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Project Acronym: IMPREX

IMproving Predictions and management of hydrological EXtremes

Final Technical Report

Period covered: from 01/10/2015 to 01/10/2019

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Overview of the results & their exploitation and dissemination

Context & approach of IMPREX

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. The limited predictability of these extremes at sufficiently long lead times results in considerable social vulnerability, also in light of the imminent increase in frequency and severity of extreme events in the future. This is recognized by the European Union (EU) who has improved its water policy instruments over the past few decades and invested in research and innovation 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 management systems are essential for water transport and hydropower, agriculture, urban water supply and other economic fields. The project motto "**Learn from today to anticipate tomorrow**" has been maintained throughout the entire execution phase of the project. Although the project is carried out under a "climate change" call of the Horizon 2020 program, initial user surveys and past experience has highlighted a large need of stakeholders to work with climate data that represent near future conditions. IMPREX has contributed to climate change assessments, but in parallel spent a lot of attention

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to the interpretation, tailoring and user appreciation of seasonal forecasts. 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 analyzed and improved.

IMPREX developed models, tools and approaches that address operational hydrometeorological forecasting and climate outlook systems, and operational system management by practitioners. For many applications the management of near-term weather extremes and long-term climate are strongly interlinked. The interaction between research and application has significantly improved by close collaboration with multi- and transdisciplinary project teams. Case studies were used to demonstrate and optimize tailormade tool development and information processing 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.

The project benefited from existing and new partnerships between the IMPREX consortium members and scientists, developers, practitioners and policymakers in water related sectors. This will lead to increased uptake and application of IMPREX approaches, while recognizing the diversity of water-related challenges within the EU.

Dissemination and exploitation of results

The dissemination and exploitation of IMPREX results has been achieved by following a number of principles:

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1. The scientific developments have been tested in a large number of sectoral case studies, where stakeholder inventories, co-design and on-site demonstration were applied. This leaves legacy of IMPREX findings within practitioners' environments and has contributed to the product portfolio of a number of consultancy SMEs and knowledge institutes engaged in IMPREX (HKV, Future Water, R2Water, CETAqua, Deltares). Legacy statements are included in each of the results highlights listed below.
2. Development of hydrometeorological forecasting systems and climate outlooks has been led by leading institutes in the field of forecasting and outlooks (MetOffice, ECMWF, KNMI, BfG, SMHI, BSC). This ensured that new developments took place in the vicinity of the operational forecasting systems, allows an effective evaluation and uptake.
3. Outreach has been spread over different target audiences and included a wide range of dissemination channels: scientific papers, conference sessions, public seminars, policy advising sessions and webinars all contributed to the legacy of the project.
4. Not only existing practices and systems have been revisited, also a number of new concepts has been developed. These generally are at a lower TRL but find their way in authoritative channels: compound events, impact based forecasting, Water Footprinting, Risk based water allocation were concepts that have reached large attention in scientific and operational environments.

The project generated 67 deliverables,70 peer-reviewed papers (plus around 20 submitted), 4 PhD theses (plus 8 on their way), 8factsheets and 4 policy briefs and a position paper. The project has about 700 followers on twitter and published several blog posts and news items.

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In addition, dissemination of results via stakeholder interactions, social media, website and educational activities ensures a long legacy of the project in the period to come.

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Selection of highlights of project outcomes and societal impacts

Contribution to improved weather prediction systems

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. Diagnostics were developed pointed at model improvement, new data assimilation set-ups have given improved forecast skill, and coupling hydrology and meteorology forecasting systems used for flood risk warnings has contributed to early warning services.

***Legacy**:* the diagnostic tools and improvements in NWP has large potential implications for accuracy of short-range prediction, particularly of soil/snow, precipitation and river discharge. The improvements do ultimately lead to a better early warning service for extreme events and better bookkeeping of the hydrological budget of a region or catchment.

Improved seasonal precipitation forecasts

The GloSEA5 seasonal forecasting system has been enhanced to improve forecast skill of anomalous rainfall in European catchment areas. A near-realtime forecast was applied for the 2018/2019 winter season, where the forecast was enriched with physical narratives of features that are indicative for rainfall anomalies. Users in the Segura basin did improve their understanding of the probabilistic nature of seasonal forecasting, including the likelihood of forecast failures.

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Legacy: The forecast postprocessing will be implemented operationally in the UK seasonal forecasting system. In the UK the system enhancement does lead to improved skill in specific regions, and longer skill assessments are being carried out.

High-resolution future weather scenarios

A "surrogate warming" experiment has demonstrated the applicability of high-resolution convection resolving regional climate models for future climate applications. Where normally these simulations are too expensive to generate a large representative ensemble, the case-study oriented approach developed here allows credible assessment of the degree to which extreme events will materialize in a future climate context.

The experiments indicate that precipitation will increase in a two-degree warmer situation. The change in the local maximum hourly rainfall in a given region exceeds the area averaged rainfall amount. 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.

Legacy: a scientific approach to create high resolution future climate event-based images at relatively low computing costs. It is being assessed by IPCC, and initiatives are ongoing to building large portfolios of simulations, allowing categorization according to driving conditions and model characteristics.

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Tool to detect sources of limitations of seasonal forecasting systems

Sophisticated experimental designs and analysis protocols allowed the identification of the source of limitations to hydrological seasonal predictability in an ensemble of forecasting systems. It does present a European clustering of areas where initial states or forecast quality limit predictability and creates awareness of environmental characteristics that contain most of the "predictable" information. An online tool allows exploring this predictability source at a very localized scale.

In most areas improving the initial state would lead to a higher discharge forecasting skill in the first month than improving atmospheric forecasts. As the lead time increases, the relative importance of improvement of the atmospheric forcing increases. In Scandinavia initial states 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 is important until 3 months ahead from June to September, pointing at the importance of accurate initial ground water information.

Legacy: The procedure has been applied to chase predictability sources of decadal forecasts. It is used in the expert guidance of the Risk Outlook material, and likely is also helpful in operational seasonal forecasting systems. It can inform implications of climate change on seasonal predictability of hydrological features.

Upgrade of hydrological forecasting model for the Netherlands

The hydrological model used for operational discharge forecasting and climate analysis used in the Netherlands is upgraded to a new physically based modelling system (wflow_sbm).

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Particularly, a new 20 year high resolution forcing data set was produced (precipitation, temperature, potential evaporation) and implemented in the operational suite RWsOS. LAI data are based on MODIS, and a simple glacier representation is included. The new model performs well under both low flow and high flow conditions. A global version of the model is being developed.

Legacy: a pre-operational new hydrological model system is being developed and is undergoing testing, for operational use in forecasting and climate analysis of Rhine and Meuse river management. The uniform model configuration for operational and scenario analyses increases model infrastructure efficiency. The model is less sensitive to calibration, making it useful in future climate analyses and operational forecasting.

Evaluation of seasonal forecasting systems for sectoral applications

In various activities an intensive evaluation has been carried out of the new seasonal forecasting system SYS5 (ECMWF), and of the GLOSEA and SYS4 forecasting systems. The evaluation has been carried out for different IMPREX sectoral applications. For instance, for Inland Water Transport 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.

Legacy: the comparison between reference and upgraded seasonal forecasting systems has increased awareness of limits and potential application of these seasonal forecasts at a range of applications, including Inland Water Transport, agricultural water resource planning

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and hydropower. Development of Climate Services for these sectors is ongoing in the Copernicus Climate Change Service.

Future climate assessment for sectoral applications

New model approaches and multi-model ensembles have allowed a better evaluation of future risks for water resource management in the Mediterranean and for shipping applications. For instance, 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. A clear difference in drought risk was displayed for different climate change scenarios.

Using the Inland Water Transportation modelling infrastructure, an outlook of the implications of various climate change projections has been made. Bias correction and selection of appropriate variables allowed a tailored assessment. Strong warming will increase the risk of low-water obstructions.

***Legacy**:* a downscaling of climate change information to sectoral impacts is carried out using decision support systems also used for operational planning and forecasting purposes in different European water sectors. This has enhanced the uptake of climate information by the practitioners' organizations and will be visible in future drought risk management plans being developed.

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Analysis of compound events

A thorough evaluation of the role of compound events for the water management of a number of regional water authorities has been carried out, leading to guidance on altered risk assessment procedures for regional water safety and/or water resources policies. 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. However, the procedure applied 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.

***Legacy**:* 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.

Risk based water allocation scheme

A revised water resource allocation scheme has been designed, altering the current risk assessments for water allocation problems in the Netherlands and Spain. The summer of 2018

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has boosted discussions on drought risk also in the Netherlands. Drought risk awareness was already present and subject of study in the context of the Dutch Delta Program. In particular, triggers for drought risk management have been exploited. In a nation-wide hydrological model, sectoral drought risk profiles were analyzed and optimized using targeted stakeholder inputs. This stakeholder involvement changed the drought risk perceptions and allowed a (preliminary) inclusion of human responses to drought conditions in the risk assessment. The already highly organized Dutch water management system did not lead to major changes in drought risk management options when including new (socio-economic) attributes of the sectoral risk profiles. However, for other areas in Europe this may be different.

Legacy: An updated drought risk analysis and management system is ready to be implemented for the Netherlands (and already is on policy level). It is not expected to give rise to major changes to the current drought risk management practice but will generate important lessons on stakeholder involvement and information usage applicable to other regions in Europe. It has become part of the commercial portfolio of companies involved in IMPREX.

Improved flood damage assessment based on open data and probabilistic modelling

For the entire model chain of flood risk, open source options for model code and input data have been assessed in IMPREX (climate/meteo data, hydrology, hydraulics and flooding, and flood damage). Evaluation of hydrological data reveals that data assimilation/calibration on discharge data is rapidly maturing, but use of soil (moisture) data is limited by lack of resolution and quality.

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In Germany and Netherlands new damage functions were defined using a Bayesian probabilistic approach, which appeared to increase the transferability of these damage functions. The flood damage model enables a short-to-medium, seasonal and long-term improved flood risk assessment for fluvial flooding. 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 use of open data allows application of this approach to the entire European domain.

***Legacy**:* progress in flood risk modelling is achieved by utilization of open data, and by development of new modelling concepts that are based on these. The work has led to progress in the development of a European wide data-driven flood risk assessment model chain. The data sets for European wide flood loss estimation are integrated into the OASIS hub (global window to free and commercial environmental and risk data tools and services) promoting the uptake of the model by both practitioners and researchers.

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Economic value of using forecasts for hydropower generation

An evaluation of the potential production gain of a collection of hydropower plants by using forecasts up to 90 days in the future reveals that when forecasts would be perfect a production gain of up to 3.4% could be gained. Utilization of current state-of-the-art forecasting products leads to a gain of about half this value. Results vary but are broadly similar across a range of European reservoirs. The values are modest but assume known (future) energy prices, which are known to affect production value significantly. Future changes in climate and in composition of the energy mix (with more renewables) may increase the forecast value in the future. It was demonstrated that improved forecasts can also improve the

Success story: Forecasting services for Inland water transport

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.

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.

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mutual adjustment of hydrological needs between different sectors, such as hydropower and irrigation.

Legacy: 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 IMPREX system operational.

Water navigation oriented probabilistic forecasting system

A pre-operational probabilistic forecasting system has been launched to support decision making in the Rhine navigation sector. Forecasts extend from the short range to the monthly time scale and are actively used by various stakeholders in the area.

An unprecedented probabilistic forecast system with a lead time of 10 days has been made available for navigational users of the River Rhine. A systematic evaluation of the forecast value, but also of the different operational strategies in response to hydrological forecasts is enabled by the development of a navigation cost structure model, incorporating operational costs and benefits of Inland Water transport. The economic impact of this forecast has been demonstrated. For short-term decisions only limited economic gains have been demonstrated, but these gains increase with an extended lead time.

Also a 6-weeks forecast is delivered to stakeholders once a week. While it shows skill for all weeks, improvements are still possible, and the tool remains for now pre-operational.

Legacy: This forecast is pre-operational but highly valued by end-users. Discussions are underway with German government agencies to make this forecast operational. If operational, the forecast horizon would also be extended to 14 days at the request of the

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users. The initial group of 5 interested users rapidly increased to 25. Interested parties include bargers, chemical companies, energy companies and government agencies to lorry companies.

Forecasting systems to service Drinking Water Treatment Plants

Several innovative services have been developed for stakeholders in the urban water sector and drinking water treatment plant (DWTP) managers.

A new monitoring and forecasting scheme for algae growth and cyanotoxin production have been developed, to control pollution risk in the drinking water treatment plant of La Contraparada. The forecasting system is based on observation-based classification trees for algae growth and cyanobacteria. The experimentation with these systems demonstrated that only generic tendencies can be detected, certainly when both algae and cyanobacteria are present, due to limited data availability. Replication and upscaling is not yet possible.

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Success story: dissemination of forecasting services for drinking water treatment plants

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.

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.

Turbidity forecasts are needed to foresee impacts of intense rainfall that give large inflows of minerals and debris, leading to high turbidity of drinking water in the catchment and aquifer. To make an effective forecast of these events, products from local observation networks and ECMWF forecasts have been transferred into turbidity indicators using regression and physical modelling techniques, leading to a turbidity forecasting system with a few hours time scale.

Legacy: New observations and forecast system components have been gathered, to support the development of operational algae and cyanotoxin forecasting systems. Stakeholders showed big interest in the results achieved, and further developments are ongoing. The prototype forecast-based turbidity warning system developed for a DWTP

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in Spain supports an optimized treatment and saves cost of water treatment management. Via the SUEZ organization the system will be distributed over a large collection of DWTPs.

Evaluation of usefulness of seasonal forecasts for water resource planning

Decisions on seasonal water management and long-term water planning is supported by integrative prediction and analysis tools such as the Aquatool Decision Support System tailored for the Jucar area. With adjusted inputs and schematization it is applied in a large number of other Spanish and international domains as well.

In IMPREX incorporation of (bias corrected) seasonal forecasts has taken place. The developments are strongly guided by stakeholder inputs and are mainly oriented to improve probabilistic assessments of vulnerability and resilience in water resources systems during extreme (multi-annual) drought events. It has been demonstrated that the role of hydrological memory dominates the information supply from the seasonal forecasting systems. Stakeholder support has been gained by extensive verification and validation of predictions.

***Legacy**:* the multidisciplinary combination of analysis and forecasting modules in Aquatool is an effective decision support instrument for operational and strategic water management in the Jucar basin. The system can be transferred to other Spanish basins, as it allows for a large diversity in basin characteristics and management culture. It is demonstrated that a close interaction between research and policy making contributes to an effective uptake of the tool in the decision structure. Extensions to the tool concerning water quality, additional verification and forecasting/scenario operations are underway.

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Updated water accounting system

Water accounting is – like financial or other resource accounting – applied in many regional basins and institutions. However, the accounting procedures and indicators vary widely, and don't allow a regional assessment of the various relevant water budget terms. In a multi-basin exploration, the Water Accounting + system has been applied and enriched with climate change information, allowing a useful comparison between these basins by agreed indicators and calculation methods. It evaluates water availability versus consumption, highlighting the role of managed resources and land use trends. 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.

Legacy: a water accounting system that is both driven by bottom-up local knowledge on regionally varying basin characteristics yet allows a uniform analysis of major trends and future projections of water availability and demands. A scientific paper documents the approach.

A Machine Learning tool to monitor impact-oriented drought

Proper management of drought risk needs to be informed by characteristics that are tailored to the region of interest. The FRIDA tool allows definition of a tailored drought risk index utilizing an objective selection and combination of local characteristics. Application in the Jucar basin identified different characteristics than the Alpine lake Como area. FRIDA generates a compounded drought risk indicator by following 3 steps: identification of basin

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characteristics, extraction of main features by a machine learning procedure, and modelling the final drought risk index. It replicated the traditional state index for the Jucar area well.

FRIDA allows a realistic identification of the current drought state and gives information on the impact of measures to alleviate drought risk. It speeds up the process of defining a risk indicator to be included in drought risk management plans and allows depicting the optimized drought risk for a range of users with potentially conflicting interests.

Legacy: Informed drought risk management is expected to become more important in drought prone areas. In 10 years from now FRIDA-generated indices will be targeted in (seasonal) forecasting and climate projections, increasing consistence of information necessary for operational and strategic decision taking. The code and datasets are online available, allowing application in other areas.

Assessment of non-European climatic drivers of European economic vulnerability

An extensive analysis is made of water consumption and trade networks of a large collection of crops used for food production. Linking the trade & production chains with ambient climate features, a climate risk profile for each of these crops can be produced. This can inform food producers or retail companies about the current and potential future vulnerability of their supply chains, and lead to formulation of coping strategies to reduce this risk.

Legacy: A consultancy start-up, R2Water, was founded to commercialize the approach and tool. **T**he procedure and its results will be transferred into a (commercial) service to private industry by (a) highlighting current risk profile, (b) enhancing these risk profiles by including

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impacts of historic or synthetic extreme weather events, and (c) an authoritative future climate assessment of these risks.

Hydrological Risk Outlook

The various components of the risk outlook are shaping up in the online tool at the IMPREX website. It is to be conceived as a website for people with an interest but not necessarily professional experience in interpretation of seasonal forecasting for hydrological applications.

A topic "Historic analysis of European hydrological risks" discusses hydrometeorological features of 5 past seasons, and comments on the way a seasonal forecast is constructed from this collection of information, to illustrate the scientific process leading up to an operational seasonal forecast. The "Visualisation tool for meteorological and hydrological data" is an entry point to the Copernicus hydrological forecasting system, which gives actual forecast information and allows tailored browsing of forecast products. A collection of "Forecast bulletins" discusses seasonal forecasts developed for the Spanish Segura basin, displaying the technical forecast information and the additional guidance and interpretation of it (in Spanish). In addition a collection of sectoral narratives is included that gives user testimonials on their use and appreciation of seasonal forecast products developed in some of the IMPREX case studies. Finally a serious game on interpretation of hydrological forecasts helps to practice interpretation and decision taking.

Legacy: the IMPREX risk outlook will not be a semi-operational product, and will not be updated with future information. However, it will remain a repository of stakeholder-oriented

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guidance and experience sharing, inspiring future product developers and users. Connection with the Copernicus Seasonal Forecasting Service is being established.

EU policy analysis on floods and drought management

A coherent analysis of European policies in flood risk and drought management was executed, highlighting the usefulness of IMPREX tools and methodologies for implementation of EU Policy Frameworks on Floods and Droughts at basin level. Policy briefs were produced about flood risk damage modelling, compound events, and risk-based drought management.

A position paper on general lessons learned from IMPREX is prepared guiding future project design to maximize relevance for the water sector. It focuses on the interfaces "science-policy making", "science-practice" and "science-science" interfaces and highlight potential approaches to overcome hurdles that appear in these interfaces.

Legacy: Three policy briefs and one position paper with recommendations on the design of research projects and building blocks of improved collaboration in the interfaces between science and policy-making, practice and scientific world itself.

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Conclusions of the project

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.

"Learn from today to anticipate the future" has been a leading principle throughout the IMPREX preparation and execution phase. We have encouraged tight interaction between science and stakeholders, as the tools and governance protocols that are part of the practitioners' institutional culture are the most effective carriers of scientific information into the everyday practice. A strong stakeholders engagement was promoted by following the rationale that the project should first be known, subsequently be liked and ultimately be trusted before science-informed changes can materialize. We have worked with stakeholders that were partly already connected to the research partners in the project, that facilitates the know-like-trust sequence. But in addition, we have worked in their setting, with their tools and procedures, and developed and evaluated forecast and climate information tailored to their environment.

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Results were not always immediately favorable. Production of high quality of forecasts and data at the very local scale is a challenging task, and at long time scales there is not a lot of opportunity to apply a comprehensive forecast skill evaluation. Also, decisions in the water sector are covering many topics and time scales, and are frequently embedded in long-lasting management cultures, in which new information and evidence needs to be benchmarked against existing information.

Stakeholder interaction, forecast system development, climate change impact analysis are all activities that take a long time to mature. For some specific applications IMPREX can present a number of success stories (see text boxes in this report). But for equally many topics IMPREX has generated an incremental contribution to the quality of forecasting systems, climate services and science-practice and science-policy interactions. It takes mutual commitment, a certain amount of coordination, creative tailoring and patience to demonstrate the added value of the scientific contributions to the real-world problems. IMPREX is happy to have been able to make this incremental contribution.

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Final assessment of Prof Andy Wood & Prof Penny Whetton,

IMPREX Advisory Board members

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

My overarching reflection at the end was the IMPREX has led to successful outcomes in many areas, some of which are easy to recognize. It's created a broad base of support for ensemble forecasting of low flows in Germany. It has allowed UKMO to explore and develop a potentially useful approach for enhancing the value of Europe-wide precipitation forecasts. It's allowed for the assessment of ECMWF weather and climate forecasts in a range of contexts, and facilitated the development of forecast-informed decision support models in a number of case studies. In Holland, it has led to the parallel operational trial of forecasting capabilities using a new class of process-based hydrologic models, in place of conceptual models that are ill-designed for a non-stationary climate (ie with separate parameters for dry and wet regimes).

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In general, though, I think it's important for IMPREX recognize aspects of legacy that go beyond the merely operational outcomes, including those above. Operational outcomes are easy to headline. But the timelines of progress are not always easily measurable within a four-year project. In my own experience of running 1-3 year transition-oriented projects, the four years of IMPREX allowed for a cycle of 'a priori design -> failure/refinement -> engagement -> trust -> co-design with stakeholders -> transition/adoption' that there is rarely time for in a shorter project.

There are other layers of legacy, however. One is the legacy of greater scientific understanding, as in the Deltares case with the new modeling, and the SMHI case with the analysis of predictability. Another is a legacy of community awareness, as in the building of support within multiple stakeholder groups within Germany for enhanced ensemble prediction. This is a critical element that will propel that work even after IMPREX is gone. And another is the legacy of personal growth and training, in the introduction of a diverse new cadre of researchers to the challenges and rewards of research-to-operations research. As their careers grow and they undertake future transition type projects, they will be less naive and more effective in accomplishing them, based on lessons learnt at length through IMPREX. Another aspect of the personal legacy is the friendships and collaborations, and interagency familiarity, that have been fostered. This interpersonal connection that oils the gears and transactions of scientific progress, and motivates good/responsible interconnected work. Networks are important. In summary, in areas where IMPREX may not yet be able to point to a concrete operational outcome, I think it can point to seeds of future ones that are embedded in these other layers of legacy. The legacy of IMPREX is multi-faceted and rich.

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Recommendations from the Position Paper on Science-Practice Research

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 open 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.

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Providing the means to follow-up prevents missing out on potentially important insights and not starting from scratch.

Recommendations for scientific research project organization:

- 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.

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IMPREX – PARTNERSHIP

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- 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
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- Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture – FR
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- 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