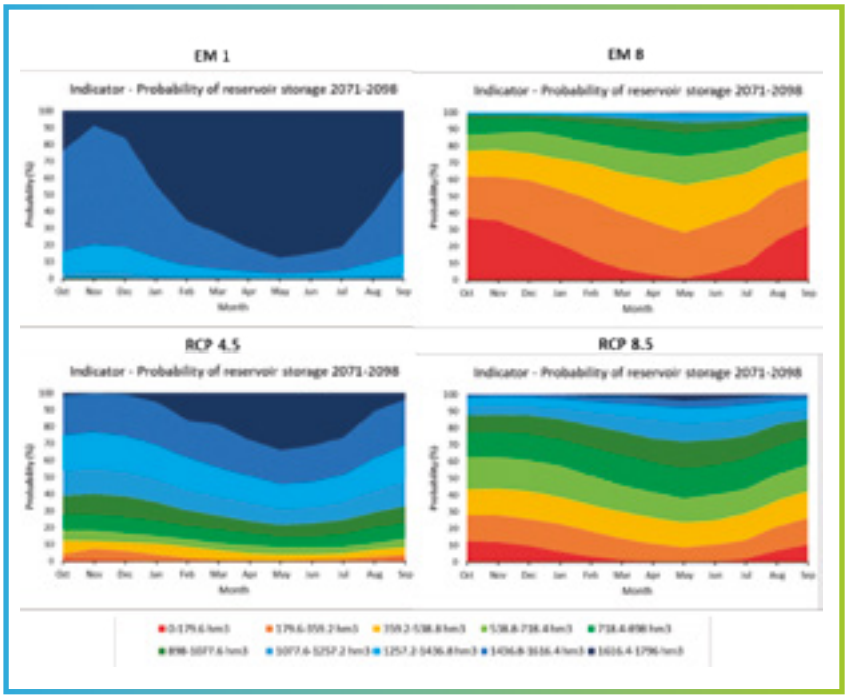
IMPROVEMENTS TO THE DROUGHT RISK MANAGEMENT TOOLKIT AQUATOOL

Within IMPREX, tools, models and approaches are improved that support decision making for both operational drought management (including water allocation) and long-term risk planning. The drought management procedures and organizations in the Spanish Júcar area (organized around the Júcar River Basin Partnership, CHJ) have a long standing tradition. Over the past decades a sophisticated Decision Support System has been developed, and the components dedicated to the data processing and quantitative modelling are embedded in a series of modules in the Aquatool decision support system.

Figure 2. Drought scenario in the Júcar River Basin District. Modified from the Monitoring of Drought Indicators Report in the area of the CHJ (May, 2018).

In IMPREX various incremental improvements have been implemented in some of these modules. First, an evaluation of the seasonal predictability of droughts in precipitation and streamflow forecasts has been carried out in the hydrological risk module of Aquatool. Then, the seasonal forecasts are incorporated in the hydrological risk assessment module of Aquatool (SIMRISK). The performance of this forecast product shows that bias corrections need to be applied, but small improvements are achieved in predicting the onset of the dry season compared to the operational procedure that is based on statistical modelling using observed precipitation records. By the main stakeholders this work is perceived as a first step towards inclusion of seasonal forecasting in the drought management support system. The tailor-made delivery of the probabilistic information for the target region was well understood and appreciated.

A range of climate change projections for the Jucar area have been evaluated, using the same decision support tool as used for operational and strategic drought management. Here a series of processing steps was carried out to adjust for biases and transfer ensemble climate projections to estimate water storage in a number of reservoirs in the area, and consequently drought risk in the catchment. Apart from considerable unforced internal variability, a clear difference in drought risk was displayed for different climate change scenarios.



The developments of AQUATOOL are rooted in a long history of decision support system development for the Júcar area. However, the system can be implemented in any Spanish basin (and other basins abroad) where the model chain and AQUATOOL calibrated modules are available. The tailoring of both seasonal forecast and climate projection results to the local decision support system, AQUATOOL, has strongly contributed to the refinement and greater acceptance among local stakeholders, although more research is needed in order to further improve the skill of the predictions.

Figure 3. Probability indicator of reservoir storage for 2071-2098 in the Jucar River System from two ensemble members (EM1 and EM8, top left and top right respectively) and the ensemble of RCPs 4.5 (bottom left) and 8.5 (bottom right).

MAPPING IMPACTS OF REMOTE CLIMATE EXTREMES ON FOOD AND MANUFACTURING CHAINS

An extensive analysis is made of water consumption and trade networks of a large collection of crops used for food production. Linking the trade and production chains with ambient climate features, a climate risk profile for each of these crops was produced. Using a trade network model (Acclimate) the global web of trade and manufacturing processes has been mapped and analyzed for impacts of flood related shocks in the system. The mapping uses a discretization into regions and sectors and is assumed to cover a majority of the total worldwide economic production. The system is driven by national/regional economic statistics, and allows mapping global trade balances between regions and the effects of cascading effects of climatic shocks on those trade balances.

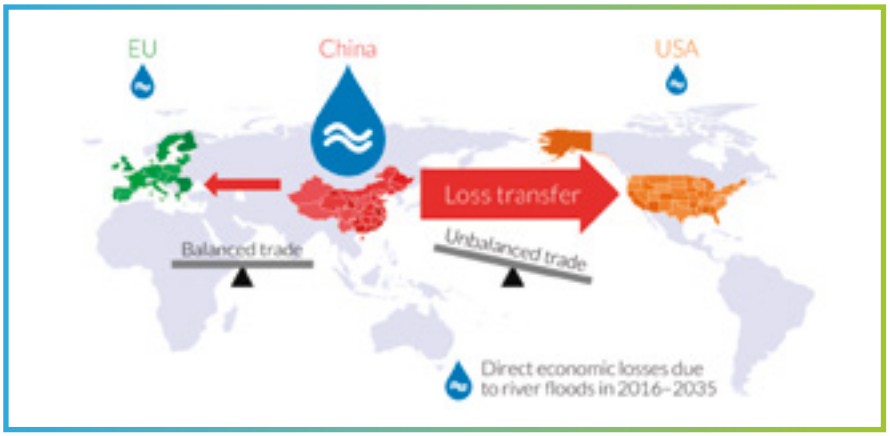


Figure 4. Economic response to river floods. Whereas the USA suffer from indirect losses damage caused by river floods in China, the European Union is much better prepared. This can be derived back to a balanced trade relationship between the EU and China in contrast to an unbalanced trade between China and the USA.

In the globalizing world trade shocks induced by floods in production areas depend strongly on the trade network. Increased trade connectivity allows faster propagation of shocks through the trade network, but also allows effective mitigation by choosing alternative supply channels. In general a strong connectivity in combination with a balanced trade relation limits propagation of adverse flood effects to partner regions and improves mitigation options.

These analyses can inform international food production or retail companies about the current and potential future vulnerability of their supply chains. This enables the development of coping strategies to reduce risk risks (i.e. through targeted portfolio diversification), or forecast-based action in the face of impeding disasters.

Results are published in high-profile academic journals and at press conferences, and are being included in follow-up research programs under the Horizon 2020 funding scheme. In addition, pre-startup funding was received to turn the results in (commercial) services for public and private institutions. The services include standardized risk assessments for reporting or stress testing companies or sectors, development of authoritative and tailor-made risk scenarios, and potentially the implementation of an early warning system fed by operational (seasonal) hydrometeorological forecasts.

Examples of other concepts and tools (documented elsewhere)

- *Probabilistic damage modelling using open data* (see factsheet on Flood Risk and policy brief on European Flood Directive): the developments allow a pan-European derivation of flood damage as function of the flooded area and exposed assets. It enters the portfolio of research and consultancy projects from agencies like Deltares.
- *Forecasting water level for ship traffic management in Central European rivers including Rhine* (see factsheet on Water Transportation): a prototype forecasting system is implemented and heavily utilized by a large group of clients; follow-up funding is provided to operationalize the forecasting system.
- *Risk based water allocation under dry conditions* (see factsheet on drought management): An updated drought risk analysis and management system is ready to be implemented for the Netherlands. It will generate important lessons on stakeholder involvement and information usage applicable to other regions in Europe.
- *Assessment of the economic value of forecasts for hydropower* (see factsheet on hydropower): the uniform procedure to evaluate forecast impacts on hydropower production value has led to changes in hydropower operation. A follow-up investment from a Regional Hydropower Agency is used to make the system developed in IMPREX operational.
- *A system dynamics model for mapping multidisciplinary interactions and trade-offs in water allocation problems* (see factsheet on drought management)
- *Mapping drought risk through an objective index definition tool FRIDA* (see factsheet on drought management): FRIDA allows a realistic tailor-made identification of the current drought state, and gives information on the impact of measures to alleviate drought risk. It increases consistence of information necessary for operational and strategic decision taking.
- *Forecasting high turbidity events in Drinking Water Treatment Plants* (see factsheet on Drinking Water supply): using observed and forecasted local rainfall, a forecast of turbidity is made allowing better management and cost savings of treatment operations. Via the CetAqua shareholder SUEZ the forecasting system will be adopted and distributed over a larger number of Drinking Water Treatment Plants.
- *Water Accounting + mapping climate change features* (see factsheet on drought management): a standardization of the "book-keeping" of water availability and consumption allows comparison and upscaling of catchment based water accounts to the European scale. At this aggregation level climate change information becomes meaningful for European Drought Management strategies.

For further information please visit www.imprex.eu and check out our interactive product demonstrator!

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IMPREX is designed to help reduce Europe's vulnerability to hydrological extremes by achieving a better understanding of the intensity and frequency of potential disrupting events. Enhancing our forecasting capability will increase the resilience of European society as a whole, while reducing costs for strategic sectors and regions at the same time. The research project brings together 23 partners from 9 countries and has received funding from the European Union's Horizon 2020 Research and Innovation Programme.

HYDROMETEOROLOGICAL FORECASTING

IMPREX has contributed to global and limited area Numerical Weather Prediction (NWP) systems operated by ECMWF, the UK MetOffice and members of the Harmonie NWP consortium. It has worked on coupled hydrology/meteorology forecasting systems used for flood risk warnings, water allocation and seasonal outlooks operated by the European Copernicus Climate Change Service. It has also worked on creating enhanced detail in climate change projections by testing new experimental designs involving high resolution convection-permitting climate models operated by the Harmonie NWP consortium and the UK MetOffice.

HYDROMETEOROLOGICAL FORECASTING: A LONG-TERM PROCESS

Less than half a century ago, skillful weather forecasting beyond a few days ahead was deemed fundamentally impossible. The atmospheric system was assumed to be too chaotic, the observations too few, the computing power insufficient, and the process understanding too limited. In contrast, we currently pick the fruits of high quality forecasts of hurricanes hitting coastal residents, timely warnings for elevated flood risks, and useful outlooks to manage agricultural practices or hydropower lake storage dynamics. This has become possible by acknowledging the need to join forces between observational experts, model developers and society-oriented forecast providers. And by accepting the need to take a long breath to build, upgrade, refine, couple, tune, tailor, test and adjust the complex forecasting systems. These systems produce today forecasts with high detail for a few days ahead to outlooks of climatic conditions at longer lead times.

The progress in the business of hydrometeorological forecasting and climate outlooks has been achieved by combining long-term resources resident in public dedicated hydrometeorological services, with focused project activities devoted to specialized components of the forecasting systems. IMPREX is happy to have made an incremental contribution to some of Europe's best hydrometeorological forecasting and climate projection systems. It has focused on crucial elements used in operational and policy-oriented decision support systems of institutions in the European water sector, while successfully embedding its findings in the development cycles of influential forecasting agencies.

HOW FORECASTS AND CLIMATE OUTLOOKS ARE CREATED

An atmospheric or hydrological prediction is designed to answer the question: what will the situation be at a certain point in the future, given the current situation? The forecast process starts by generating a picture of the current situation, the so-called "initial state" of a forecast. This is usually obtained by combining a previous forecast for the current time with observations of the current situation in a blending process called "data assimilation" which accounts for the uncertainties in both components. The initial state is progressed into the future by a sophisticated numerical model that contains the governing physical processes.

As the forecast lead time becomes longer, the forecast becomes more uncertain. Therefore, a number of simultaneous but slightly different forecasts will spread as lead time increases, due to imperfections in the observations and model formulation. This "ensemble forecast" reflects the uncertainty of the forecast, which is useful information in many decision contexts managing hydrological risks.

Global models are used to capture the entire planetary atmospheric system as a whole, while regional models are nested to provide spatial additional detail. Observations are used to initialize the forecasting systems, but also to carry out substantial verification guiding next-generation model improvements. Until systematic errors have been eliminated in the forecasting systems, observation-guided bias-adjustment remains an essential step in any hydrometeorological forecasting system.

Forecasts for the short- to medium-range (say, up to 2 weeks ahead) and for seasonal or longer time scales share this principle of dependence on a combination of initial states and model formulation, but have different keys to provide successful outlooks. While at the short- to medium range the majority of information resides in an accurate high-resolution representation of the initial state and dynamics of primarily the atmosphere and land surface, the slow memory of oceans, vegetation and ice masses play an increasingly important role at the seasonal and longer time scales. Also the level of spatial and temporal detail at which meaningful information can be provided decreases with longer lead times.

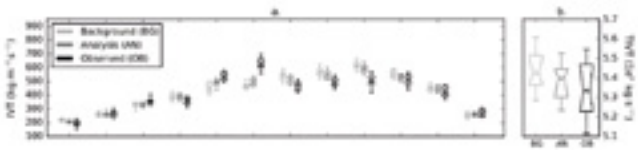
Climate models are basically similar to models used for NWP. However, they are not designed to make a prediction based on the current situation, but on possible responses of the climate system to changing boundary conditions such as greenhouse gas concentrations and land use. Therefore initial conditions are not a key element, while model physics, ensemble projections, and verification of the quality of the projections are similarly important as for NWP systems.

THE IMPREX CONTRIBUTION TO THE DEVELOPMENT OF HYDROMETEOROLOGICAL FORECASTING AND CLIMATE OUTLOOKS

Progress has been achieved on model systems addressing different time scales and environmental domains:

- Prediction of hydrology and meteorology at short-medium range (up to a couple of weeks)
- Detection of benefits of better atmospheric observations to predict Atmospheric Rivers

Atmospheric rivers (ARs) are responsible for most of the horizontal transport of water vapor outside of the tropics and can cause extreme precipitation and affect the atmospheric circulation. The state-of-the-art weather forecasting systems used to forecast ARs and their impacts frequently have large errors in the water vapor transport. Research suggests that improved measurements of low-level winds, and to a lesser extent water vapor, would potentially enhance the prediction skill and reduce the uncertainty of these high-impact events significantly. This would yield benefits for hydrometeorological prediction.

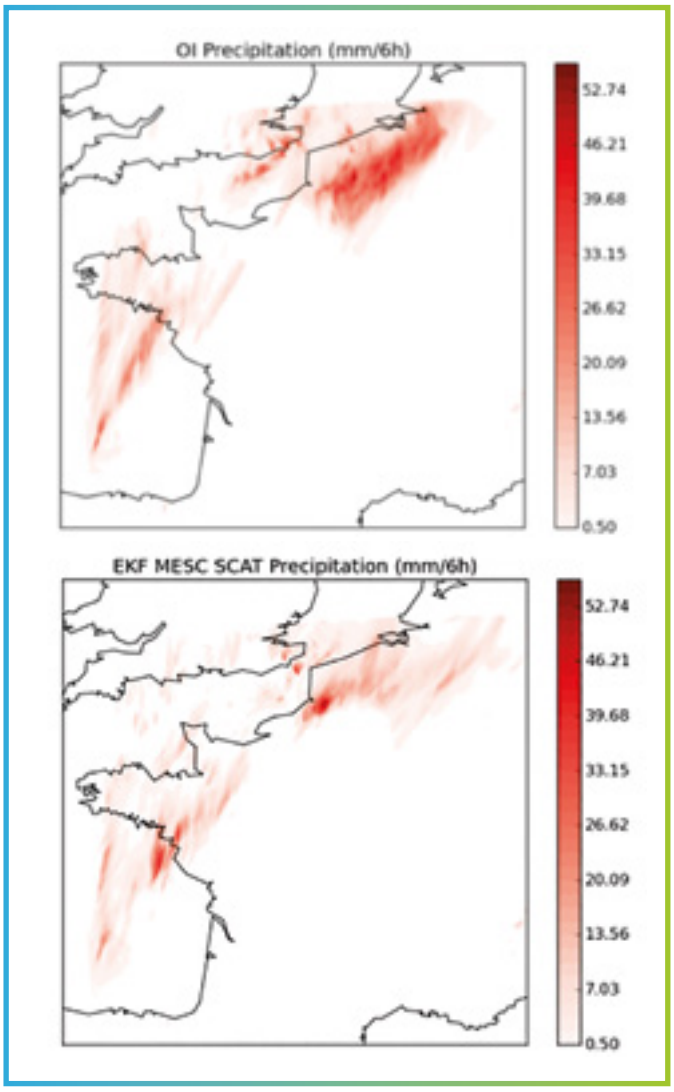


Transect of an Atmospheric River. Shown is the Integrated Vapor Transport (IVT) as function of horizontal position within an atmospheric river. The light grey symbols denote the ECMWF forecast model first guess, the black symbols the in situ observations, and the dark grey symbols the ECMWF analysis that makes use of this observations, improving on the first guess[1].

[1] *Lavers, D. A., Rodwell, M. J., Richardson, D. S., Ralph, F. M., Doyle, J. D., Reynolds, C. A., Tallapragada, V., and Pappenberger, F. 2018: The Gauging and Modeling of Rivers in the Sky. Geophysical Research Letters. doi:10.1029/2018GL079019.*

Testing of an alternative land surface/soil moisture module in a Numerical Weather Prediction model for Europe

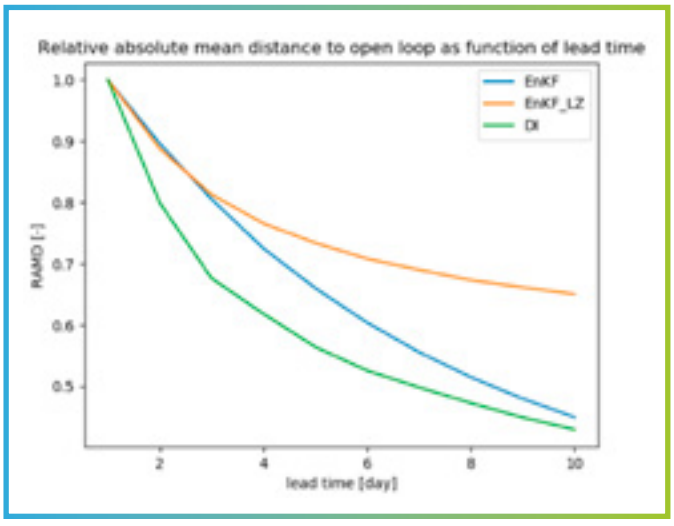
A state-of-the-art limited-area NWP system (Harmonie) was used to investigate the impact of enhanced surface data assimilation on the short-term prediction of extreme precipitation events. Improvements were applied to the background error statistics, application of a Kalman-filter, and utilization of satellite based soil moisture information. The effect on short-term prediction of extreme precipitation events was investigated in a number of case studies carried out over France, Italy and Sweden. Verification scores and subjective evaluation of one particular case showed that enhanced surface data assimilation did have an impact on short-term prediction of severe precipitation events and can lead to improved short-term forecast.



Rainfall forecast for a particular heavy-rainfall event with the original system (top) and the system incorporating the new land surface treatment (bottom).

Data assimilation of lake level and snow in hydrological river discharge and navigation models

Data assimilation methods have the potential to improve hydrological forecasts by reducing errors in the initial state of the model at the time of forecast. Popular variables that have been used to update the initial state are snow, soil moisture and discharge. The potential of using lake level measurements in state updating was explored. By means of a synthetic model experiment and a real world case applying the Ensemble Kalman Filter (EnKF) to a hydrological model of the Swiss Rhine, it was found that lake level measurements do contain information that could be related to upstream hydrological states and that there is therefore potential for improving the forecasts for longer than 10 days.



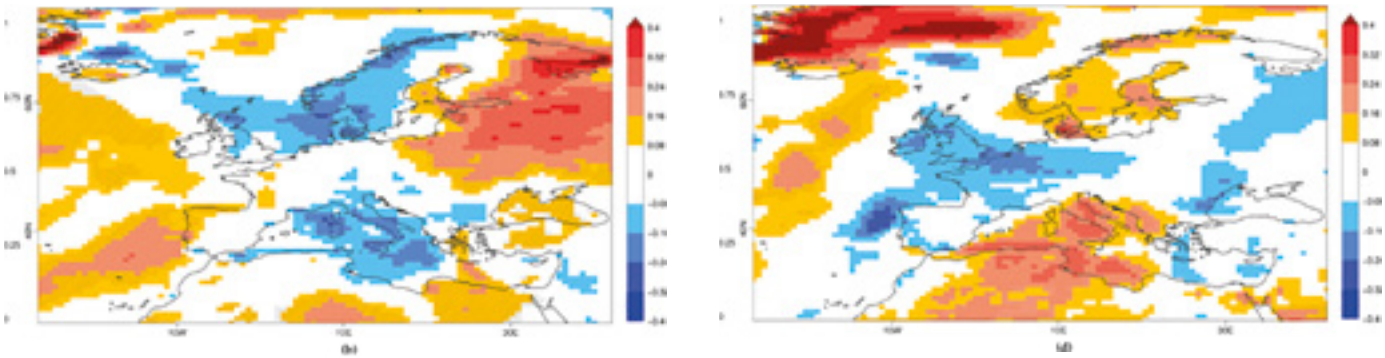
Relative absolute mean distance (RAMD) between forecasts from different initial conditions: 1) EnKF with Lake level, Upper Zone and Lower Zone states updated (EnKF), 2) EnKF with Lake level and Lower Zone Updated, 3) Direct insertion of lake levels. Updates with the EnKF were done based on lake level observations. The figure shows that effects of Direct Insertion rapidly diminish, while an EnKF with LZ succesfully contributes to forecast quality for a longer time.

PREDICTION AT SEASONAL TIME SCALES

Evaluation of the skill of seasonal forecasting systems

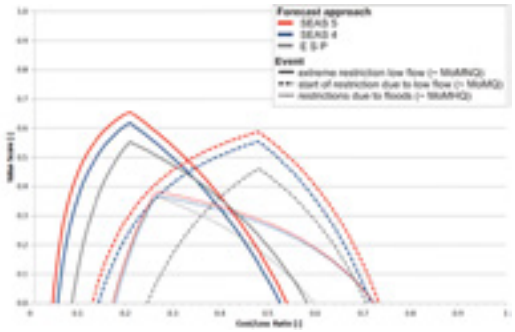
Seasonal forecasting is routinely carried out by a few meteorological services in Europe, including ECMWF and UKMO. They are intended to give probabilistic forecasts of generic climatological characteristics (including temperature, precipitation and solar radiation) one to 6 – 9 months ahead, allowing for anticipating anomalous climate conditions for agriculture, hydropower, river transport and other water-related sectors. The forecasting systems require extensive testing and calibration over long climatological periods, and system updates are implemented typically once every ~5 years. A new ECMWF version System 5 became operational in 2017, and in IMPREX verification and benchmarking against alternative seasonal forecasting systems has been carried out.

The temperature and precipitation forecasts from four climate models have been assessed using both deterministic and probabilistic approaches[2]. A number of Weighted Multi-Models (WMMs) ensembles were constructed from the individual models, and their respective forecasts were assessed. Consistent with existing literature, seasonal climate prediction skill over Europe was found to be fairly limited. A simple WMM system performs better than more complex combination systems, but does not always outperform the single best model within the multi-model ensemble.



A comparison between the skill of ECMWF System 5 and the earlier version System 4 gives a mixed picture. Orange and red areas show places where seasonal mean temperature in System 5 outperforms results from System 4 in Summer (top panel) and Winter (bottom). Blue areas show the opposite.

Also for a number of sectoral applications the usefulness of different (sub)seasonal forecasting systems was assessed and compared. For instance, seasonal forecasts are used to guide shipping transportation management of inland rivers[3]. A forecast can create economic value when it assists in optimizing the load and timing of transportation subject to river conditions. A comparison of the economic value of ECMWF Systems 4 and 5 was carried out, benchmarked against a statistical forecasting method. The maximum relative economic value one for perfect forecasts, while for a zero value no added value of the forecast compared to the (optimal use of a) climatology-based forecast can be demonstrated. The decision strategy behind the relative economic value assumes that i) the user aims at a long-term economic optimum (minimizations of expenses resulting from the preventive actions as well as the losses), ii) the user acts risk-neutral, and iii) the decision to take preventive actions solely depends on the financial costs and losses (economic gain is the only aspect the user bases the decisions on). It was shown that particularly in the first forecast month the potential economic value of System 5 slightly outperformed the previous System 4 and statistical methods. In the second forecast month no significant difference between System 4 and 5 was shown.



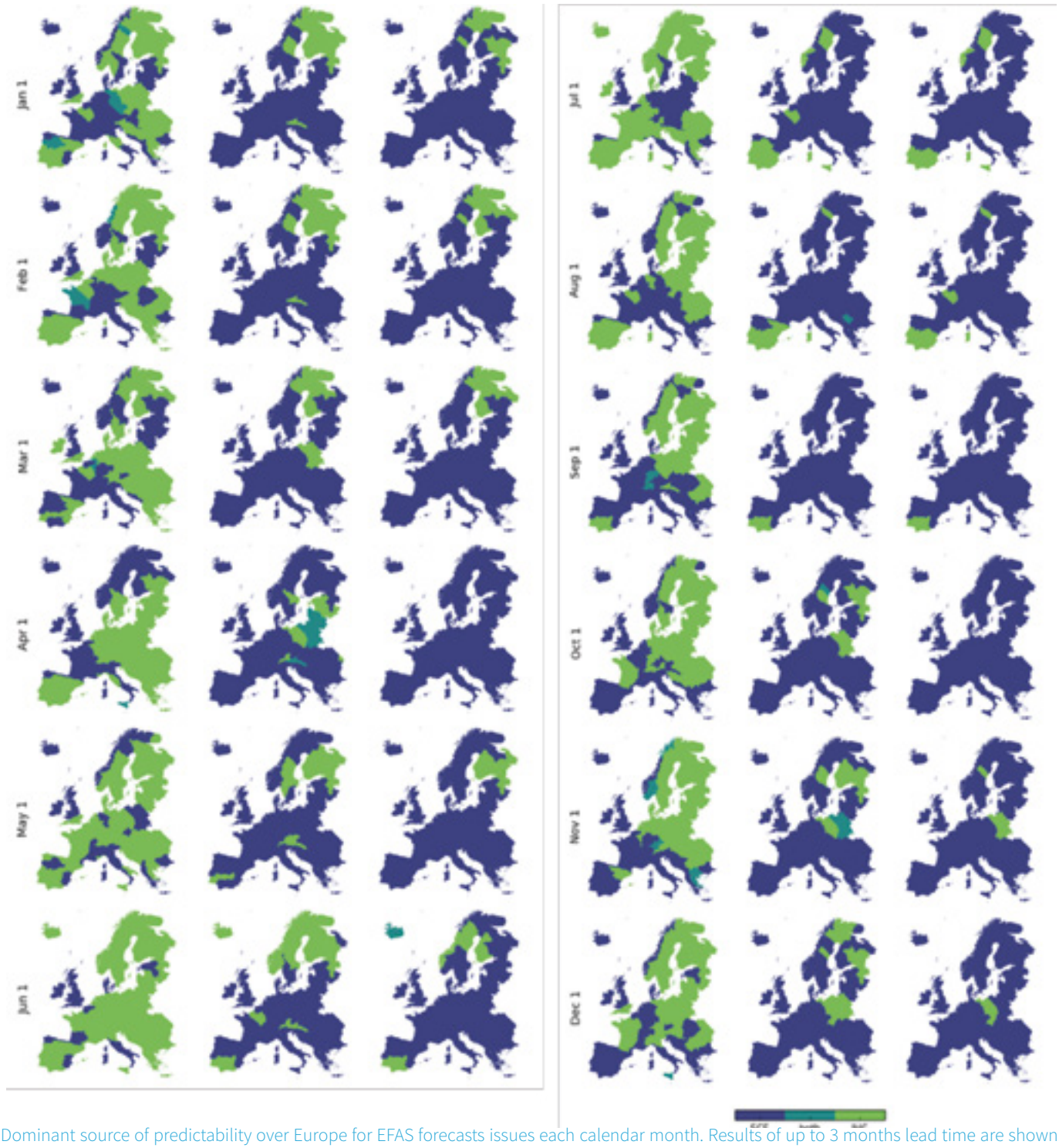
Index of economic value as function of cost/loss ratio for different types of events (restricting low flows, start of low flows, restriction due to floods) for shipping transport over the Rhine river for the first forecast month produced by System 5 (red curves), System 4 (blue) and the statistical model (grey). The System 5 curves are (slightly) higher in all domains

[2] *Mishra, N., Prodhomme, C. & Guemas, V. Clim Dyn (2019): Multi-model skill assessment of seasonal temperature and precipitation forecasts over Europe; doi.org/10.1007/s00382-018-4404-z*

[3] *Meißner, D., B. Klein & M. Ionita, 2017. Development of a monthly to seasonal forecast framework tailored to inland waterway transport in central Europe. Hydrol. Earth Syst. Sci. 21(12), 6401-6423. https://doi.org/10.5194/hess-21-6401-2017*

Improving seasonal forecasts of river discharge: do we need better initialization or better models?

Seasonal forecasts of river discharge are routinely produced using meteorological seasonal forecasting systems driving hydrological models. The European Flood Awareness System (EFAS) operated for the major European river systems by the Copernicus Climate Change Service and SMHI's European seasonal forecasting service are examples of such a forecasting system. The quality of any forecast depends on a combination of the quality of the initial conditions used to start the forecast, and the quality of the meteorological forcing for the prediction. For streamflow forecasting a potentially significant fraction of the skill can originate from information about the initial state of the system: anomalies in soil moisture or ground water, snow pack and water present in lakes and river network can give a persistent signature to the streamflow amount from a few weeks up to several years ahead.



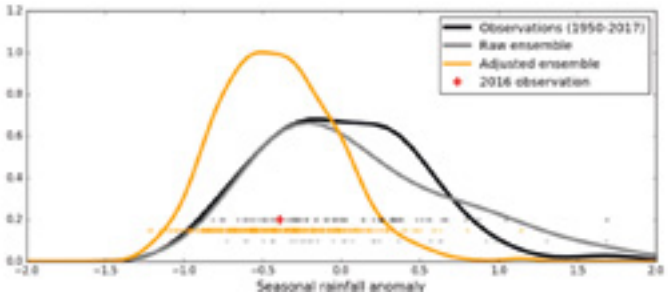
Dominant source of predictability over Europe for EFAS forecasts issues each calendar month. Results of up to 3 months lead time are shown. Green areas denote predominance of the role of initial hydrologic conditions, and in dark blue areas the atmospheric forcing is more important.

A systematic analysis of the factor that drives streamflow predictability has been carried out for 74 EFAS regions[4]. Forecast skill against the model's climatology was calculated for up to 3-months forecasts starting each calendar month. On average, to forecast the coming month, in most areas improving the initial state would lead to a higher discharge forecasting skill than improving atmospheric forecasts. As the lead time increases, the relative importance of improvement of the atmospheric forcing increases. In most areas, river flow forecasts three months ahead are more sensitive to improved atmospheric forecasts than to improved initial states. However, temporal and spatial variabilities are shown. For instance, in Scandinavia initial states also play a dominant role also for longer lead times, showing the importance of good initial snow and lake information. Over the Iberian Peninsula, the initial state dominates the uncertainty for forecast issued from June to September, a signal which persists until three months of lead time. The very dry climate highlights the importance of accurate initial ground water information, which has a long memory. Conversely, in rain-driven regions such as the UK or Norway, the quality of atmospheric forecasts drives discharge forecast skill the most, even for the month ahead. These results are used to benchmark seasonal forecasting systems and guide their further development to enhance performance and usefulness. A European sensitivity assessment tool is now available online for SMHI's European seasonal forecasting service[5].

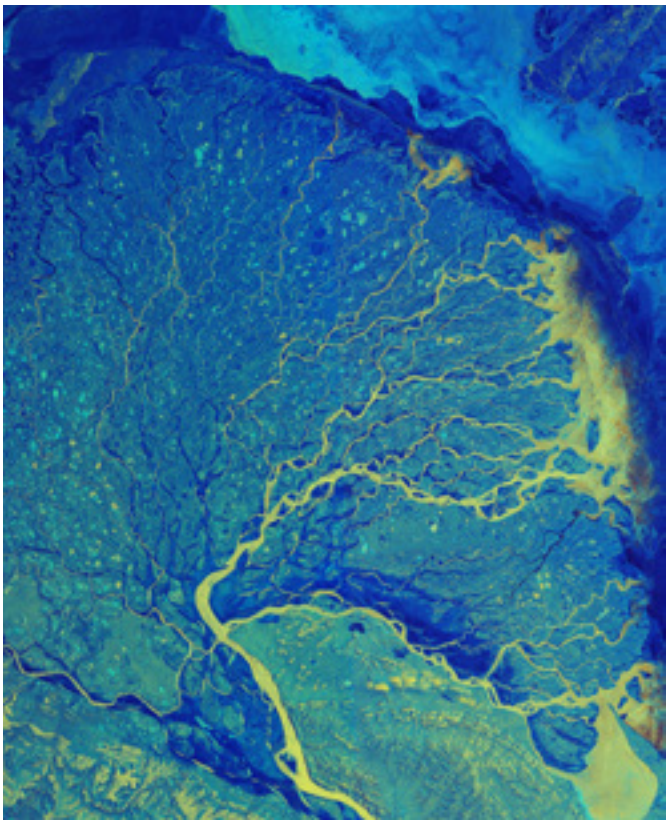
An enhanced precipitation forecast signal in the MetOffice seasonal forecasting system

Limited skill of seasonal forecasting systems is caused by inherent limitations of the predictability of weather at a longer lead time, and by limited quality of the models and initial states used to produce the forecast. In addition, the noise from seasonal forecasting systems is filtered by the application of large ensembles to produce the forecasts, but usually some of the signal is also filtered away. Statistical postprocessing techniques can be applied to enhance this signal, and to adjust the modelled correlations between large scale climate characteristics (such as the North Atlantic Oscillation; NAO) and local weather phenomena (rainfall) using observed correlations.

Two post-processing steps were applied to output from the GloSea5 seasonal forecasting system operated by the MetOffice to improve the forecast skill of precipitation. In the first step the forecast signal in the NAO prediction is increased by fitting a linear regression between the ensemble mean NAO index and the NAO index derived from observations, and scale up the predicted signal by the slope of this regression, increasing the signal-to-noise ratio of the NAO forecast. In the second step, observations are used to replace the forecasted precipitation in Europe by analogues from the historical record, to improve the local precipitation prediction. Results in the dry Eastern Iberian area, where two case studies explore the use of seasonal forecasting for water resource management in the basins, show that a small improvement in local precipitation forecasts can be seen for winter, but not in summer. Further testing and adjustment to the operational Decision Support Systems is still required.



Seasonal rainfall anomalies for a NAO-positive year (2016) for the Jucar basin. The improvement of the forecast by using the empirical relationship between the NAO index and precipitation anomalies is evident with the adjusted forecast ensemble (yellow) much better reflecting the observed anomalies (red) compared to the raw model output (grey).



[4] *Arnal, L., Wood, A. W., Stephens, E., Cloke, H. L., and Pappenberger, F., 2017. An Efficient Approach for Estimating Streamflow Forecast Skill Elasticity, J. Hydrometeorol., 18, 1715–1729, https://doi.org/10.1175/JHM-D-16-0259.1*

[5] *https://hypeweb.smhi.se/explore-water/forecasts/seasonal-forecasts-europe*

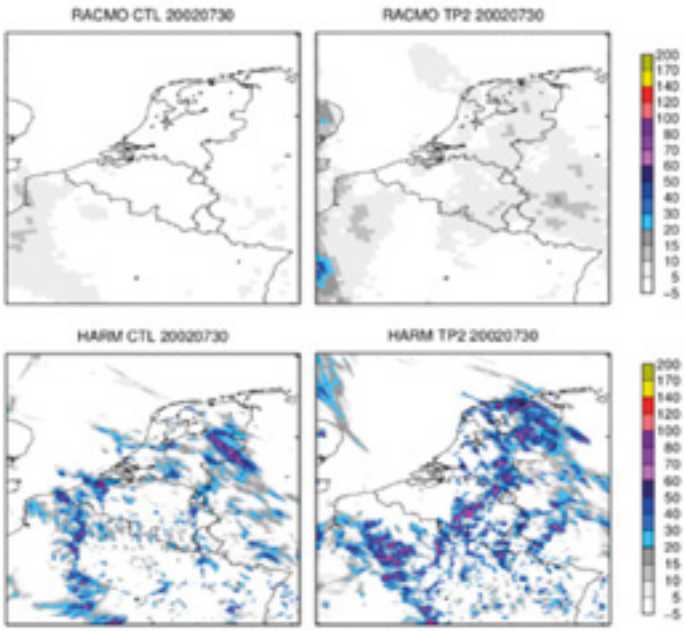
Development of convection permitting climate models for heavy rainfall

While most regional climate models (RCMs) are still operated on a relatively coarse spatial resolution, climate change effects on heavy precipitation are governed by processes at a much smaller spatial scale. In the international CORDEX community a coordinated development of so-called Convection Permitting RCMs (CPRCM) is taking place, in order to improve the climate projections for these high-impact heavy precipitation phenomena. In simulations with a CPRCM for 10 historical summer seasons covering Scandinavia, West-Central Europe, East-Central Europe and Southwestern Europe it is shown that the model produces stronger high-intensity precipitation extremes than coarser scale RCMs. Comparison to observations reveal that deficiencies in both the models and the (relatively coarse-scale) reference data sets contribute to a pertaining bias in these simulations, and further work is needed.

A simple "surrogate warming" experimental set-up

A disadvantage of the high resolution CPRCMs is that their considerable computational power demand limits their application in comprehensive climate change assessments. Running long time slices of present-day and future climate is costly, and requires substantial data processing capabilities to deal with the large data volumes. Alternative climate change assessments make use of so-called "surrogate warming" experiments. In this set-up, a CPRCM is set-up to reproduce a number of historical events or shorter episodes, and reruns of these episodes are carried out after changing the initial and boundary conditions of the CPRCM to represent a warmer world. The results are thus indicative to answer the question: "how would this episode or event have looked like if the world would have been warmer?"

The surrogate climate change experiments indicate that precipitation will increase in a two-degree warmer situation. The results show that the change in the local maximum hourly rainfall in a given region exceeds the area averaged rainfall amount, which is an indication of the added value of the CPRCM over the RCMs. However, the experimental design focuses on exploration the potential climate change influence of particular events, and findings from these analyses cannot always be generalized to depict a representative climate change signal. Sometimes a very strong amplification of the precipitation extreme is shown, while in other cases no changes are seen at all. The application of the method to a substantial number of events helps to interpret "Future Weather" simulations in terms of climate change.



Example of a heavy precipitation event in the control climate (left panels) and the simulations corresponding to a 2° warmer world (right panels). The top panels show results with a coarse resolution RCM, while the bottom panels depict results from the CPRCM.

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Graphic design by Arctik.

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INNOVATIVE APPROACHES FOR FLOOD RISK ASSESSMENT

New hydro-meteorological forecast and risk management products by IMPREX improve the operational efficiency of European flood management and help mitigate the vulnerability to hydro-meteorological extremes.

Floods are one of the most frequent natural hazards worldwide leading to high socio-economic impacts. Various phenomena can cause a flood, mostly related to heavy precipitation falling on saturated or frozen soil, but also related to other drivers such as sea surge. The probability of occurrence of floods caused by the coincident occurrence of multiple flood drivers, so called compound events, may change with changing climate, especially in Southern and Eastern Europe.

Flood risk analysis is an integral part of the EU Floods Directive, requiring tools for reliable risk assessments on various scales. Currently no systematic monitoring of flood events is taking place, which would significantly improve effective flood risk management. Reliable hydro-meteorological forecasts, loss estimation and analysis of multiple hazards are needed to effectively implement a flood risk management system.

IMPREX TOOLS:

IMPREX developed two innovative approaches to face existing challenges and improve flood risk assessments:

- A Probabilistic Flood Loss Estimation Model
- Mapping compound events and their impacts

PROBABILISTIC FLOOD LOSS ESTIMATION MODEL –

A practical tool to quantify and reduce uncertainties in flood loss estimation, allowing improved risk management and real-time assessments.

Flood loss modelling and risk assessments are widely used for example by insurance companies to assess potential losses and defining pricing structures.

Traditionally, flood models are often based on simplified assumptions offering deterministic flood loss estimations. Most of these models have a limited representation of uncertainties, generating concrete but often wrong estimations of flood risks. Particularly the uncertainty related to the damage caused by a flood is poorly covered.

Probabilistic flood loss estimations provide a comprehensive set of information, allowing for efficient risk management and real-time assessment

A probabilistic, multi-variable Flood Loss Estimation Model for the private sector (BN-FLEMOps) has been developed within IMPREX. The model enables a short-to-medium, seasonal and long-term improved flood risk assessment for fluvial flooding and has been developed in close consultation with relevant stakeholders, including insurance companies. Compared to the traditional

deterministic estimation of flood loss, a probabilistic approach is especially suitable for planning purposes and real-time assessments where flood loss uncertainties play an important role. The BN-FLEMOps model enables probabilistic flood loss estimation for residential buildings at a European level, relying primarily on open access background information.

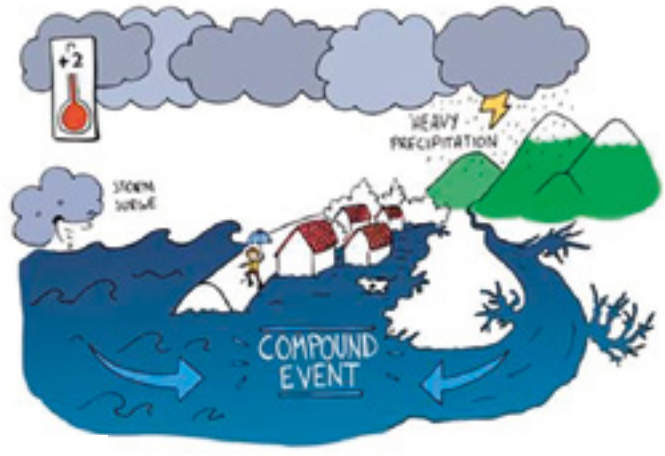
Within the framework of IMPREX, the model has been applied and validated successfully in three European river basins with varying spatial scale in Germany, Italy and Austria. BN-FLEMOps data sets for European wide flood loss estimation will be integrated into the OASIS hub (The global window to free and commercial environmental and risk data tools and services) promoting the uptake of the model by both practitioners and researchers. Transferring the model to different European regions is feasible through an updating approach with empirical data from the target regions.

Apart from (re)insurance and asset management agencies, the target group also includes NGO's, EU policy makers, national governments, and local, national and European water authorities involved in assessing risks and impacts associated with extreme events.

MAPPING COMPOUND EVENTS AND THEIR IMPACTS –

Analysis framework to support river basin authorities in realistically estimating risks and related impacts of interconnected climatic processes

Extreme events, such as floods and storms often result from a combination of interacting processes across different spatial and temporal scales. In order to efficiently design flood hazard and risk assessments, IMPREX analysed and assessed so-called 'compound events": a combination of processes contributing jointly to major impacts, such as heavy precipitation and storm surges (see figure 1). Compound events can cause extreme flood events even if individual drivers are not extreme. In recent years, compound events caused some of the major flood events within Europe as for example the flood event in 2013 and 2014 in the South West of the UK which was caused by heavy precipitation on an already saturated soil in combination with high sea water levels.



The emergence of compound events

IMPREX research demonstrated the need to consider the complexity of impacts of extreme events to improve modelling and risk assessments. The project has provided an analysis framework and tested it in a number of case studies in the Netherlands and the UK.

Case study results show that the developed approach supports decision-makers in realistically estimating impacts and related risks of interconnected climatic processes. The effect and role of compound events and compound drivers is very case specific and cannot easily be captured in a single tool. Yet, a better understanding of compound events enhances the realism of flood statistics and consequently the reliability of flood hazard maps. It provides a basis for improved cooperation between various stakeholders that are active in the field of flood risk management, such as climate and social scientists and decision-makers on various levels.

CASE STUDY

IMPREX partners collaborated with different companies in the European insurance industry.

For calculations of premiums and definition of solvency requirements, many insurance and reinsurance companies regularly use flood loss estimation tools. In collaboration with IMPREX partner GFZ, German Research Centre for Geosciences, insurance companies tested and applied the probabilistic flood loss estimation tool for assessing future flood risk.

> *The model represents an important step forward in flood risk modelling, because it delivers reliable flood loss estimations and additionally considers uncertainty information.*
> *Collaboration partner of international reinsurance company.*

The companies applied the model for residential buildings in various European areas, feeding it with extensive local data and information. The model offers a comprehensive response to (re)insurance needs by delivering reliable information to evaluate flood risks.

Referring to a large pool of experiences, some companies stated that data availability is a crucial aspect for transferability of damage assessment tools, essential for reliable risk assessments. Mapping the inherent uncertainty is important for achieving this reliability. A consistent package of tools that support considering uncertainty is an indispensable asset for involved companies.

> *The model should be made available for as many practitioners as possible as it might significantly strengthen societal resilience and it improve risk awareness.*
> *Collaboration partner of international reinsurance company.*

Working with the probabilistic flood loss estimation tool, the companies successfully conducted a flood risk analysis and have been convinced of the advantage of working with a probabilistic, multi-variate approach. Insurance companies rely on risk information on affected regions during certain timespans as this determines the level of insurance. The presented tool offers the possibility to adapt the loss model to regional characteristics to meet that need.

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HYDROMETEOROLOGICAL PREDICTIONS FOR THE HYDROPOWER SECTOR

- POTENTIAL ECONOMIC BENEFITS

New IMPREX approaches increase operational efficiency of the hydropower sector by demonstrating the economic gains of hydrometeorological forecasting combined with efficient management approaches.

The hydropower sector is highly sensitive to meteorological and hydrological extreme events such as floods, droughts and storms. However, hydropower is also characterized by its flexible and reliable electricity production, which is largely due to its capacity to store water in reservoirs. Storing water means storing energy at one time for its use at a later time. This key advantage paves the way for efficient hydropower management through (1) fostering the integration of local and large-scale intermittent renewable sources (e.g. wind and solar photovoltaics) in the energy grid system and (2) by providing water services beyond electricity generation that are in line with different water demands, e.g. for irrigated agriculture and environmental preservation services.

In the face of changing climate and accompanying extreme events with potentially severe impacts on future water resources availability, the demand for accurate weather and climate services in the hydropower sector increases. Weather and climate services are needed for different purposes along the chain of energy generation, management and planning. Long-term planning of energy production and ensuring energy supply security during peak demands are two examples where these services are indispensable.

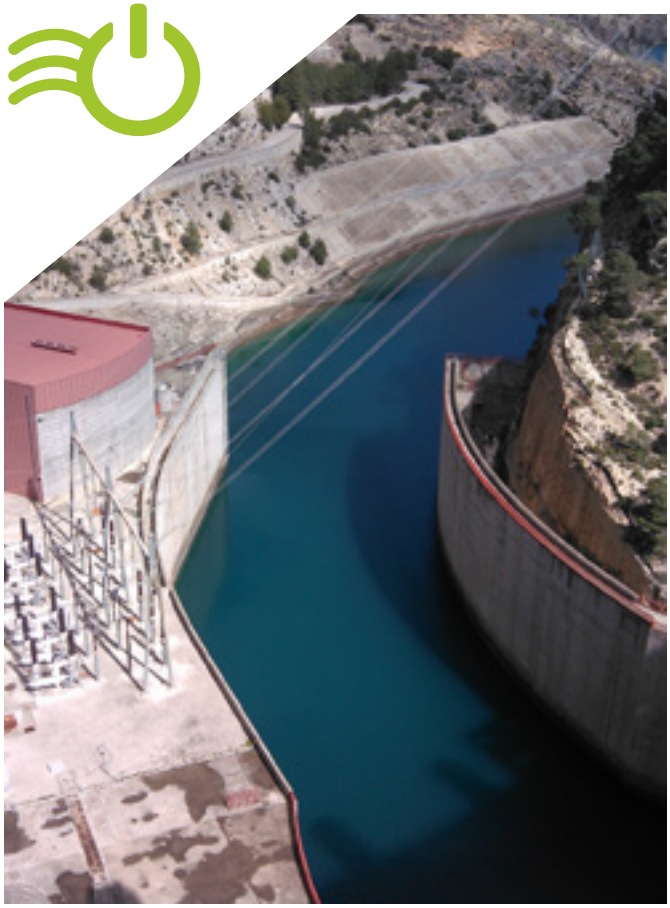


Photo credit: Hector Macian-Sorribes

Optimal weather and climate services also contribute to efficient management of other topics, such as:

- Multi-use reservoir management
- Space-time allocation of water resources for energy generation
- Flood and drought risk mitigation
- Integration with other climate-related renewable energy sources (e.g., wind and solar power)
- Climate adaptation
- Strategic and sustainable energy planning to secure economic growth and environmental preservation

Predicting extreme events is also important to guarantee power plant and dam security for the safety of people, and to reduce or prevent environmental impacts. The economic value of water resources for hydropower production relies on accurately predicting river inflows and ensuring that electricity generation is balanced with demand in real time. It is thus important for electricity companies to anticipate water resources and adequately allocate available electricity in periods of high demand.

IMPREX developed new forecasting products and hydropower management procedures that contribute to better inform decisions on electricity production planning and, as a result, to the optimization of energy production and revenue. Based on these products and procedures, IMPREX investigated the potential economic benefits of improved hydrometeorological predictions, including extremes, at short-, medium-, and long-ranges in the hydropower sector.

Despite the anticipated benefits from using weather and climate services, uptake of state-of-the-art products by practitioners in the hydropower sector is still limited. IMPREX shows that there is space for improving the economic performance of the sector. Guidance is needed in order to adequately use and process data and information in the existing operational and planning procedures.

PRODUCT PRESENTATION

IMPREX developed a robust approach to quantitatively demonstrate the economic impact of climate and water forecasts in the hydropower sector. The approach includes the following components:

- Quantification of the economic value of hydrometeorological predictions in four independent case studies in Europe, representing different climate conditions and hydropower management setups that can be found in current operational settings
- A proof-of-concept on the use of benchmarks and enhanced predictions to identify starting points for system improvement towards better economic performance in hydropower production
- Improved reservoir-based hydropower management strategies at different time scales, adapted to specific needs of local stakeholders
- Guidance on how hydropower optimization can benefit the most from hydrometeorological predictions

COMPETITIVE EDGE

- The approach considers short-term optimised operations, risk-based decision-making and optimisation of management procedures on a longer term, thereby potentially increasing the economic benefits in hydropower reservoir management and planning.
- The methodologies developed, tested and demonstrated within the four different case studies can be transferred to other European locations with similar operational contexts.
- The approach brings together climate- and market-oriented strategic viewpoints, spanning multiple time horizons of sectoral operations and planning.
- The quantitative assessments allow the integration of other interests of water users in the same river basin (e.g., hydropower managed together with irrigated agriculture).

STAKEHOLDER ENGAGEMENT

Electricité de France (EDF) closely accompanied the development and testing of the IMPREX assessments in the case study carried out in France. Operational management and decision-making at EDF strongly depends on river flow forecasts. The company runs an expert-based hydrological ensemble prediction system to monitor the risk of extreme events and to predict inflow to reservoirs located at upstream valley areas on a daily basis.

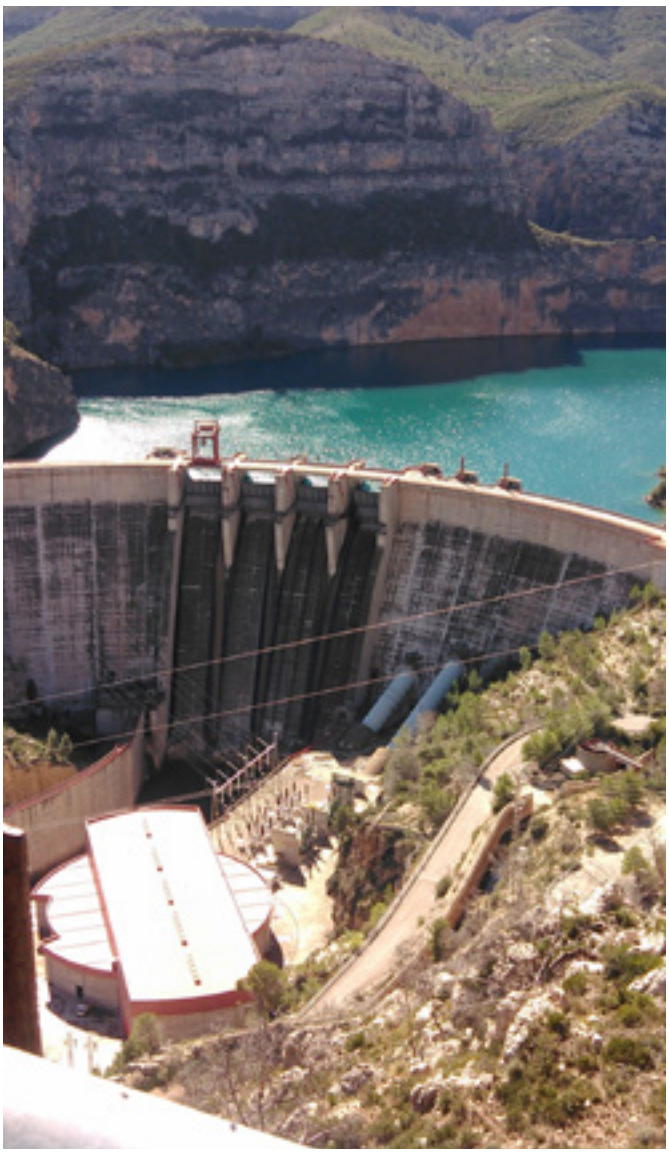
Forecasts and management approaches have been used both by the EDF unit responsible for the optimisation and trading of resources and by the local hydraulic centres responsible for dam security and reservoir management. IMPREX provided a proof-of-concept to quantify the value of hydrometeorological predictions. Therefore, the team linked river flow forecasts for different time horizons to water reservoir management models to optimise energy production. In order to assess the impact of the forecasts used, different calculations were made to quantify both the quality and the sector value of hydrometeorological predictions. Outcomes of the collaboration with EDF confirmed that systematically overestimating reservoir inflows can lead to large economic losses on hydropower revenue when the considered reservoirs have a small storage capacity and short-range (7 days ahead) forecasts are used. An important lesson learned is that flow forecasts which are biased and have the tendency to forecast extremes exceeding the observed values, negatively impact the optimal daily management of a reservoir on the long run.

> *Beyond the question of hydrometeorological forecast's value for the hydropower sector, the modelling work developed in IMPREX provides valuable support to test and demonstrate the decision process it simulates*
> *Rémy Garçon, forecasting and hydrometeorology expert, EDF*

Overall, the science-practice collaborations within IMPREX have shown that it is essential to embed both climate-oriented and market-oriented dynamics in real-time decision-making. It was highlighted that medium- and long-term decisions are mostly driven by climate and hydrology at the local scale, whereas daily and sub-daily decisions are often determined by the energy market.

> *In a society where human resources are limited, it is difficult to show the value of operational hydrometeorological forecasts. The work carried out within IMPREX has taken a decisive step in this direction.* *Rémy Garçon, EDF*

Working with EDF and other hydropower companies in IMPREX has shown that fluctuations of both the climate system and the electricity market need to be considered in scenario analyses for the hydropower sector, and within management procedures and optimization approaches.



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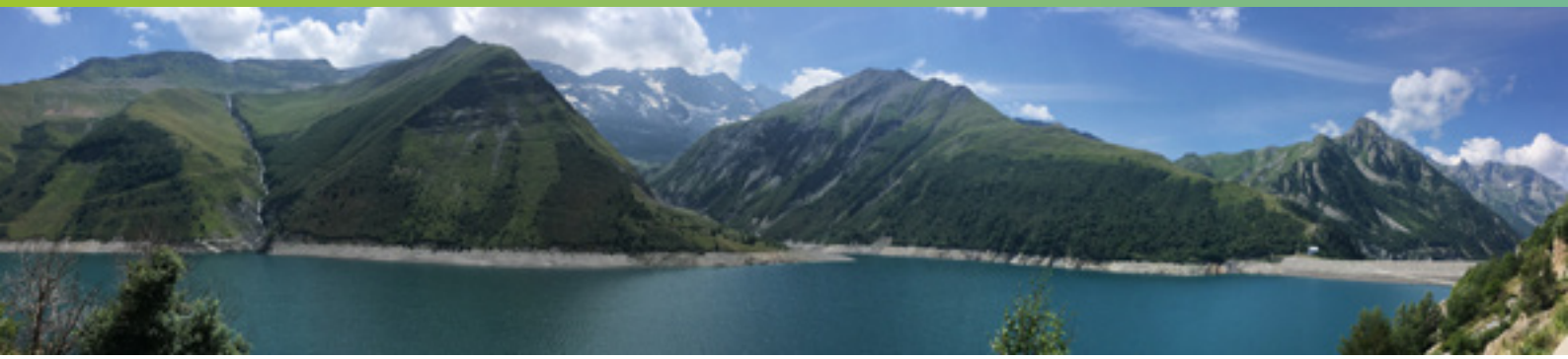

POLICY RELEVANCE

The European climate and energy policy aims at building up and sustaining an affordable, secure and sustainable energy system. Within this system, hydropower constitutes an important pillar for all European regions. In 2012, it corresponded to 11.7 % of the European net electricity generation and about 60 % of electricity from renewable resources. As a leading renewable energy resource, hydropower is therefore a key sector in achieving the EU targets for the reduction of greenhouse gas emissions and the transition to a carbon-neutral economy.

IMPREX developed strategies and approaches to enhance the value of reservoir water. By co-assessing forecasts and reservoir operation rules, IMPREX demonstrated how climate and water forecasting systems can be integrated into reservoir-based hydropower management to foster interactions among water users and bring value to climate services and society.

The project results have the potential to contribute to a positive development of European and nationwide strategies to reshape energy systems through reliable demonstration of benefits of improved hydrometeorological predictions and integrated management strategies, both in terms of economic gains (revenues) and societal gains (secure and optimized electricity production).

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IMPROVED FORECASTING AND RISK MANAGEMENT FOR THE WATER TRANSPORT SECTOR

New hydro-meteorological forecast products by IMPREX boost the operational efficiency of the European water transportation sector and help mitigate the vulnerability of waterway transport to hydro-meteorological extremes, in particular low flows.

Inland waterway transport along free-flowing rivers such as the river Rhine is susceptible to hydrological phenomena such as droughts or high discharge events, affecting safety and efficiency. Low stream flows and low water levels limit the maximum cargo carrying capacity of vessels and increase their energy consumption and their travel time.

Inland waterway transport is highly vulnerable to hydro-meteorological extremes

The 2018 low flow situation in many European Rivers, including the Rhine and Danube, has demonstrated the wide-ranging impacts of floods on the sector, from pressure and reduced vessel loading to a week-long gridlock. Showing the severity of this drought, a record-low water level was registered at Kaub gauge, a water transport bottleneck in the Middle Rhine. The extreme low-flow situation had a particularly severe impact on waterway managers, but also hit shipping and logistics companies and economic sectors that rely on waterway transport, such as industrial enterprises or power plants. As a result, waterway users and managers faced many a challenge in adapting their operational management procedures accordingly.

Hydro-meteorological extremes can be managed with accurate forecasts over a range of time scales

In the waterway transport sector, safety and efficiency are at risk due to hydrological impacts from short-term to climate time scale, illustrating the urgent need for new products for short to climate time scale forecasts to ensure efficient, strategic management within the waterway transport sector.

Climate change projections will be all the more important in future to ensure optimal fleet planning for shipping companies as well as for sustainable infrastructural waterway management. In light of this, stronger focus on climate change analyses and projections for the transportation sector should be considered in future research.

PRESENTATION OF IMPREX PRODUCTS

The IMPREX project developed two innovative approaches to help the transportation sector deal with hydrological extremes:

- **A pre-operational probabilistic water level forecasting system for traffic and transportation covering up to a 10-day forecasting period**
- **A pre-operational probabilistic forecasting system to improve waterway management (e.g. sediment management) and to aid logistics decision-making within river systems covering up to a 6-week period**

PRE-OPERATIONAL PROBABILISTIC FORECASTING SYSTEMS

IMPREX developed and implemented new forecasting systems for German waterways to give stakeholders improved navigation-related forecasts for better decision-making.

Longer lead times enhance decision-making processes

IMPREX delivers forecasts for discharges and water levels with lead times of more than four days. This was achieved by improving the hydrological modelling and output post-processing of existing forecasting systems. Forecasts with a longer lead time give companies a basis for better logistics planning, enabling them to take advantage of the maximum possible vessel load capacity for guaranteed economic efficiency. Possible savings are within the range of around EUR 5 million per year, with medium- to large-sized vessels benefitting more than small vessels owing to their larger transport volume.

The forecasts further allow decision makers to factor in any necessary transportation restrictions caused by floods. To achieve the longer lead times, extended-range meteorological forecasts were combined with an improved chain of hydrological, hydrodynamic and statistical models.

Economic benefits from rational decision-making facilitated by probabilistic forecasts

Deterministic forecasts are limited to relatively short-term lead-times as knowing related uncertainties becomes more relevant with longer lead-times. IMPREX developed probabilistic approaches that consider uncertainties, improving the basis for efficient and risk-based decision-making. Probabilistic forecasts include accurate uncertainty information, providing a more reliable basis for decision-making. IMPREX provides probabilistic forecasts on future water levels that exceed lead times of four days for the first time ever.

The 10-day and 6-week forecasting approaches that were implemented within IMPREX are based on recent hydro-meteorological ensemble forecasting systems. These comprehensive inputs are driving hydrological models for Central European Rivers, hydrodynamic models for the waterways as well as statistical models for the relevant gauges.

Various stakeholders already enjoy the benefits of using the new forecasting products. Besides waterway and harbour managers, the target user group also includes companies that rely on waterway transport, such as industrial enterprises, transmission network operators and river basin authorities. To fully understand and use these free-of-charge probabilistic forecasting models efficiently, knowledge and capacity development is helpful, although the products can be employed even with basic background knowledge. In-depth knowledge of the capabilities of the forecasts has been transferred to potential users in interactive stakeholder workshops.

COMPETITIVE EDGE

- **IMPREX's approach enables long-term planning, risk-based decision-making and the optimisation of management procedures on the longer term, thus increasing economic benefits.**
- **Very little training is needed, with experts in the field grasping the information in the 10-day forecast, in particular, with relative ease.**
- **The methodologies developed for waterway transport can be transferred to other rivers and other parts of Europe.**

CASE STUDY RIVER RHINE

EnBW, one of the largest energy supply companies in Germany, is pushing the expansion of its renewable energy business – primarily wind and hydropower – at the same time running state-of-the-art conventional power stations to secure energy supply. Waterway transport accounts for the biggest share in fuel logistics even though it is susceptible to hydrological extremes.

> *I am impressed by the model performances. The model ensures a responsible approach to dealing with inevitable uncertainties in forecasting*
>
> *Dr. Christoph Elsässer, analyst for energy meteorology at EnBW*

During extreme low-flow periods in past years, shipping companies reported up to 85 percent less cargo to avoid running aground, requiring more ships to transport the same quantities. During the second half of 2018, the low water situation resulted in transport restrictions, a sharp increase in logistics costs and reduced power plant availability. These disturbances in the company's waterway transport resulted in significant higher transportation costs. For both economic and ecological reasons, there is no viable alternative to water transport for the company.

The IMPREX pre-operational probabilistic forecasting system, which has a lead time of 10 days, creates an important added value for EnBW in the form of improved logistics planning security. The company worked closely with IMPREX for a period of two years, testing and implementing the system successfully.

The forecasting product has now been integrated into EnBW's management processes and is being used on a daily basis. Especially in summer and autumn, when low flow periods are likely to occur, the 10-day forecasts are instrumental in optimising management processes. Although there will be a comprehensive structural change within the German energy sector in future years, reducing fossil energy sources by 2038, waterway transport will remain an important mode of transportation for EnBW. For this reason, the company needs tools that can deal with hydrological extremes that are likely to occur with increasing frequency in future as a result of climate change.

> *Models such as these are an absolute must. There is a huge demand for these kinds of forecasts and this will become even more so the case in light of climate change*
>
> *Dr. Christoph Elsässer, EnBW*

POLICY RELEVANCE

EU-supported River Information Services (RIS) are a set of services designed to support inland waterway transport by improving safety and efficiency with the help of optimised traffic and transport processes. RIS include geographical, hydrological and administrative data on waterways as well as other data relevant to navigation in the short, medium and long term.

IMPREX has shown that the probabilistic forecasting products developed help make waterway transport more reliable and more efficient. More efficient decision-making processes will ultimately improve safety on European waterways. The possibility of integrating the results of the probabilistic forecasting systems presented into the RIS should be considered in order to have a positive impact on inland navigation traffic and transport management within the EU.

For further information please visit www.imprex.eu and check out our interactive product demonstrator!

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Forecasting systems for river transport management
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IMPREX is designed to help reduce Europe's vulnerability to hydrological extremes by achieving a better understanding of the intensity and frequency of potential disrupting events. Enhancing our forecasting capability will increase the resilience of European society as a whole, while reducing costs for strategic sectors and regions at the same time. The research project brings together 23 partners from 9 countries and has received funding from the European Union's Horizon 2020 Research and Innovation Programme.

URBAN WATER SUPPLY SYSTEMS

New water quality forecast approaches by IMPREX enhance the operational efficiency of water treatment plants and help reduce freshwater resources' vulnerability to hydro-climatic extremes.

Billions of cubic meters of freshwater are used in Europe every day for drinking purposes, but also for irrigation, manufacturing, heating, cooling and in service sectors such as tourism. Research shows that urban water supply is susceptible to weather extremes such as droughts and floods, particularly in southern Europe. This vulnerability puts a huge strain on Europe's water supplies and quality, challenging treatment capacity, drinking water safety and supply reliability. Especially droughts frequently pose mayor threats to human health, as water quality can drop significantly even during short drought events.

IMPREX developed operational methods to ensure optimal control of drinking water quality

Within IMPREX, various innovative services have been developed, including predictive water quality models, a methodology for linking meteorological and climate information to water quality models, and new treatment techniques to control water quality risks. The aim is to improve the operational and risk management procedures of drinking water treatment plants (DWTP) as well as the planning of water infrastructure.

The solutions developed within IMPRX help plant operators and water managers to anticipate the effects of heavy rain and drought episodes at an early stage, enabling effective and efficient decision-making within the operational plant management.

On longer time scales, water safety plans (WSPs), as constituted by the World Health Organisation (WHO), support a broad assessment and management approach to deal with risks caused by extreme events, including all steps in water supply from reservoir to consumer. Even though climatological and hydrological forecasts enable significant improvement in the definition and implementation of the WSPs, this is not a common practice in Europe. However, IMPREX results strongly support the uptake of water quality forecast approaches into the processes of successfully defining WSPs.

A considerable need for 'climate guidance' for plant operators and water planners has been observed within project activities. Guidance on how to anticipate future conditions and how to interpret and operationalise the corresponding scenarios is needed for efficient and effective management of urban water resources.

IMPREX WATER QUALITY TOOLS

Within IMPREX, researchers developed and applied innovative methodologies to predict water quality changes with lead times up to several months. Advanced monitoring campaigns and pilot implementations of new treatment techniques to improve the management of climate-driven algal growth and cyanotoxins production have been conducted successfully in several Spanish river basins.

The target group of the IMPREX approaches includes managers of small, medium and large DWTPs using surface water as well as decision-makers in water infrastructure planning.

IMPREX TOOLS:

A - Management of high turbidity events for DWTPs
B - Advanced control of the risk of cyanotoxins for DWTPs
C - Forecasting algae development in water reservoirs

A. Forecasting and management of high turbidity events based on meteorological drivers

High turbidity events are generally caused by intense rainfall, which frequently leads to disruption of treatment processes and causes additional costs (through the need to use more chemicals in the treatment process) and health risks (due to the rapid modifications and changes in the treatment system).

The developed approach, tested in various Spanish river basins, optimises operational management of DWTPs, reducing the costs of chemicals and energy input. Safety risks were reduced, and water supply continuity was secured. The approach can be adapted to forecast different target variables tailored to the needs of the plant operator.

AT A GLANCE

- ***Forecast & processes tested:*** Forecasting of high turbidity events based on meteorological drivers (3 to 36 hours in advance).
- ***Methods and climate inputs:*** Statistical model based on machine learning, using observations (including radar), meteorological forecast (from ECMWF) and other variables.
- ***Results and integration in decision-making:*** The model skill is satisfactory to forecast events 36 hours out. The algorithms are currently tested with a larger database and integrated into one of the SUEZ* real-time platform for an operational use.

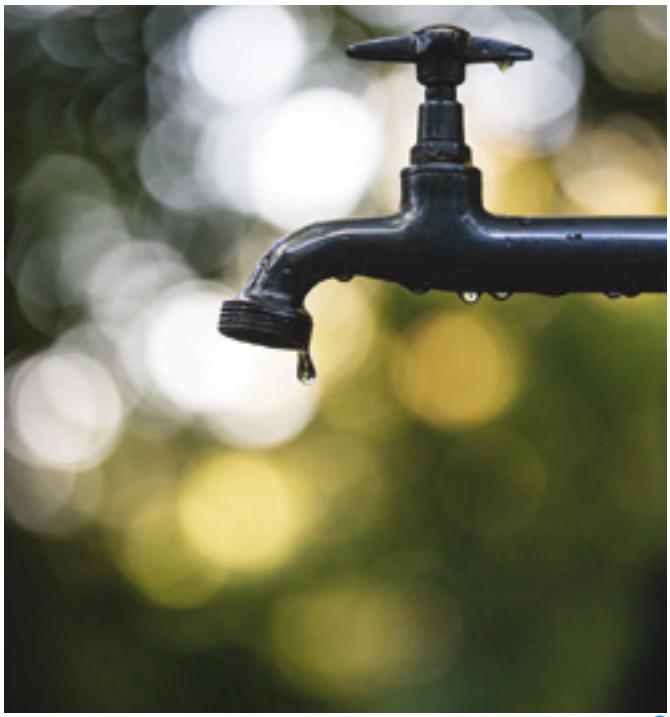
B. Advanced control of the risk of cyanotoxins for DWTP

The management of water quality is based on detection of pathogens and toxic substances monitored at different key locations in the drinking water plant and supply channels. However, this methodology proved to be inefficient or too slow to identify and manage risks adequately, especially in case of cyanotoxins: water quality analyses can take several hours, are conducted at a low frequency (daily or weekly) and are particularly costly.

The new IMPREX approach supplements this monitoring by utilizing past information on the dependence of cyanotoxins on external hydrometeorological drivers (e.g. sunshine, temperature, wind and rainfall). The approach is very time-efficient and less costly than the usual water quality analyses.

AT A GLANCE

- ***Forecast & processes tested:*** Forecasting algae growth; new treatment processes.
- ***Methods and climate inputs:*** Statistical model using meteorological forecasts, regression based on multiple variables.
- ***Results and integration in decision-making:*** Risk management guidelines have been developed and capacity building events have been carried out to facilitate implementation processes enabling an easy uptake by other DWTPs in Europe. The indicators developed as part of IMPREX have been implemented in operational procedures of La Contraparada DWTP and are taken into account in the dosing of reagents for water treatment.



** Suez is an international utility company which operates i.a. in the water treatment sector.*

C. Forecasting algae development in reservoirs

Algae development in water reservoirs challenges the water treatment due to an increase of suspended solids and the potential presence of toxins harmful to human health. Algae blooms can be caused by factors such as high temperatures or high concentrations of nutrients caused by droughts and heavy rain events.

The new forecasting approach combines the use of meteorological and seasonal forecasts with modelling of chlorophyll-a within reservoirs. Thus, risk management procedures and operational management as well as long-term infrastructure planning are supported by forecasting reliable baseline information.

AT A GLANCE

- ***Forecast & processes tested:*** Forecasting algae development under changing climatic conditions.
- ***Methods and climate inputs:*** HUMEDAL dynamic model, use of climate change projections (inflow), meteorological and seasonal predictions.
- ***Results and integration in decision-making:*** The model provides reliable information on the evolution of the trophic state of reservoirs.

CASE STUDY

AQUATEC, a SUEZ company, is in charge of managing the water intake of a treatment plant in Spain, ensuring an adequate water quality and controlling the potential risk of cyanotoxins. The company worked with IMPREX, using the newly developed approach to control risks of cyanotoxins within the reservoir of a selected DWTP in south-eastern Spain.

During IMPREX, AQUATEC applied the approach in close cooperation with plant personnel, controlling the risk of cyanotoxins and improving risk management strategies. Together with AQUATEC, the DWTP analysed different drivers of algal growth and took additional samplings, contributing to the standardization of the identification and quantification of the algal community. It has been established that climate variables which are easily measurable (such as temperature and sunshine hours) considerably influence algal growth. This resulted in an update of the decision-making process of the DWTP, which now uses the algal growth indicators that have been identified. This allowed detecting risks at an early stage and preparing for emergency situations in order to guarantee both reliable and safe drinking water supply and the DWTP's economic efficiency.

During an extreme drought event in October 2018, a rare species of cyanobacteria affected the DWTP. With the information provided by the IMPREX approach, the algae growth was detected at an early stage, which facilitated adequate and timely management steps.

> *Working with IMPREX changed our company's strategy of managing cyanotoxins. Now, the risk management is characterised by a lot more certainty. We have a much safer basis for decision-making now, using a relatively simple but reliable approach developed within IMPREX*
>
> *Isabel Hurtado (AQUATEC)*

In order to upscale the use of the innovative approach, IMPREX successfully conducted a webinar for plant operators of SUEZ Spain to broadcast the approach to controlling the risk of cyanotoxins and to promote the accompanying risk management guidelines. The knowledge acquired will be useful for the SUEZ Group to follow the WSP approach as required by Spanish legislation.

In the face of changing climate, new species of bacteria are spreading, posing a major threat to water supply security. Each cyanobacteria bloom has different drivers and develops differently. New data, for instance from satellite platforms and historical data, are needed to allow for early risk detection.

For further information please visit www.imprex.eu and check out our interactive product demonstrator!

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DROUGHT PREPAREDNESS, MITIGATION AND MANAGEMENT

– Innovative approaches for the agricultural sector

- *New hydro-meteorological forecast products by IMPREX allow for more proactive drought management in the European agricultural sector*
- *New drought risk management tools help mitigate the agricultural sector's vulnerability to prolonged droughts*
- *Innovative products contribute to stable economic development and increased European food security*

The likely increase of droughts, affecting local and regional economies, poses a major threat to the agricultural sector in Europe and would lead to substantial economic losses. The unusually hot and dry European summer of 2018 resulted in severe water scarcity. Food producers suffered, not only in southern Europe but also in northern parts of the continent where agricultural systems are not well adapted. In the future, water will become even scarcer in many regions due to climate change impacts.

Drought risk can be defined as the interaction between natural drought hazards and their impacts on society and the environment. IMPREX developed approaches to assess drought risks that consider both the probability of drought-related hazard events and their possible socioeconomic and environmental consequences. This factsheet will outline key IMPREX contributions.

Proactive drought risk management for drought-induced disasters

To improve proactive drought risk management within the agricultural sector, an objective knowledge base and adequate tools and methodologies are needed. Calling for a more sustainable solution, UNISDR (2009) suggests a systematic process to prevent, mitigate and prepare for drought-induced disasters. This includes climate change analysis, prediction of drought damage under certain conditions and assessments of the effectiveness of management options and interventions. This is offered within IMPREX.

Economic benefits from rational decision-making facilitated by probabilistic forecasts

Improved weather and climate services, such as improved temperature and rainfall forecasts, are indispensable for

efficient decision-making and drought management within the agricultural sector. The IMPREX research project has contributed substantially to improved hydrological and meteorological forecasts and their uptake. Together with end-users, IMPREX developed probabilistic approaches that quantify and visualize uncertainties, improving the basis for efficient and risk-based decision-making.

Forecasts with longer lead times enhance decision-making processes

IMPREX identified considerable interest in predictions with an extended lead time, especially seasonal predictions. Forecasts with an extended lead time enable the agricultural sector to adopt better logistical planning of resources and operations, and decision-makers to take preventive actions to reduce the impacts of droughts.

IMPREX incorporated seasonal forecasts of precipitation into the AQUATOOL decision support system for water resources management and risk-based water allocation. Risk mapping is facilitated through the FRIDA framework for index-based drought analysis, which quantifies impact-based indices for efficient drought management and through a methodology for efficient water accounting that synthesizes climate change impacts on agricultural water use. To improve the approach to complex interactions, IMPREX offers tools for quantify drought impacts and a framework to assess the cost-efficiency of adaptation measures to better cope with water scarcity. IMPREX also developed the drought risk assessment and management tool as well as a methodology for risk-based allocation and a system dynamics model.

IMPREX TOOLS:

- Improved AQUATOOL modules
- Framework for Index-based Drought Analysis (FRIDA)
- Water accounting methodology to synthesize climate change impacts on agricultural water use
- Drought risk assessment and management tool
- Methodology for optimization of water allocation
- The system dynamics hydro-economic model of adaptation to droughts

AQUATOOL – A Decision Support System (DSS) for water resources management and risk-based water allocation

The AQUATOOL decision support system maps the essential hydrology of a basin and its demands to then track the consequences of specific hydrometeorological scenarios on this system. By explicitly representing water supply risks, an optimization of the basin system can be generated. The tool is used by a wide range of water resources managers in Spain and other places.

The IMPREX project upgraded AQUATOOL with an improved risk-based approach. This enables more realistic, probabilistic risk assessments and scenario generation through the incorporation of tuned meteorological forecasts. IMPREX also provided an incremental improvement by addressing multi-sectoral water demands in the risk profile.

AQUATOOL facilitates the generation of data needed for river basin and drought management plans

The tool has the potential to establish the basis for European river basin and drought management plans, as demonstrated by its current use in most Spanish river basins.

AQUATOOL consists of several modules that can be combined in various ways to adapt to specific user needs. Three important AQUATOOL modules have been used and further refined within IMPREX:

- **SIMGES** – a general water management and allocation module for river basins
- **SIMRISK** – a risk assessment module designed for river basin management
- **EVALHID** – a hydrological module focussing on water availability within a river basin

AQUATOOL supports efficient and effective river basin management by enabling high-quality drought risk analyses and measuring efficiency as well as long-term planning within a river basin e.g. water management and allocation simulations and probabilistic assessment of water shortage and vulnerability.

FRAMEWORK FOR INDEX-BASED DROUGHT ANALYSIS (FRIDA)

– A machine learning-based tool to define impact-based indices for drought monitoring and management

Drought sensitivity to hydro-meteorological variables is different for each river basin as it depends on factors such as topography and land use. This sensitivity can be captured in one or several drought monitoring indices that can contribute to the development of the drought management plans as put forward by the EU Water Framework Directive. To support the definition of drought indices, IMPREX developed a Framework for Index-based Drought Analysis (FRIDA), which generalizes and automatizes the selection process of the variables used in the index formulation and facilitates the stakeholder participation process.

FRIDA can be used to define basin-customized drought indices in any European drought-prone river basin.

FRIDA relies on state-of-the-art feature extraction, machine learning, data fusion and artificial intelligence techniques for the synthesis of a heterogeneous and multi-source dataset (e.g. water stored in reservoirs, river flow and precipitation) into a compact basin-specific drought index. This index can be used by river basin managers, at the local, regional and national scales to monitor the onset and evolution of drought events and to support operational drought management.

WATER ACCOUNTING METHODOLOGY TO ASSESS CLIMATE CHANGE IMPACTS ON AGRICULTURAL WATER USE

– A single framework to extract information from multiple river basin-level studies

Water accounting is the process of communicating information related to water resources and the services generated from consumption use in a geographical domain (such as a river basin, a country or a land use class) to users such as policymakers, water authorities, managers, etc. Water accounting can be useful to standardize information from a wide range of sources and can extract policy-relevant indicators.

Pan-European information on climate change impacts on water resources for agriculture is scattered: while there are many river-basin level studies, they currently do not reach the European decision-making-level. IMPREX developed a water accounting framework which allows a standardized examination of climate impacts on water resources availability and use for agriculture across multiple studies and river basins. Typically, water accounting is used to report on past water resources, but here it has been used to map future climate change impacts.

- **Use of a single framework to synthesize river basin-level climate impact studies**
- **Methodology assures that local system knowledge (infrastructure, socio-economic, legislative, etc.) is not neglected in assessments at the pan-European level**

The IMPREX methodology for water accounting is especially useful for channelling and presenting different climate impact case studies (and data) in one single framework, enabling a direct comparison of different European river basins. The approach has been tested and validated based on five European river basins and has the potential to integrate and synthesize a much higher number of studies across Europe, thus generating information for policies on water and agriculture at the European level. Information on climate impacts and the potential for adaptation measures can be assessed, with the principal advantage that the underlying data sources are backed up by local experts at the river basin-level.

DROUGHT RISK ASSESSMENT AND MANAGEMENT TOOL

– Quantitative risk-based decision-making for fresh water management

IMPREX developed the drought risk assessment and management method and tool, including a cost-benefit analysis of current water resources management practices as well as a quantification of cost-efficiency of alternative drought risk reduction strategies.

A comprehensive risk profile as a reliable basis for decision-making

The IMPREX drought risk assessment and management tool enables an integrated risk assessment for present and future situations, including an analysis of the effects of climate change and the effectiveness and benefits of adaptation measures. The cost-benefit module also allows for an innovative approach to water allocation. The tool and underlying method provide proactive drought risk management within the agricultural sector and between different sectors that rely on water, such as waterway transport. The method delivers a systematic process to mitigate and prepare for drought damage.

The result of the tool is a comprehensive, objective risk profile that offers a good basis for decision-making. The profile is the outcome of a stakeholder process substantiated with data and model results. The risk profile identifies opportunities and measures and quantifies their subsequent consequences as a yearly expected damage value. By combining drought damage with the probability of drought occurrence, it is possible to quantify drought-related risks in present and future situations while taking into account the influence of climate change associated with various adaptation measures. Examples are controlling water flows in major waterways, local infrastructural solutions to supplement water and local adaptations by the end-users.

Figure 2: A schematic overview of a drought risk assessment framework

FORECAST-INFORMED WATER MANAGEMENT

– An approach to reduce multi-sectoral conflicts

IMPREX adopted a cross-sectoral approach to analyse river basin management strategies and investigate the value of IMPREX forecasts for different end-users. The approach has been demonstrated in the Lake Como basin, which is characterized by the presence of competing multi-sector interests (e.g. flood control, irrigation supply, hydropower generation, environmental protection).

IMPREX established a participative co-design approach with local stakeholders to develop a set of evaluation indicators that take into account differing interests. The IMPREX forecasts value was quantified in terms of end-user economic benefits from using forecast information to prompt anticipatory operations and manage extreme events. Moreover, IMPREX forecasts allow the reduction of existing conflicts across sectors by supporting the identification of compromise management solutions that better balance the competing demands.

Optimal water allocation between sectors based on IMPREX' forecast accounts for:

- **Economic gains with an average of 1.2% of farmers' annual profit, which raises up to 1,6% during extreme droughts for irrigated agriculture**
- **Economic gains with an average of 1,6% of the annual revenue for a company in the hydropower sector**

These cost savings are projected to increase under climate change conditions.

Figure 3: Lake Como basin and its multi-sectoral stakeholders

THE SYSTEM DYNAMICS HYDRO-ECONOMIC MODEL OF ADAPTATION TO DROUGHTS

Within IMPREX, cross-disciplinary knowledge has been integrated into the development of a new system dynamics modelling tool for the assessment of adaptation investment scenarios. Based on a stakeholder consultation process, the model delivers a qualitative and quantitative representation of the network of dependencies that affect water supply, demand and value.

Integrating scientific and end-user knowledge as part of a participatory approach enhances operating efficiency

The system dynamics model provides advice on optimal investment scenarios in adaptation measures. Consulted stakeholders include regional, local and river basin authorities as well as researchers from relevant fields, including experts in water resource management and economists.

The model consists of two modules: a regional system dynamics economic module linked to a hydrological module. Projections from regional climate models serve as input for the hydrological module to explore the impact of different climate scenarios. In addition, different socio-economic scenarios and adaptation strategies have been explored. In particular, regional investment flow scenarios have been simulated, which will help improving water use efficiency in the face of upcoming droughts.

CASE STUDY – Drought Management within the Júcar River Basin in Spain

The Júcar river basin, a typical Mediterranean basin, suffers from recurrent multi-annual droughts. Adequate adaptation management strategies to increase resilience to both excess and lack of water are essential to buffer economic risks.

Long-lasting and extensive droughts make the allocation of water resources among competing sectors especially important. Within the Júcar river basin, agriculture accounts for about 80% of the total water demand. With its heavy dependence on sufficient water resources, the sector is vulnerable to restrictions in the water supply, which lead to reduced yields, loss of annual crops, and persistent damage to permanent crops. These experiences highlight the importance of implementing a proactive drought planning and management approach in order to cope with extensive droughts.

> *AQUATOOL improves drought risk management by delivering information on efficiency of concrete drought risk adaptation measures, thus avoiding temporal and permanent loss of crops due to water deficit*
> *- Teodoro Estrela, CHJ*

AQUATOOL has been tested and implemented within the Jucar river basin and many other Spanish river basins. The tool provides the basis for efficient operational management. The Júcar river basin Partnership (CHJ in Spanish), a public-private participatory institution that unites all relevant stakeholders of water resources management within the basin, manages and allocates water among urban, agricultural, hydropower and industrial users within the Júcar river basin. Within the framework of IMPREX, CHJ together with the Technical University of Valencia (UPV) applied the AQUATOOL decision support system, especially the modules EVALHID, SIMGES and SIMRISK, for hydrological modelling improved by the incorporation of seasonal forecasts, to simulate the performance of the water resources system in general and to conduct a risk assessment for selected adaptation measures specifically.

> *The use of this combination of modules will help to improve early warning systems and strategic decision making during droughts to ensure urban water supply and prevent water quality problems - Javier Macian, Aguas de Valencia*

The AQUATOOL modules provided a clear added value for CHJ by showing the developments of water demand and reservoir storage. The IMPREX approach is especially helpful for dry years, when effective and efficient drought management is indispensable. AQUATOOL's skilled meteorological forecasts and improved schemes to link forecasts to local hydrological conditions have been used successfully to reduce uncertainties of decision-making.
IMPREX shows that improved accurate forecasts over a range of time scales are in high demand within the Mediterranean. That is why AQUATOOL can be an essential tool to improve effective drought management.

> *The work done within IMPREX has significantly improved the results of estimating drought risks - Javier Macian, Aguas de Valencia*

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EUROPE'S GLOBAL WATER RISK

New IMPREX approaches boost the operational efficiency and help reduce the European economy's vulnerability to hydro-meteorological extremes occurring worldwide, in particular drought and flood events.

Impacts of extreme weather events and climate change on European economic sectors, such as agri-food and manufacturing, have traditionally been addressed locally. Impacts within the European borders have been assessed through sectoral risk assessments, including an analysis of related policies. However, sources of vulnerabilities of many sectors to extreme weather events often lie outside Europe. In a globalized, highly connected world, dependence on raw material imports, demand/supply relations and trade balance are intensifying. Climate change impacts outside the European borders are expected to increase economic risks for agri-food importers in the Member States. The effects manifest in various ways, including biophysical impacts on remote agricultural production resulting in unexpected supply shortages, damage or delays to supply-chain infrastructure, changes in overseas production and world commodity prices.

IMPREX research shows that this vulnerability has not yet been addressed adequately in climate adaptation, bilateral trade and international development policies. IMPREX focused on mapping dependencies of the European economy on water resources outside its borders and assesses the vulnerabilities of these dependencies to water scarcity and droughts as well as flood damages, both now and under changing climate conditions.

Activities within IMPREX highlight sectoral dependencies throughout the European region, but also consider EU-wide strategies, such as the Climate Adaptation Strategy and the EU's trade policies.

PRODUCT PRESENTATION

The IMPREX project developed two innovative approaches to help European economy dealing with hydrological extremes:

- ***WATE:*** *WAter, Trade and Economy tool*
- ***Acclimate*** *– A unique model of loss-propagation in a global supply network*

WATE – WATER, TRADE AND ECONOMY TOOL

WATE, developed by FutureWater, is used to assess water dependencies of economic sectors and their supply chains' vulnerability to droughts and water scarcity.

More specifically, the tool displays

- Water used in agricultural production globally, including soil moisture and irrigation requirements for many different crops and processed products
- Trade of agri-food commodities and virtual water for agri-food products between nations
- Water scarcity and drought severity in crop producing regions and their changes under climate change
- Water footprint calculations for production, consumption and imports/exports.

The input requirements for the tool range from trade statistics and agricultural yields to climate and hydrological projections, water use statistics (industrial, domestic and irrigation) as well as agricultural production statistics and locations.

WATE allows the compilation of

- Agricultural import dependency maps
- Water dependency maps (virtual water imports) showing the water used to produce imported products
- Maps of imports' vulnerability to drought severity and water scarcity in different time periods (e.g. historical, climate change), and country profiles of water dependencies and vulnerabilities.

WATE has been commercialized in terms of consultancy services on climate change impacts. A consultancy start-up, R2Water, was founded to commercialize the approach and tool.

ACCLIMATE – A GLOBAL MERCHANDISE NETWORK MODEL

Acclimate is a loss propagation and agent-based model developed at Potsdam Institute for Climate Impact Research (PIK). It is designed to analyse cascades of economic losses induced by climate shocks (primarily floods) in a global supply network. The tool simulates indirect and direct effects along global supply chains for time scales of days to months after flood events. Using national sectors as agents, the model can be applied to study the global propagation of losses induced by idealized disasters. Input data to feed the model was provided by e.g. FLOPROS: an evolving global database of flood protection standards that gives explicit information on current flood protection at the global level (developed at the Institute for Environmental Studies (IVM).

Figure 1 presents the assessment process of the trade shifts due to global flooding events using Acclimate. China is projected to have the largest direct flood losses. While the USA will suffer indirectly along its supply chains due to its unbalanced trade relationship with China, the EU is much better prepared for future global flood losses.

The Zeean project, financed by the German ministry BMBF, aims to further develop Acclimate into a tool that models and predicts the indirect impacts on the supply chain attributed to local production failures taking into account all relevant interdependencies within the global network.

ACLIMATE assesses reasonable leverage points and identifies dynamic bottlenecks

Within IMPREX, the model was further developed to incorporate the output of fluvial flood simulations as direct losses. In addition, it advanced the state of the art in modelling indirect losses of disasters by explicitly allowing the incorporation of downstream impacts and mitigation actions to (unanticipated) shock events. Acclimate has the potential to consider other drivers than flood damages. Further activities will focus on global impacts caused by heat waves and hurricanes.

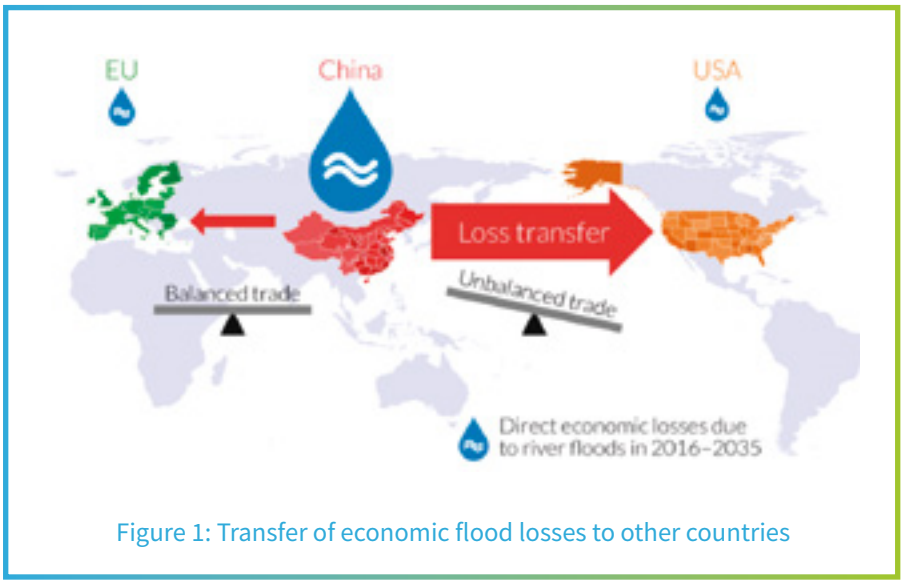

Figure 1: Transfer of economic flood losses to other countries

COMPETITIVE EDGE

- *The products presented here enable a new perspective on regional and national trade and economy policies. By explicitly displaying projections of indirect and direct future losses, IMPREX illustrates the EU's large susceptibilities to climate effects outside its borders and provides quantified information on supply-chain risks to multi-national actors, economic sectors and consumers.*

- *IMPREX further increases understanding of supply chain dependencies in terms of water use. Vulnerabilities of the European economy on global production and supply of goods caused by hydrological extremes were detected.*

USE CASE SCENARIO

ChocolateDreams is a modern cocoa processing plant and chocolate producer based in the Netherlands. The company relies on cocoa produced in Ivory Coast, where flood events occur on a regular basis and droughts frequently strain business procedures. In recent years, flooding on cocoa plantations and prolonged drought have led to a significant reduction in main crop harvest. Delays and failure of deliveries affected not only local producers but also European companies, such as ChocolateDreams.

To analyse dependencies and vulnerabilities to weather extremes under changing climate conditions on the one hand and to effectively adopt adaptation measures to business risks on the other hand, the company uses the commercial services offered by R2water, a company created by partners during IMPREX, and ran through a multi-stage consultation process. This way, the company intends to be prepared for planned business expansion. Import's vulnerability of imports to extreme events is elaborated for current and future climate conditions. A comprehensive risk assessment focuses not only on first-tier suppliers, but also takes the entire supply chain into account. R2water provides better access to information on climate change impacts and the associated financial risks while displaying potential production loss risks at seasonal to climate time scales. Relying on international commodity supplies, the company's dependencies are mapped to better understand water-related vulnerabilities and secure business.

Lessons learned within IMPREX include the need for increased adaptive capacity and resilience. ChocolateDreams intends to develop business strategies that further promote the mitigation of negative consequences of remote climate extremes. Associated risks need to be taken into account when developing future bilateral relations with trade partners and suppliers. The company also wants to channel investments into measures that will increase resilience and strengthen water governance to ensure sustainable production in key producing regions. Concrete adaptation measures may include working with supplying farmers to enhance water use efficiency and soil protection as well as improving production efficiency and the use of idle capacities.

POLICY RELEVANCE

IMPREX' work shows that the private sector, individual member state governments and the EU community have an important role to play in supporting relevant producers in developing countries to ensure that climate change impacts are effectively mitigated. To assist producers and importers and to increase awareness of the risks that climate change poses to the agri-food business, EU policies and business strategies should consider that the EU's economy is highly dependent on goods produced in regions that are vulnerable to water related impacts.

For further information please visit www.imprex.eu and check out our interactive product demonstrator!

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IMPREX is designed to help reduce Europe's vulnerability to hydrological extremes by achieving a better understanding of the intensity and frequency of potential disrupting events. Enhancing our forecasting capability will increase the resilience of European society as a whole, while reducing costs for strategic sectors and regions at the same time. The research project brings together 23 partners from 9 countries and has received funding from the European Union's Horizon 2020.

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POLICY BRIEF

The importance of including compound events in the implementation of the Floods Directive

MAIN MESSAGES

- The phenomenon known as compound flooding, caused by the coincident occurrence of multiple flood drivers such as high precipitation events, storm surges or high runoff rates, has caused some of the most destructive flooding in Europe. To date, however, the compounding nature of multiple drivers has not been given sufficient consideration in current flood hazard and risk scenarios developed, for example, in the context of the Floods Directive. This may lead to a biased assessment of flood risk, both for current and future climate conditions.

- IMPREX puts forward a host of reasons as to why it is important to incorporate compound events into flood hazard and risk assessments, providing related methods and tools:

  - Incorporation of compound events can enhance the reliability of flood statistics and consequently flood hazard maps

  - Probability of compound events may change in the future climate

  - Compound events may call for different flood measures, making it imperative to factor them into the flood risk management plans drawn up

→ Better understanding of the emergence and impact of compound events is needed. Particular attention should be paid that the correlation between flood drivers is quantified more clearly. More emphasis on and support for related research is needed.

→ Awareness and knowledge of compound events needs to be increased at all levels of river basin management.

→ Compound events should be factored in at every stage of implementation of the Floods Directive. The explicit mention of compound events in the Floods Directive as well as in related Guidance Documents should be given proper consideration.

BACKGROUND

In October 1998 and January 2012 in Delfzijl in the north of The Netherlands, discharge of heavy precipitation on the polder to the sea was blocked due to storm surges happening at the same time, leading to unprecedented flooding. The 2013/2014 flood in the South West of the UK was caused by heavy precipitation on an already saturated soil in combination with high ocean water levels. A common feature of these events was that they were caused by the joint occurrence of two or more drivers, such as heavy precipitation, storm surges at sea or increased water levels in a river, which ultimately led to these extreme events. Even though compound events are known for causing some of the worst flood events, they have often been viewed as an ancillary issue in hazard and risk assessments towing to the difficulties in characterizing and predicting them. Research has shown, however, that compound floods are not only among the most destructive but are also far more common in Europe than often perceived, which is why it is all the more imperative that they be taken into account in flood statistics as well.

Within the framework of the Floods Directive all Member States are obligated to put in place flood risk management plans to prevent, prepare for and ensure protection from flooding. In line with the Directive, flood hazard and risks are assessed in order to define flood scenarios for different return periods. The Floods Directive accounts for the great variety of flood causes by urging Member States to prepare for different types of floods that are relevant in their territory. Neither in the Floods Directive nor in related Guidance Documents, however, are compound events mentioned. Further, compound events are not sufficiently taken into account when developing flood hazard maps in the Member States. In light of the current debate on how to make Europe fit for future climate and weather conditions, compound events could well become even more relevant, especially given the potential impact that changes in weather patterns and the projected sea level rise - a new flood driver - have on the probability of occurrence of compound events.

The research project IMPREX has explored the occurrence of diverse examples of compound flood events for the current as well as the future climate in five case studies in the Netherlands and in the UK. The results underline the need to factor in compound events in implementing the Floods Directive.

RELEVANCE OF COMPOUND EVENTS

Compound events can cause extreme flood events even if individual drivers are not extreme in themselves

Compound events can be found in any areas of natural hazards, for example, droughts, wildfires, storms and floods. Multiple definitions of compound events have been proposed. The common denominators of most definitions are, however, the coincident or consecutive occurrence of more than one driver, resulting in amplified risk and, ultimately, an extreme (e.g. flood) event. It is important to mention that the individual drivers of compound events in themselves do not necessarily have to be extreme to cause an extreme hazard. Even average precipitation, for example, can cause flooding if it occurs in combination with previously saturated ground.
IMPREX has developed methods to estimate the likelihood of different cases of compound flood events.

Incorporation of compound events can enhance the reliability of flood statistics and consequently the reliability of flood hazard maps

One of the challenges faced in implementing the Floods Directive in Member States is the development of reliable flood statistics as the basis for flood hazard maps. Usually flood probabilities are derived from historical flood data that is integrated into hydrological models used to derive useful statistics. Future climate conditions are mapped by manipulating or replacing the input data with information from future climate projections. For events that are governed by multiple drivers, assumptions are made on the statistical correlation between these drivers, which have a big impact on the outcome of the flood probability estimate.

A difficulty that stands in the way of an accurate derivation of the correlation structure is that observational records are only available for limited time spans, which may not cover very extreme events driven by a rare combination of multiple drivers with an unknown mutual dependence. This in turn may lead to biases in the derived flood statistics and risks. On the basis of a number of case studies of compound flood events, IMPREX has enhanced the understanding of the statistical dependence of flood drivers. For instance it provided a method involving a high resolution regional climate model simulation for current and future climate conditions, which was coupled with hydrological and/or hydraulic models. It provided much longer time-series of relevant variables than available from observations. This approach was used to analyze statistical dependencies between drivers of flood events when deriving flood risk. This method was applied to different case studies in order to quantify the effect of the dependency between flood drivers and how this might change in future climate. The method was thus shown to be transferable to other applications.

The results highlight not only the need to incorporate compound events into flood hazard assessments. In fact, they also show that it is possible and should be further explored for the implementation of the Floods Directive.

Probability of occurrence of compound events may change in future climate

One of the biggest unknowns in climate research is the effect of the changing climate on weather patterns. This leads to great uncertainty in future climate scenarios and, consequently, flood scenarios. This also gives rise to challenges for Member States when it comes to drawing up flood hazard maps in the context of implementation of the Floods Directive. When considering changing weather patterns it is important not only to look at changing patterns of isolated flood drivers but also to explore more deeply how climate change alters the correlation structure between such drivers, as this may affect the probability of compound events. A change in the correlation between drivers can be caused by altered large-scale atmospheric circulation patterns affecting storm statistics, or changes in hydrological phenomena that affect flood risk, increasing or decreasing it accordingly; in both cases, the potential impact on the financial risk and preparatory measures is substantial. For this reason, a better understanding of the driving forces behind compound events is paramount.

The current debate on how to give greater consideration to climate change impacts in flood hazard and risk maps should not leave out the potential changes in the probability of extreme events due to compound scenarios.

Compound events may call for different flood measures, making it imperative to factor them into the flood risk management plans drawn up

The Floods Directive requires Member States to select appropriate flood measures based on a prior assessment of flood hazard and risk. When it comes to choosing flood measures that also take compound scenarios into account, however, there is limited understanding and experience. This becomes especially critical if flood measures designed to counteract flooding caused by individual drivers, fail in compound events. IMPREX has investigated a few such cases which show that compound events may require different flood measures than those that would be necessary if the driver were to occur on its own. One case study shows how the coincidence of extremely high river discharges of River Rhine and Meuse in combination with storm surge off the Dutch coast and projected sea level rise does not allow for the water to be discharged to the sea, which in turn leads to a huge flood risk resulting from the fact that the flood measures can no longer work here. The same holds true for another case study, where the simultaneous occurrence of peak flows meant two rivers (Dommel and Aa) were no longer able to discharge into the River Meuse, resulting in severe flooding

The outcome here shows how vital it is to take the risk of compound events into account when evaluating suitable flood measures, for example, when putting together programmes of measures as part of flood risk management plans.

RECOMMENDATIONS

IMPREX not only provides evidence on why proper consideration of compound events is much needed also in the context of implementation of the Floods Directive, but also shows how compound events can be incorporated into flood statistics, enabling better preparation and protection from some of the most destructive floods ever seen. Based on the work conducted within IMPREX, the following recommendations are made:

- **Improve the understanding of compound flood events and the correlation between drivers through research.** The integration of compound events into flood scenarios is crucial to be able to accurately gauge the probability of extreme events and improve flood statistics. Better understanding of underlying meteorological and hydrological processes of compound events is needed. A first step has been taken in the form of the European COST action DAMOCLES, a recent initiative (involving IMPREX partners) that seeks to coordinate research and improve the assessment of compound events.

- **Raise awareness of compound events with policy and decision makers and strengthen related management capacities.** Several EU Member States have had hands-on experience with compound events. This experience should be actively shared in order to deepen our knowledge and bridge the gap between research and practice.

- **Include compound events in the European policy framework for flood risk management.** Flood risks resulting from compound events need to be taken into account at every stage of implementation of the Floods Directive, from deriving flood statistics and developing flood hazard maps to determining flood measures. Proper consideration should therefore be given to the possibility of explicitly specifying compound events as a potential flood source in the Floods Directive as well as in related Guidance Documents.

This policy brief was compiled by adelphi based on the work done within the context of the research project IMPREX with special contributions by Bart van den Hurk (Deltares), Dorien Lugt (HKV Consultants), Emma Aalbers (Royal Netherlands Meteorological Institute) and Albrecht Weerts (Deltares). Graphic design by Arctik.

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POLICY BRIEF

Probabilistic Approaches for Improved Flood Risk Assessment and Management under consideration of uncertainties

KEY MESSAGES

- One of the challenges faced by Member States in implementing the Floods Directive is how to factor in uncertainties in flood hazard and flood risk assessments within flood risk management strategies. Tools are needed to support decision-making on appropriate flood measures under consideration of uncertainties.

- Probabilistic methods quantify and visualize uncertainties by providing results as a set of potential values with their corresponding probability of occurrence. The research project IMPREX shows how the implementation of the Floods Directive could benefit from the use of probabilistic approaches in calculations on flood occurrence and flood damage:

  - Probabilistic flood occurrence projections could improve flood hazard maps depicting uncertainties of potential flood scenarios, including climate change impacts

  - Probabilistic flood damage assessments foster a more realistic understanding of potential flood risks and can help identify more efficient risk management measures

  - Probabilistic approaches can improve early warning by extending lead times for water level and river discharge forecasts

  - Probabilistic approaches can bolster more rational decision-making, e.g. in the context of drawing-up flood risk management plans, by factoring in all the possible hazards and risks

→ The potential that probabilistic approaches have with regard to the implementation of the Flood Directive should be explored systematically, e.g. for the development of flood hazard maps, economic damage assessments, and establishing programmes of measures. Research and development of probabilistic approaches ought to be supported.

→ Guidance on the potential of probabilistic approaches and how to include them in the various implementation steps of the Floods Directive should be provided, e.g. through CIS Guidance Documents.

→ Capacity building to support the use of probabilistic approaches should be offered at river basin district level or management unit level. Knowledge exchange across EU Member States should be facilitated.

INTRODUCTION

For decades, floods have been causing tremendous damage across Europe. Better flood forecasts and flood scenarios are needed to improve flood risk management and mitigate the future impact of floods. For years, Europe has been working on improving flood management. The introduction of the Floods Directive has obligated Member States to set up flood hazard and risk maps as well as management plans that will aid flood prevention, protection and preparedness and will serve as a basis for a uniform European approach.

One challenge in implementing the Floods Directive, and flood risk management in general, is the uncertainties associated with flood scenarios and forecasts, which in turn result from uncertainties related to models, the underlying driving forces and the potential effect of climate change. While it is crucial to reduce uncertainties e.g. through improved modelling, forecasting and scenario development will always include inherent uncertainties. It is therefore important to learn how to deal with uncertainties in flood risk management.

Currently, most flood forecasts and scenarios developed in the field of flood hazard and risk assessments make use of deterministic approaches which only provide very limited information on the uncertainty of predicted values. Decisions in flood risk management, e.g. on potential flood measures, therefore tend to not sufficiently reflect the full bandwidth of possible inundation scenarios or potential damage.

The research project IMPREX has explored probabilistic approaches in different fields of water management including the water transport sector, flood damage assessments as well as drought risk management. This approach was also found to offers great potential for improved flood hazard and risk assessments and, consequently, flood risk management, supporting the implementation of the Floods Directive in Member States.

ADVANTAGES OF PROBABILISTIC APPROACHES

Probabilistic approaches visualize and quantify uncertainties

Probabilistic approaches display predictions as a bandwidth of possible values supplemented by the possibility of occurrence of each possible value. This is achieved by calculating distributions instead of fixed values. In comparison, deterministic approaches provide predictions as single static mean values alongside a safety factor, without providing any information on how likely different deviations from the mean actually are. This not only potentially creates a false sense of security in the predicted value but also deprives decision-makers of important information.

Probabilistic flood occurrence projections could improve flood hazard maps depicting uncertainties in potential flood scenarios, including climate change impacts

The Floods Directive requires Member States to compile flood hazard assessments in the form of flood hazard maps for flood scenarios with low, medium and high probability. The review of the Floods Directive has shown that in some Member States uncertainties in flood scenarios are already presented in flood hazard maps as a deviation from the hazard line. However, the likelihood of this deviation is not yet represented. The use of probabilistic approaches for flood hazard maps could add important information by presenting the likelihood of different inundation scenarios. Furthermore, by incorporating different climate projections into hydrological models, the uncertainty of long-term river discharge scenarios was shown in IMPREX allowing for a probabilistic hazard assessment approach. Applying this approach in the context of flood scenario development could help represent future climatic developments in flood hazard assessments and helps keep the focus on the most relevant, rather than on the most likely scenarios. This could support Member States with decision-making over suitable long-term flood prevention measures under consideration of the full bandwidth of potential hazard scenarios.

Probabilistic flood damage assessments foster a more realistic understanding of potential flood risks and can help identify more efficient risk management measures

A realistic assessment of flood risks provides the basis for the implementation of efficient measures. The Floods Directive therefore requires the development of flood risk maps. In various Member States the qualitative approach of flood risk maps are complemented by quantitative, e.g. economic, flood damage assessments. These approaches remain, however, inconsistent. IMPREX has shown that probabilistic flood damage models can present the probability of potential economic flood damage for different inundation scenarios, which helps create awareness of the full range of possible damage. The approach developed is based on models that employ Random Forest methods as well as Bayesian networks and are fed with damage data from various floods in Germany and the Netherlands. This approach was developed on the micro- (house) scale and was up-scaled to a meso- (community) scale in order to make it applicable to all of Europe. While on a local level, detailed building information serves as the input data, on a meso-scale, open-source data are sufficient for the purpose of applying the model. This approach also reduces uncertainty by using more predictor variables such as inundation duration and building characteristics in comparison with depth-damage functions. By providing the model as well as proxy data for all of Europe, the approach can be applied directly in the context of flood risk assessment across Europe.

Probabilistic approaches can improve early warning by extending lead times for water level and discharge forecasts

The Floods Directive requires Member States to improve early warning in order to assure that the necessary preparations can be made in the event of an imminent flood. One challenge faced by Member States is that short to medium term forecasts of river flow or water level become more uncertain with increasing lead times due to the large uncertainties associated with hydrological forecasting. Due to the chaotic-deterministic behaviour of the atmosphere, one of the largest sources of uncertainty in flood forecasting is the future development of the weather. Deterministic forecasts that do not take uncertainties into account are only to be used for short lead times in flood forecasting as they represent only one possibility for the future development of the variable of interest. To extend the lead times of forecasts, we have no option but to quantify the uncertainty. Probabilistic forecasts can improve early warning by providing information on the uncertainty of the forecast of future flows and water levels. Even though the uncertainty of forecasts increases with increasing lead times, they are still an important early warning tool that gives decision-makers useful information, enabling them to prepare for possible flood situations. IMPREX has shown that probabilistic approaches can deliver useful forecasts for large river basins with lead times of up to 10 days for improved transport cost planning in inland waterway transport. This approach could potentially be transferred to applications in flood risk management.

Probabilistic approaches can bolster more rational decision-making, e.g. in the context of drawing-up flood risk management plans, by factoring in all the possible hazards and risks

The Floods Directive requires Member States to draw up flood risk management plans based on flood hazard and risk assessments. Due to the predominant use of deterministic approaches, the extent to which uncertainties are reflected in decisions e.g. on matters such as appropriate flood prevention and protection measures is currently somewhat limited. By using probabilistic approaches, the full bandwidth of potential flood hazards or risks, including their probability, can be derived; helping Member States put more efficient programmes of measures in place with respect to compliance with the Floods Directive. While a proper risk-based decision-making process would require a combination of probabilistic hazard and risk assessments to thoroughly reflect the entire bandwidth of possible flood risks, applying a probabilistic approach in either flood hazard or risk assessments is an important step in the direction of more rational decision-making in the definition of suitable flood measures.

CONCLUSION

In sum, probabilistic approaches have great potential to support flood risk and hazard assessments and can help Member States develop efficient flood risk management plans within the framework of the Floods Directive and prepare for imminent floods in time. IMPREX has showcased some of the possible applications and advantages of probabilistic approaches. The following recommendations can be derived from the work carried out as part of the IMPREX project:

- **The potential of probabilistic approaches for the implementation of the Floods Directive should be explored systematically in all implementation steps, from flood occurrence, hazard, and damage and risk assessments to the development of efficient flood risk management plans. This will require additional research into probabilistic approaches as well as into optimal incorporation of such approaches into the management process. To facilitate this, close cooperation with research institutes is needed alongside increased support for further research in this area.**

- **The CIS Working Group on Floods might consider addressing and promoting the use of probabilistic approaches in CIS Guidance Documents for the Floods Directive**

- **The use of probabilistic approaches as a basis for decision-making is not straightforward. It is therefore important to build up capacities for decision-making under uncertainty at management unit or river basin district level. In addition, dedicated knowledge exchange between Member States is to be encouraged and fostered.**

This policy brief was compiled by adelphi based on the work done within the context of the research project IMPREX with special contributions by Bastian Klein (BfG Federal Institute of Hydrology), Heidi Kreibich (GFZ German Research Centre for Geosciences) and Bart van den Hurk (Deltares). Graphic design by Arctik.

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POLICY BRIEF

Towards successful implementation of preventive drought risk management in Europe!

MAIN MESSAGES

- The European Commission report on the implementation of the Water Framework Directive (2019) has shown once more: drought risk management is still not where it should be. Still, only few Member States have either set-up drought risk management plans or have otherwise covered the topic extensively within river basin management plans. At the same time, climate change increases the pressure to act on making Europe more resilient to droughts and water scarcity.

- Appropriate acknowledgement of the importance of preventive drought risk management by Member States and the European Commission (EC) is needed, paired with respective concrete steps, such as:

  - On EU-level: setting up a firm policy framework for drought risk management, providing improved guidance and support for its implementation, and paying sufficient attention to local features in assessing drought risk across Europe

  - At Member State level: increasing capacity to adequately respond to current and future drought risk, e.g. by enhancing the drought monitoring and forecasting infrastructure at basin level, to, among other, monitor and develop basin-specific drought indices that can complement regional stakeholder assessments; or by improving anticipatory operational drought risk management

- The research project IMPREX has developed innovative tools and approaches that support improved drought risk management at various administrative levels.

BACKGROUND – EU POLICY FRAMEWORK ON DROUGHTS

Summer 2018 has shown once more that drought risk is not only limited to Mediterranean regions but can also affect Northern Europe, a region that is not known for frequent water scarcity issues. Climate change will increase the severity of water stress across Europe further in the next years and decades, in some regions more than others. Timely adaptation is of major importance to make Europe climate-resilient.

It can be argued whether Europe is up for this task. The latest implementation report of the Water Framework Directive (2019) concluded: the implementation of preventive drought risk management in Member States is still not where it should be. Apart from a number of positive exemptions, in most Member States systematic approaches to drought risk management were still lacking. Whereas half of Member States have by now at least acknowledged the relevance of the matter for their territory, only six Member States (Cyprus, Czech Republic, Spain, Italy, The Netherlands and United Kingdom) have provided drought risk management plans. The European Commission urged the remaining Member States to develop and adapt such plans and to monitor droughts by means of established and agreed drought indicators.

The need for a systematic approach to Drought Risk Management in Europe was first acknowledged by adopting the non-binding 'Communication on Water Scarcity and Droughts' (EC droughts communication) in 2007, which promoted, among other, the set-up of drought management plans, monitoring of drought and water scarcity indicators and systematic knowledge and data collection. In successive years several revisions followed, an expert group started working on indicators, the European Drought Observatory (EDO) was initiated and guidance documents were formulated. In spite of these actions a first implementation review of the droughts communication in 2012 (the 'Blueprint to safeguard Europe's Water resources') concluded that Member States had not progressed sufficiently in adopting the promoted measures. Instead of enhancing attempts to improve drought management or making drought management binding after this review, it appears as if not many concrete follow-up actions have been initiated since then. Also the emphasis on the need of drought management within the European Climate Adaptation Strategy in 2013 was not followed by a release of mandatory regulations for Member States to attend to drought management.

LESSONS LEARNED FROM IMPREX ON IMPLEMENTATION OF DROUGHT MANAGEMENT AT BASIN LEVEL

Besides the unbinding nature of the EU policy framework on droughts, also the implementation of drought risk management at river basin level faces practical barriers related to the development of drought indicators, drought risk plans, or agreement on water allocation schemes. The work of the research and innovation project IMPREX provides some valuable insights for improved implementation of the existing policy framework on droughts at basin level.

Defining basin-specific impact-based indices is essential to efficiently manage local drought risk

The EC droughts communication stresses the need for the development of drought management plans and drought indicators. While the focus of the European Commission as well as EDO has been put on developing continental-scale drought indicators, hydro-meteorological characteristics are varying widely between different river basins. This variability has to be accounted for by establishing locally appropriate hydrological and meteorological indicators and thresholds (indices). This is also stressed in the Guidance Document 'Drought Management Plan Report' published by the European Commission. However, until now insufficient tools and approaches are available for this.

IMPREX developed a framework for index-based drought analysis (FRIDA) which allows the customized design of basin-specific impact-based indices. The framework, based on advanced machine learning algorithms, offers an automated procedure for selecting the most relevant hydroclimatic variables to design an index that reflects the actual local impact of a drought. The tool can be applied in all European river basins and Member States and can be complementary and supportive to draw-up drought management plans.

Enhancing monitoring infrastructures on basin level is key to manage present and future drought risk

The need for improved drought monitoring has been stressed repeatedly, e.g. in the EC droughts communication. The Guidance Document on 'River Basin Management in a changing climate' furthermore urges that 'priority' should be given to monitoring and detecting the effect of climate change on water resources. In this context, a big effort has been taken by the European Commission to provide space-based/earth observation data with the help of Copernicus and to support the development of hydrological modelling as well as global GIS datasets. However, in order to adequately manage drought risk locally, extensive monitoring of variables at basin level, such as streamflow data or information on agricultural productiveness and water consumption is indispensable. IMPREX has emphasized once more: even the most innovative approaches, such as machine learning approaches (FRIDA), or advanced less data intense modelling approaches (Water Accounting Framework) still require availability of extensive basin-specific data. Investing in the set-up of basin-level monitoring remains indispensable.

Considering seasonal forecasts when developing decision-support-tools for drought risk management helps manage drought situations in time

Decision-support-tools help in adequately managing available water resources and managing water allocation, specifically in times of droughts. However, even the most advanced tools mainly utilize monitored historical data. Consequently, upcoming climatic developments and weather patterns are not included routinely in decision-making. Making use of seasonal forecasts, especially climate model-based forecasts, in drought risk management tools can support more foresighted water allocation and water management approaches.

IMPREX developed additional methodologies based on the decision-support-tool shell AQUATOOL, which is applied in Spanish basins and other parts of Europe, that allow integration of tuned seasonal forecasts into the system. AQUATOOL allows for a more anticipatory management of scarce water resources on river basin level and allows for more sustainable allocation of available resources.

Harmonizing water accounting approaches between basins while integrating local climate impact assessments allows for more evidence-based decision making at EU-level and at the same time enhances acceptance at basin level

The 'Blueprint to safeguard Europe's Water resources' urged Member States to pursue water accounting targets on river basin level. While water accounting is typically based on monitoring of historical water resources, the 'guidance document on the application of water balances' stressed the need of incorporating climate change scenarios into water accounts. However, even though water balance indicators and climate impact studies are available for most basins in the EU, practical approaches of integrating basin-specific climate impact assessments into water accounts are still missing.

Local water accounts or climate impact assessments of European basins miss comparability and therefore don't provide a basis for effective EU policy action on water scarcity and droughts. European/global scale climate impact assessments, in turn, often lack local system information on e.g. water abstraction or additional information on water management practices, and are therefore not readily adopted by local stakeholders.

Thus, a single framework is necessary that i) translates basin-specific information and climate studies into homogenous drought indicators for all major European basins (providing a common ground for EU-level decision making) and ii) provides a tool to integrate climate impact studies into water accounting frameworks.

IMPREX developed an innovative Water Accounting Framework that allows the assessment of climate change impacts on blue and green water resources for agriculture across Europe. This approach has the great advantage that it creates comparability between different basins in terms of climate (change) effects on water resources and therewith provides a useful decision-support-tool for European policy makers. Novel to the approach is that it allows building on existing basin-level studies that are backed-up by local stakeholders and expert knowledge. So far, this is missed in large pan-European modeling studies. Applying the IMPREX tool may pave the way for creating greater acceptance of EU-level information and policies among local decision makers.

WAYS FORWARD – CONCLUSION AND RECOMMENDATIONS

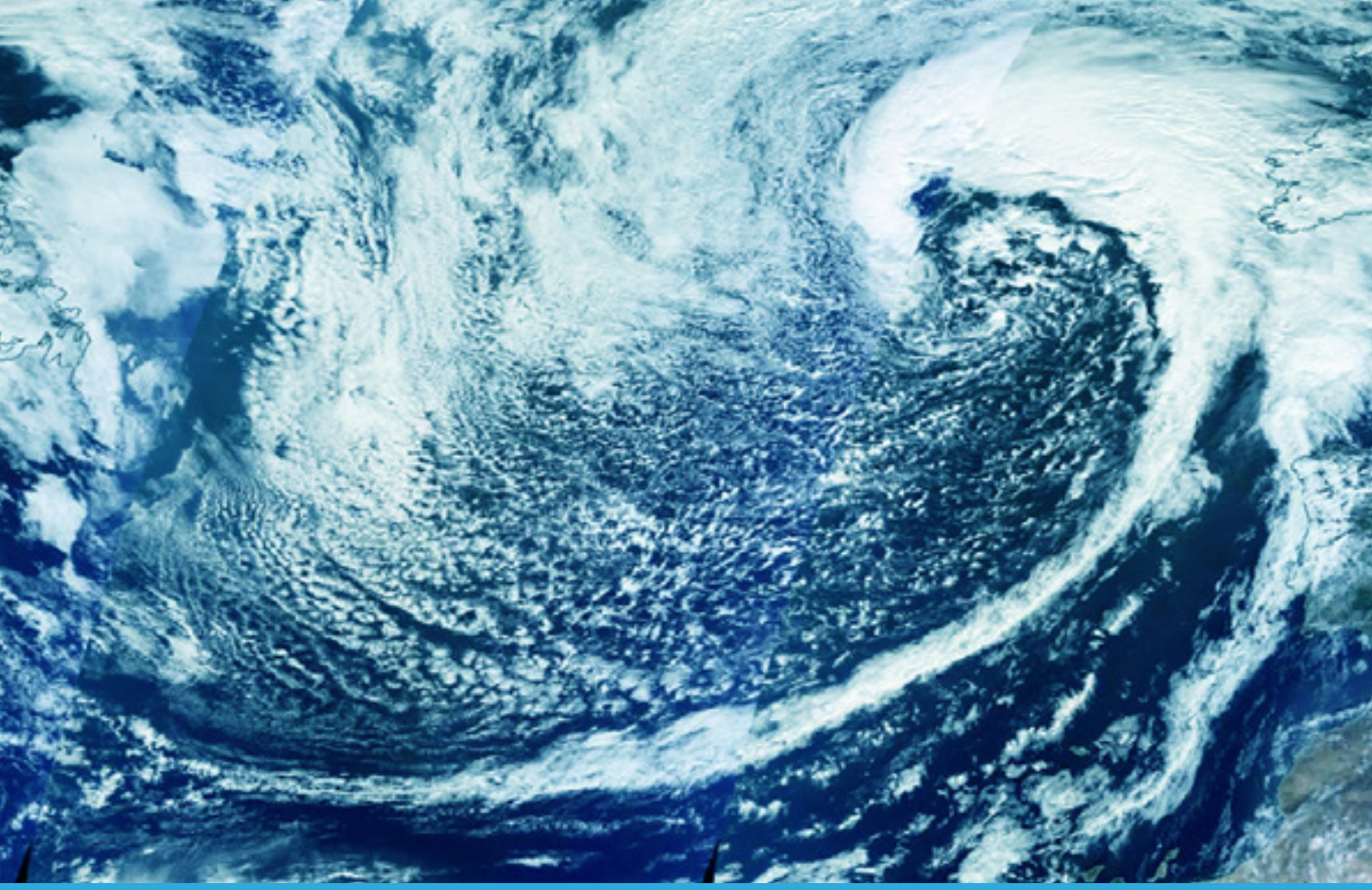
It requires joint efforts of the European Commission, Member States/national water management (authorities) as well as research to build-up preventive drought risk management

AT EU LEVEL

- The European Commission should consider paying more tribute to the importance of preventive drought risk management by putting it back on the political agenda
- A comprehensive and binding policy framework for drought risk management should be developed, e.g. by making drawing-up of drought management plans mandatory
- More guidance and practical support would help implementation of drought risk management; for example by bringing a lively Working Group on Droughts within the framework of the so-called EU Common Implementation Strategy back to life
- Greater attention needs to be paid to local features in determining policy measures and providing support to basins with specific needs (the IMPREX Water Accounting Frameworks is a helpful tool for this)

AT MEMBER STATE LEVEL

- Member States need to acknowledge the importance of preventive drought risk management, e.g. by setting up DMPs and pay tribute by increasing the capacity of adequately responding to drought risk by:
  - setting-up better drought monitoring and forecasting infrastructures
  - monitoring the most significant drought indicators and defining basin-specific indices
  - assessing the regional water balance in the face of climate change and taking into account local expert knowledge to prepare for future water allocation
  - integrating available forecasts, especially seasonal forecasts into decision-support-tools and/or developing such tools at first hand



This policy brief was compiled by Theresa Lorenz and Annika Kramer (adelphi) **based on the work of the research project IMPREX with special contributions by Dr Johannes Hunink** (FutureWater)**, Prof Bart van den Hurk** (Deltares)**, Prof Joaquin Andreu** (Universitat Politecnica de Valencia) **and Dr Matteo Giuliani** (Politecnico di Milano)

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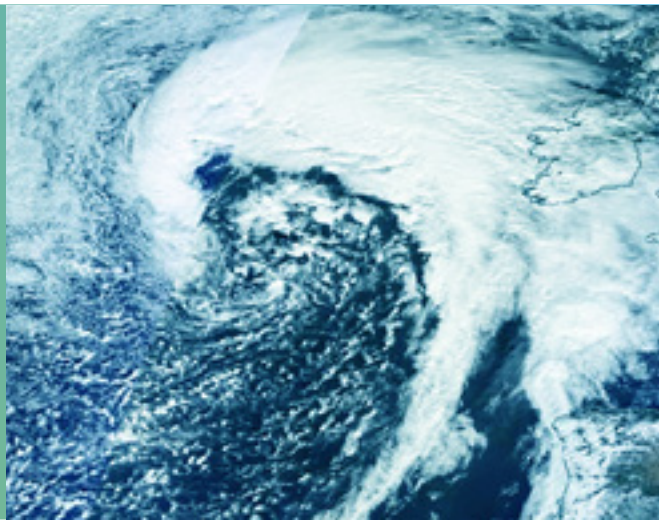
POSITION PAPER

Towards more action-oriented research and climate services

Lessons learned from IMPREX



This paper presents lessons learned on successful science-policy, science-practice and science-science interfaces for increased impact of research and innovation. The paper provides recommendations on research policy, program design and project organization for more fruitful European research.

INTRODUCTION

Population growth, urbanization and a changing climate ask for sustainable adaptation strategies of the water sector in Europe. This comes with a continued need for tailored knowledge and improved tools in the field of water management and climate services to support design and implementation of sustainable adaptation strategies. This need has been recognized in the past decades and is reflected in a multitude of funding programs that were initiated within the European Union. These programs usually require close collaboration with (water management) practitioners, contributions to relevant policy processes and networking and coordination with other research activities. Due to these requirements European research can reflect on a collection of advancements that not only include scientific progress but are also demonstrated by a multitude of new concepts and tools that are implemented to support sustainable water management. Their success is strongly supported by feedback-loops between science, practice and policy.

To ensure progress, it is crucial to regularly evaluate success factors as well as obstacles of large European research and innovation projects. The four-year Horizon 2020 funded research and innovation project IMPREX brought together 23 partners in 14 work packages to deliver around 60 deliverables which encompass a multitude of approaches, tools and methods for water and water-dependent sectors. Building on its collaborative approach, the project provides valuable lessons for improved cooperation with policy-making and practice as well as for project organization and design of research programs of future initiatives.

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SCIENCE - POLICY INTERFACE
How can research and policy processes be aligned?

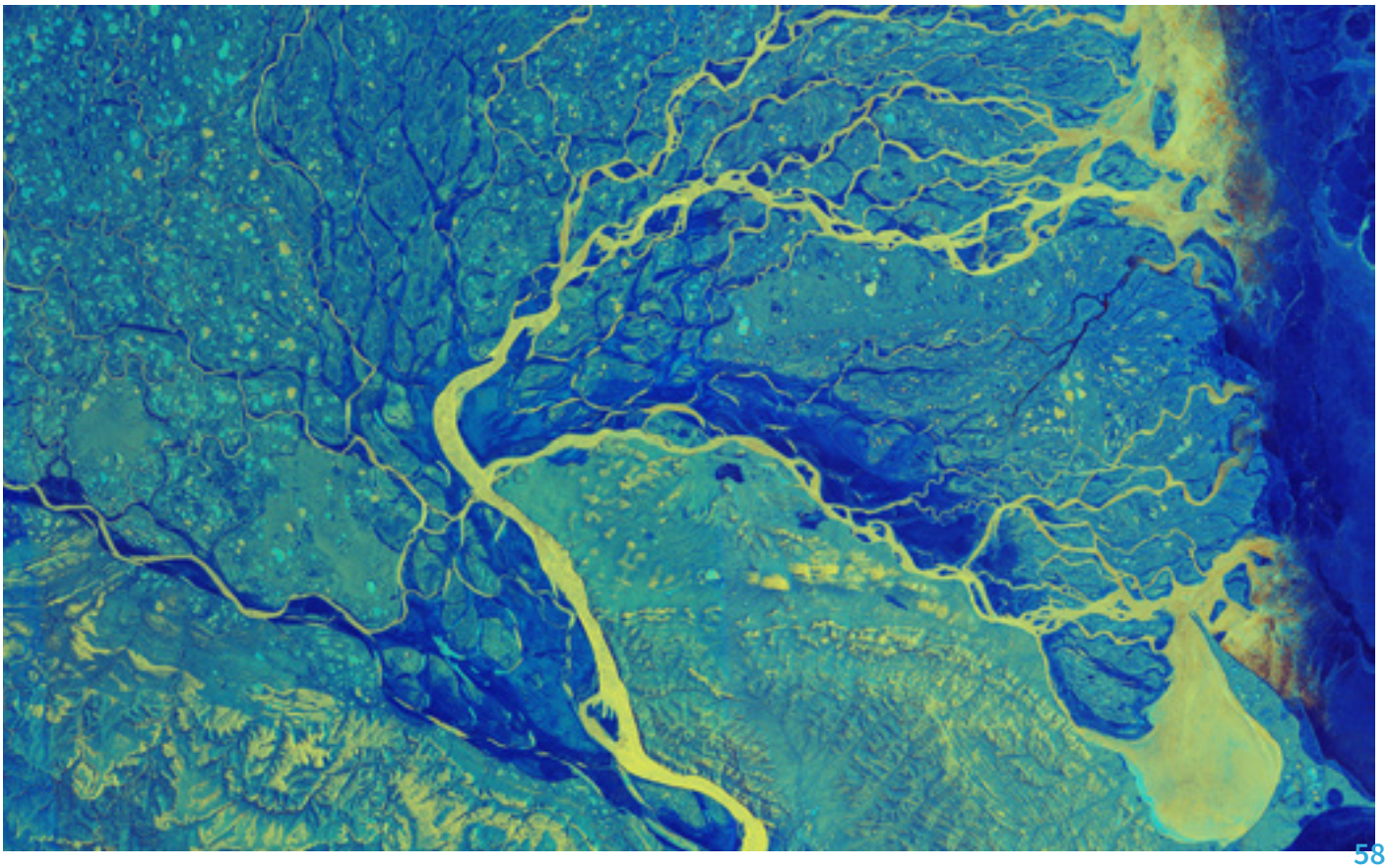
The past decades have brought increasing awareness of the benefits of collaborations between research and policy-making. Growing attempts to open policy review processes to scientific experts, a variety of exchange programs between scientists and policy-makers, and a broad range of science-policy conferences bear witness to this development.

However, despite this general development, cooperation between science and policy-making within the frame of research projects is still subject to improvement. Efforts are required from both sides.

Effective communication from science to policy-making requires significant synthesis and translation efforts, since focus of attention and style of communication differ greatly between science and policy. Moreover, it requires understanding of European policy frameworks and processes as well as networks to identify and use windows of opportunities to transfer scientific knowledge into policy processes. From the policy side, it requires willingness to learn from science and to base decisions on scientific evidence. Moreover, entry points for research results into decision-making processes are needed.

IMPREX showed that involving with experts in science-policy interfaces (policy consultants) was a great addition to efforts taken by scientific partners. Within IMPREX, for example, this helped facilitating a presentation of IMPREX policy recommendations to high-level audiences in relevant policy events (in this case the EU CIS Working Group on Floods).

However even with expertise and experience in policy consulting, transfer between science and policy is still not straight forward and requires close monitoring of policy processes and discourse and investigation to identify available opportunities. For example, within IMPREX it was a lucky coincidence that project runtime synchronized with the review of the Water Framework Directive, which offered a variety of opportunities to contribute scientific findings to current political debates. This is often not the case for research projects of short- to medium-term runtimes.



SCIENCE - PRACTICE INTERFACE
How much collaboration and at which stage is actually beneficial for all parties?

Close collaboration between research and practice is often considered key to providing tools and methods that are relevant for and tailored to practical needs. Therefore today, most research and innovation programs successfully meet the requirement to collaborate with practitioners in research projects, and the tendency is upward.

However, time-limitation of both parties, trust issues, different expectations and the balance between transferability of results and their tailoring to the specific needs of partners make these joint research efforts challenging at times. Especially since practitioners that are well known for their willingness to be engaged are swamped with requests for collaborations.

Within IMPREX, building on established long-lasting cooperation helped joint understanding of planned research outcomes and (pilot) implementation. Communicating openly on resources required from both parties as well as on restrictions, e.g. in data availability and sharing, helped create realistic expectations and trustful relationships. A well designed stakeholder participation process supported efficiency and effectiveness of cooperation throughout the project. This included a more intensive kick-off phase to identify stakeholder needs, followed by looser stakeholder engagement throughout the research process and again closer engagement in the final implementation phase. The experience shows, good expectation management as well as well-designed engagement cycles are key to making cooperation successful! Nevertheless it also became apparent that stakeholder engagement - no matter how well managed - retains considerable resources on both sides which gives rise to the question: “how much collaboration is actually good and needed and at which stage?”

SCIENCE- SCIENCE INTERFACE
What is needed to learn from one another?

One interface that still receives relatively little attention in making the output of research more efficient is the science-science interface in terms of coordinating research and communicating results in the research world.

It is taken for granted that research builds upon the latest insights in the field. However, in designing research projects, scientists are often not aware of all relevant work conducted by other research groups - or valuable research outcomes, like models and data sets are simply not shared openly and transparently. A major driver hereof is the ever growing competition in the scientific world, a general publication bias towards “successful” research paired with a lack of investigation of unexpected results. Consequentially research misses opportunities to learn from experience thus proceed efficiently.

While this calls for a paradigm-shift in research towards more openness and acknowledgement of the value of unexpected results, research projects can attend to related issues effectively.

For instance, collaborating with legacy-rich institutes in research projects, as done in IMPREX, facilitates exploitation of knowledge of latest research and scientific developments (in addition, it promotes implementation of research findings in operational applications.) IMPREX furthermore showed that building an open and transparent atmosphere, characterized by data exchange and sharing and frankly discussing all results (not only expected or desirable ones) is an important step to open debates, an increased level of learning from each other and creating well-reflected results. Furthermore, IMPREX required different research groups to provide results, data and models to other work packages right from the beginning.

RECOMMENDATIONS

RECOMMENDATIONS FOR THE EUROPEAN COMMISSION:

- **Actively invite and facilitate contributions from research to policy processes.** Continuous and active reaching out to the scientific by policy-makers world will support evidence-based policies. New formats, like regular workshops or scientific consultation could facilitate research contributions. Moreover, permanent communication channels, like platforms, could support continuous engagement that is independent from e.g. review processes.
- **Ensure coordination between policy processes and research programs.** Close coordination between DG Research and DG Environment helps align processes and opens up entry points supporting transfer of research results into policy processes.

RECOMMENDATIONS FOR RESEARCH PROGRAM DESIGN:

- **Acknowledge that transferring research results into policy processes requires significant time and expertise.** In order to care for fruitful output from science-projects to policy-making, research funding program should allow for allocation of respective resources.
- **Carefully evaluate the right level of required involvement of practitioners.** Building and maintaining trustful relationships with practitioners takes time. Requirements for cooperation between science and practice within short- and medium-term research projects therefore need to be realistic and time-frames be adjusted accordingly, e.g. by extending project runtimes and/or allowing for longer kick-off phases if much cooperation is required.
- **Facilitate implementation of research results.** Uptake of research results beyond the end of research projects can be facilitated e.g. by supporting spin-offs or funding implementation programs, like EU Life.
- **Provide funding for replication studies and follow-up research.** Unexpected results and "unsuccessful" experiments may offer great opportunities to learn and develop innovative solutions. Providing the means to follow-up prevents missing out on potentially important insights and not starting from scratch.

RECOMMENDATION FOR ORGANIZING RESEARCH PROJECTS

- **Collaborate with intermediaries to translate research results into policy advice.** Transferring science into meaningful recommendations for policy-makers requires dedicated effort. Cooperating with partners with specific expertise and experience in this work is sensible and helps finding appropriate formats, networks and windows of opportunities.
- **Building-up and sustaining networks with practitioners should be made a constituent task of project management.** Long-standing cooperation between research and practice provides the basis for most effective and successful collaborations. To ensure networking is attended with enough attention, it is sensible to make it an explicit task in research design right from the beginning.
- **Plan cooperation and stakeholder engagement well in advance.** Prescient interaction management right from the beginning safes time and resources throughout the course of the project.
- **Acknowledge the value of unexpected and "failed" research attempts.** To learn from mistakes and progress jointly, sharing all results is crucial. Project coordinators are well advised in making this a priority and caring for the needed open and transparent atmosphere.

This policy brief was compiled by Theresa Lorenz and Annika Kramer (adelphi) **with special contributions by Prof Bart van den Hurk** (Deltares). It is **based on the work of the research project IMPREX** and **inputs from IMPREX partners received during a workshop** on "Challenges and opportunity of/for applied science (Lessons learned from IMPREX)" **at the IMPREX General Assembly** (18– 20 June 2019)

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CONCLUDING REMARKS

Climate change is expected to exacerbate the stress on water resources within Europe. Changes in land use and water needs, including large-scale agricultural irrigation, have only served to reinforce this trend. Predicting and understanding the possible impacts of current and future extreme events on water resources is of the utmost importance the with regard to the establishment and development of suitable management measures that will enable us to combat the risks associated with climate change effectively. To facilitate this, reliable scientific information combined with tailor-made management strategies that include innovative approaches and tools are needed. Following this approach, IMPREX has helped improve society's ability to better anticipate and respond to future hydrological extreme events in Europe.

> *IMPREX has moved the field forward significantly and will be a highly valuable resource for improving the understanding, prediction and management of hydrological extremes in Europe.*
>
> ***Dr Penny Whetton***
> *Honorary Research Fellow at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and chair of the IMPREX Advisory Board*

Project activities have been instrumental in improving the operational decision support systems developed by involved partner institutions. At the same time, IMPREX has made important contributions to various hydrometeorological forecasting and climate projection systems in Europe and provided good practice examples for improved management planning in support of EU water-related policies. Scientific publications are already being picked up, water management support tools are already in use, policy recommendations have been received by relevant decision makers at EU and national level, and new business opportunities are being refined in preparation for market uptake.

The IMPREX website presents practice-oriented case study examples, a prototype of a seasonal hydrological risk outlook, and an E-guide containing valuable information on new and updated tools and approaches for (potential) users. For more details, see **www.imprex.eu**.

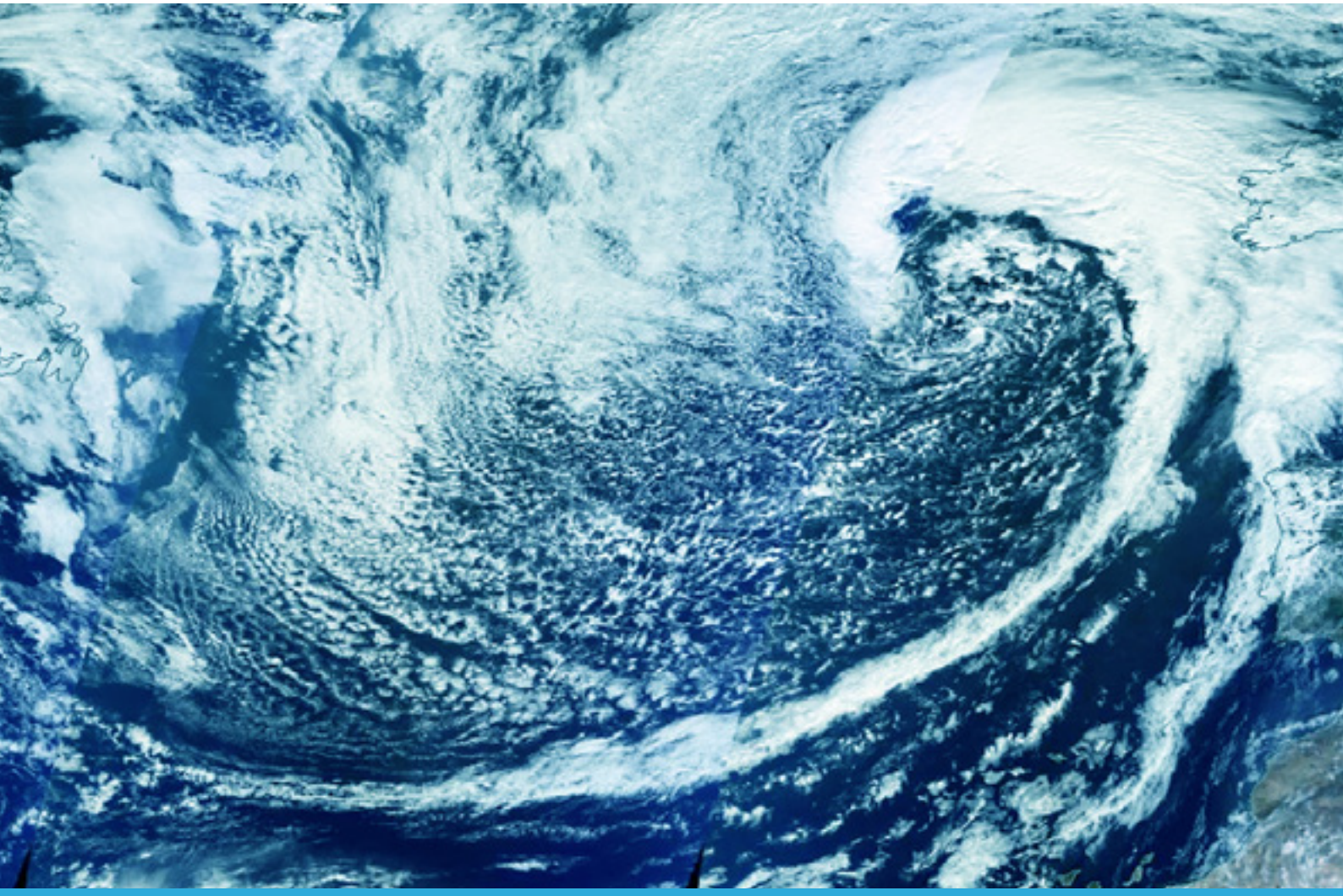
> *The legacy of IMPREX is multi-faceted and rich.*
>
> ***Dr Andy Wood***
> *Research Scientist at NCAR Research Applications Laboratory and member of the IMPREX Advisory Board*

Sector-specific applications and case study examples show that the knowledge developed by the project partners supports risk management and adaptation planning, not only at regional but also at national and European level. In most cases, it has been shown that the approaches and tools developed can be applied to other European river basins following adjustments to local conditions.

The project has actively trialed various stakeholder interaction principles, including working intensively with practitioners, utilizing existing client relations, and prototyping business opportunities as well as monitoring result uptake in research and practice. Lessons learned are documented and are inspiration for new multi- and transdisciplinary activities in the future.

PARTNERS

- Koninklijk Nederlands Meteorologisch Instituut – NL (project coordinator)
- Adelphi Research GmbH – GE
- Arctik – Environmental communication – BE
- Barcelona Supercomputing Center - Centro Nacional de Supercomputación – ES
- Bundesanstalt für Gewässerkunde – GE
- Centro Internazionale in Monitoraggio Ambientale - Fondazione CIMA – IT
- Cetaqua, Centro Tecnológico del Agua, Fundación Privada – ES
- European Centre for Medium-Range Weather Forecasts – UK
- FutureWater SL – ES
- Helmholtz-Zentrum Geesthacht – Zentrum für Material- und Küstenforschung GmbH – GE
- Deutsches GeoForschungsZentrum – GE
- HKV Lijn in Water BV – NL
- Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture – FR
- Met Office – UK
- Politecnico di Milano – IT
- Potsdam-Institut für Klimafolgenforschung – GE
- Stichting Deltares – NL
- Stichting Vu-VUmc – NL
- Stichting Water Footprint Network – NL
- Sveriges Meteorologiska och Hydrologiska Institut – SE
- The Research Committee of the Technical University of Crete – GR
- The University Reading – UK
- Universitat Politecnica de Valencia – ES



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