Climate Services 19 (2020) 100180

Contents lists available at ScienceDirect

Climate Services

journal homepage: www.elsevier.com/locate/cliser

A method of assessing user capacities for effective climate services

David Samuel Williams[a,*], María Máñez Costa[a], Dmitry Kovalevsky[a], Bart van den Hurk[b], Bastian Klein[c], Dennis Meißner[c], Manuel Pulido-Velazquez[d], Joaquín Andreu[d], Sara Suárez-Almiñana[d]

[a] Climate Service Center Germany (GERICS), Helmholtz-Zentrum Geesthacht (HZG), Germany
[b] Deltares, previously at Koninklijk Nederlands Meteorologisch Instituut (KNMI), Netherlands
[c] Bundesanstalt für Gewässerkunde (BfG), Germany
[d] Research Institute of Water and Environmental Engineering (IIAMA), Universitat Politècnica de València (UPV), Spain

A B S T R A C T

Translating and incorporating climate information into decision-making and policy planning processes is challenging. In tailoring climate data to sector-specific user needs, climate services are seen as key mechanisms for facilitating this translation and incorporation, supporting climate change adaptation and sustainable development. The European water sector is especially in need of tailored climate data for informing climate-smart action and reducing human and economic impacts of climate change. This was the objective of the EU Horizon 2020 Project IMPREX (IMproving PRedictions and management of hydrological EXtremes). The paper shows how pre-identified shortcomings were addressed in the design of climate services in IMPREX, and how this process elucidated new research priorities for improving the effectiveness of climate services. The paper finds the use of participatory methods helped identify stakeholder needs, and advocates for the greater consideration of user and institutional capacity for integrating climate services into decision-making and policy planning processes.

1. Climate services as mechanisms for climate change adaptation and sustainable development

Global warming is changing the operating space for decision-makers and policy planners, in particular through increasing the intensity and frequency of hydrological extremes. For every degree of average global surface warming, the probability of increased intensity and frequency of hydrological extremes grows significantly in many populated places of the world (IPCC, 2018). With limited progress on decreasing the dependency of the world economy on fossil fuels to limit global warming to 1.5 °C or 2 °C in accordance with the Paris Agreement (UNFCCC, 2017), and climate projections indicating the 1.5 °C threshold to be reached within the next two decades (Jacob et al., 2018), decision-makers and policy planners will have to adapt to changing hydrological conditions to mitigate and avoid human and economic damage.

Contemporary climate change research has assessed the differences between global impacts of 1.5 °C and 2 °C warming, and concluded these to be significant (Schleussner et al., 2016). A study undertaken at the European scale identified economic vulnerability of the European water sector to both 1.5 °C and 2 °C global warming scenarios (Jacob et al., 2018). This illustrates the benefit of early adaptation through mechanisms and services to support and facilitate climate-smart decision-making for water management.

Building climate scenarios, aided by highly developed projection systems, can be an effective tool to assess the impacts of changes in climatic conditions on social systems (Berkhout et al., 2014). Climate scenarios are seen as key for supporting decision-makers in deliberating future actions (van den Hurk et al., 2018). This however reveals a conundrum: while the quantity and quality of climate data being generated is increasing steadily, its uptake and implementation by decision-makers is still severely lacking (Dilling and Lemos, 2011; Olazabal et al., 2019; Webber, 2019). Importantly, previous research has found no discernible link between improved climate projection systems and climate-smart decision-making or action (Lemos and Rood, 2010; Lorenz et al., 2017; Naustdalslid, 2011).

The efforts of climate scientists in improving climate projection systems (Hewitt et al., 2013) are not well balanced with the attention paid to the development of user-driven approaches to apply these projections in practical applications (Feldman and Ingram, 2009; Hewitt et al., 2013; Vincent et al., 2017). A radical paradigm shift in environmental resource management to enhance the human dimension in climate change adaptation and transformation (Pahl-Wostl et al., 2010) calls for an intensification of development of practice-driven climate change assessments. A lack of knowledge concerning the integration of forecasts and projections into decision-making and policy planning systems can be observed (Hewitt et al., 2013).

Governance and institutional context, and their role in science-

* Corresponding author.
E-mail address: david.williams@posteo.net (D.S. Williams).

https://doi.org/10.1016/j.cliser.2020.100180
Received 28 August 2019; Received in revised form 15 May 2020; Accepted 30 July 2020

based decision-support for climate change adaptation and sustainable development, is also highlighted as a key area which has so far been under-exploited in climate change science (van den Hurk et al., 2016). This reflects the notion that user decisions are not only influenced by the quality and usability of climate information. Rather, user decisions are shaped by a multitude of factors, including institutional hierarchy, power, political will, and expertise, which have all been found to significantly affect the flow of scientific information into decision-making and policy-planning processes (Nost, 2019; van Kerkhoff and Lebel, 2006). Moreover, as climate change adaptation progresses from impact assessment to policy planning and implementation, water management organizations face a series of multi-dimensional barriers and challenges for successful adaptation: cognitive barriers to cope with uncertainty and risks; role of values in selecting adaptation options; lack of information relevant to their scale of influence; inadequate human and financial resources; lack of trust, confidence and leadership; lack of consistent and clear policies; and focus on short term issues (Azhoni et al., 2018; Eisenack et al., 2014). By developing tools which support water management for current day operational practices, closely analysing experiences at short time scales, and incorporating the current day practice of users into risk and impact assessments, some of these barriers could be partially overcome (van den Hurk et al., 2016).

The utilization of climate information to enable actionable climate research has led to a focus on climate services for supporting climate change adaptation and sustainable development (van den Hurk et al., 2016). Climate services comprise of more than using models to predict the impacts of climate change and climate variability (Hewitt et al., 2013). They include the production, translation, and delivery of usable climate information to support climate change adaptation, reducing risk and contributing to human security and sustainable development (Adams et al., 2015; Buontempo et al., 2018; Vaughan et al., 2016). Deducing from the growing body of literature on climate services as mechanisms for climate change adaptation (Larosa and Mysiak, 2019; Palutikof et al., 2019), successful climate service provision needs to strike a balance between scientific results in the form of meteorological and hydro-meteorological forecasts and projections, activities to tailor outcomes of these to user needs, and development of user capacities to optimize translation and incorporation of usable weather and climate information into decision-making and policy planning processes (Fig. 1).

Optimizing translation and incorporation of climate data into decision-making and policy planning processes is addressed by the EU Horizon 2020 Project IMPREX (IMproving the PRediction and management of hydrological EXtremes), in which weather and climate projections were tailored to the sector-specific needs of users in a number of hydrological sectors in Europe (van den Hurk et al., 2016). This perspective article is iterative, first demonstrating how the development of climate services was designed to overcome the pre-identified shortcomings around the lack of user-centric climate service development (Adams et al., 2015; Vaughan et al., 2016). Then, out of this initial process, further research areas for enhancing the effectiveness of climate services are presented. The discussed methods and results were

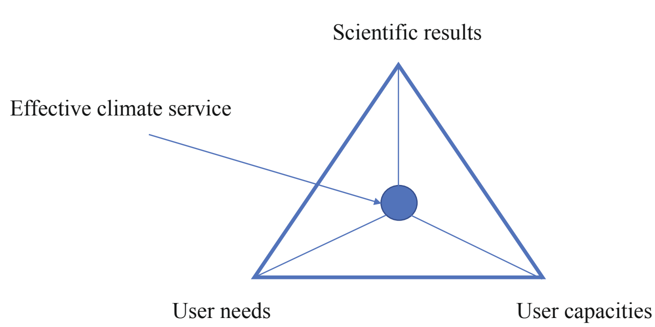

Fig. 1. Three dimensions of successful climate service provision.

developed in a participatory manner with scientists and stakeholders in the IMPREX project (imprex.eu), which also provides a repository for numerous project reports and other additional information. Two case studies illustrating the process of developing prototype climate services, as well as a shortcoming of this process, are presented in Section 2. The Capital Approach Framework (CAF) is then proposed as a strategy to overcome this shortcoming in Section 3 and applied ex ante in both case studies in Section 4. A discussion on the implications for the widening scope of our understanding of climate services is then presented in Section 5.

2. Case studies for climate service prototype development

One of the primary ways in which climate change will impact society is through systematic changes in the amount of water availability, exposing regional populations to increased risk of droughts and floods (Feldman and Ingram, 2009; Hewitt et al., 2013; van den Hurk et al., 2016). Within IMPREX, nine case studies from the European water sector were selected. An assessment of the existing schemes of operation was first undertaken to inform appropriate climate service development. Fig. 2 shows the present prediction and projection systems in relation to the use of information for the existing schemes of operation in applications from the European Water sector at varying spatial and temporal scales (van den Hurk et al., 2016).

As a representative illustration, two case studies are presented here: water supply in a densely populated river basin in southern Europe, and Inland-Waterway-Transport (IWT) in a river basin in western Europe. In both cases, tailoring meteorological and hydro-meteorological projections to the sector-specific user needs was applied to support the exploration of options to adapt to hydrological extremes. Current day practices, strategic management structures and user involvement were identified through participatory modelling workshops, explained in greater detail in each case study context.

2.1. Water allocation in the Júcar River basin

The hydrological system in Spain is split up into hydrographic districts and aligned with river basins. The Júcar River Basin District (JHD) is located in southeastern Spain and is comprised of 9 water exploitation systems. The JHD is named after the Júcar River Basin (JRB), flowing over a length of 512 km from the Montes Universales mountain range and emptying into the Mediterranean Sea in the town of Cullera, south of Valencia. The JRB extends across 22,378 km^2, and the average volume of water resources in the entire basin is approximately 1,605 hm^3/year. The JRB has a high water exploitation index, with up to 88% of average annual water resources demanded for economic use. Of this, 80% is used for irrigation in agriculture. Urban, industrial and hydropower account for the rest (Confederación Hidrografica del Júcar, 2015).

The region is characterized by a semi-arid climate, as well as high spatial and temporal variability of precipitation, causing high seasonal and inter-annual variation in river flows and leading to recurrent multiannual droughts (Carmona et al., 2017; Hunink et al., 2017). The frequency and intensity of droughts has made the JRB one of the most climatically vulnerable regions in the western Mediterranean. Regional climate models project a decrease in rainfall combined with an increase in extended dry spells and evaporation, leading to a higher risk of droughts in the region (Kovalevsky et al., 2019a; Lehner et al., 2006; Marcos-Garcia et al., 2017). Furthermore, climate projection systems reveal both a high level of uncertainty around the availability of water resources in the future, and a rise of the regional average temperature, declining amounts of annual precipitation, and increasing interannual variability, leading to reductions in hydrological inflows to rivers and groundwater recharge (Carmona et al., 2017; Pulido-Velazquez et al., 2015). Due to the high dependency of economic and social functions on sufficient water availability, the impacts of climate change in this

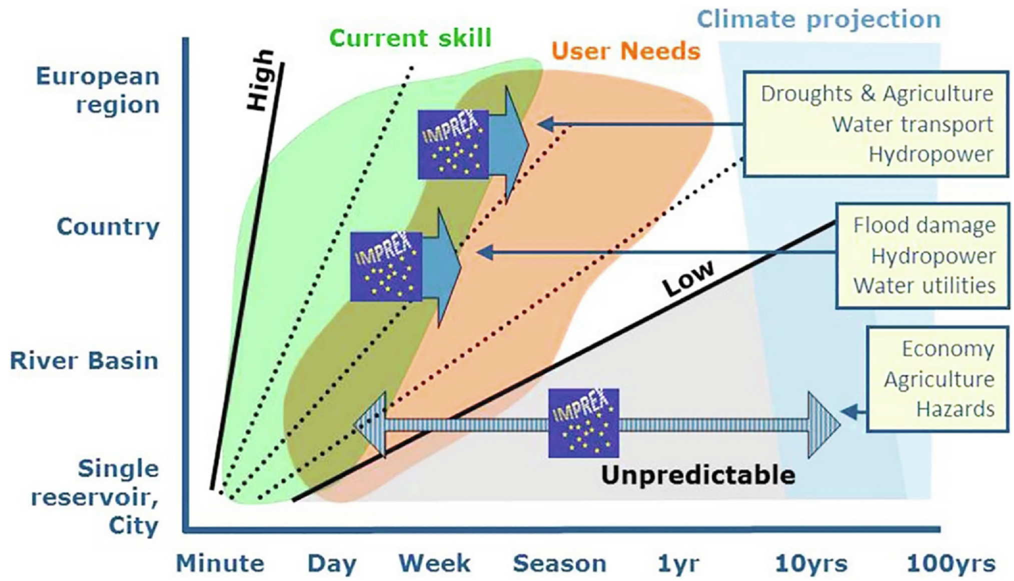

Fig. 2. Concept for assessing of the existing schemes of operation in European Water sector to inform climate service development (van den Hurk et al., 2016).

region could be severe (Carmona et al., 2017).

To cope with recurrent drought periods, the hydrological system in the JRB is highly managed. Management strategies include water storage infrastructures, conjunctive use of surface and ground waters, and drought management plans (Andreu et al., 2013; Hunink et al., 2017). This is in addition to significant institutional and legal developments, such as the early establishment of the Júcar River Basin Public-Private Partnership (Confederación Hidrográfica del Júcar, CHJ) in 1936. The CHJ is a participatory body including all major sectors of water users, national, regional, provincial and local representatives, NGOs, labor unions, farmers associations, as well as a central administration unit. To fulfil its main objectives of protecting the public water domain and minimizing the impacts of floods, water scarcity and drought, the CHJ is in charge of water allocation, approving annual water distribution plans, and water infrastructure developments (Carmona et al., 2017).

Sector-specific user needs for climate information were identified in participatory modelling workshops with actors from the water sector in the JRB (Máñez Costa et al., 2017). Participatory modelling is a method for identifying and understanding user needs as a basis for developing a family of models and climate services (Máñez Costa et al., 2017; Voinov and Bousquet, 2010), and for providing valuable user information for environmental systems modelling (Vennix, 1996), in particular supporting river basin management (Andreu et al., 2009; Antunes et al., 2006; Videira et al., 2009; Williams et al., 2019). The inclusion of stakeholder knowledge during the prototype development phase also increases the likelihood of acceptance and use of final outcomes, fostering trust in science (Krueger et al., 2012; Sedlacko et al., 2014). During the process, learning is reciprocal, enhancing not only the knowledge of climate service developers, but also the stakeholders' understanding of these services and the system dynamics under various climatic conditions (Voinov and Bousquet, 2010). This allows stakeholders to better grasp the scale and operation of complex systems (Krueger et al., 2012).

The workshops were attended by 11 stakeholders, ranging from municipal officials, water utility companies, river basin authorities, insurance companies and farmer unions. Individual models were developed with each stakeholder before these were synthesized to a group model (Hovmand, 2014). Group models can be used as integrated conceptual frameworks for adaptive risk management, revealing the underlying dynamics, as well as tensions and dualities of the system under investigation (Hovelynck et al., 2010). This group model was then presented and validated at a participatory workshop with the stakeholders. For a detailed representation and description of each model, in addition to the group model, and further information on the process, please refer to Máñez Costa et al. (2017).

These workshops revealed the key challenges for decision-makers in managing water availability and allocation in the JRB, including the lack of reliable seasonal forecasts feeding into water resource allocation decisions, and interannual and longer term climate projections of droughts needed for long term resilience planning (Carmona et al., 2017). Real-time management decisions are taken in a proactive manner, generating future hydrological scenarios with stochastic modelling (Andreu et al., 2009), but without the incorporation of any seasonal climate projections (Carmona et al., 2017). Future planning decisions are taken without using long-term climate projections, only with average estimates of increase or decrease of hydrological flows (Estrela et al., 2012; Marcos-Garcia and Pulido-Velazquez, 2017).

To support climate-smart decision-making for adaptation and management of hydrological extremes, Interdisciplinary Knowledge Integration (IKI), consisting of the conceptual integration of user perspectives (Hovelynck et al., 2010), was chosen as a participatory modelling approach. It is designed to identify the different sectoral needs concerning temporal and spatial scales of weather and climate information (Andreu et al., 2018; Kovalevsky et al., 2019a; Máñez Costa et al., 2017). Downscaled weather and climate variables are then transformed into hydrological variables (river in-flows, water-levels in aquifers, etc.); variables related to the state and operation of water resource systems; and indicators which serve to assess the impacts and risks. In this way, forecasts and projections of weather and climate variables can be translated into impacts and associated risks for each sector (Andreu et al., 2018).

Using the IKI approach, qualitative system dynamics (SD) models were co-produced with stakeholders during participatory modelling interviews and served as a basis for developing a family of quantitative SD models. These models use climate projections and seasonal weather forecasts as inputs, producing the information tailored to specific user needs and relevant for assessing the adaptation options in the JRB. In particular, a family of SD hydro-economic models has been developed, with socioeconomic and hydrological modules of various degrees of complexity (Kovalevsky et al., 2019a; Kovalevsky and Máñez Costa, 2019; Máñez Costa and Kovalevsky, 2018; Rubio-Martin et al., 2020). On the basis of these SD models, a translation of drought hazards derived from multi-scale drought indices into integrated drought risk maps for the JRB was performed, taking into account the different user needs in terms of drought hazard and risk information aggregated over different time scales (Kovalevsky et al., 2019a). The generic methodology of drought indices computation and drought risk mapping developed has been applied to climate projections delivered by REMO2009 and CCLM4 regional climate models, but can be easily transferred to utilize data from seasonal weather forecasts. Additionally, an SD model was developed exploring the dependence of the demand for weather index-based insurance products for agriculture on the skill of regional seasonal forecasts (Kovalevsky and Mañez Costa, 2019).

Based on information co-produced during participatory modelling, IMPREX further formulated the ambition to improve the availability of tailored seasonal and inter-annual climate projections able to predict droughts through two major innovations. First, by developing long-term inter-annual forecasts of future precipitation, temperatures, and flows under climate change, to assist the CHJ in optimizing water allocation plans (Hunink et al., 2017). Second, by developing seasonal forecasts for precipitation, temperature and flows, to reduce uncertainty in probabilistic impact forecasts used for decision-making in seasonal action plans and mitigation measures (Hunink et al., 2017).

2.2. Inland-Waterway-Transport on the Rhine River

The Rhine River is the longest river in Western Europe, spanning across 1,230 km and draining an area of approximately 200,000 km^2 (Klein and Meißner, 2016; Shabalova et al., 2003). Originating in the Swiss Alps, the Rhine River flows through Lake Constance along the German-Swiss border, dissects western Germany and the Netherlands before emptying into the North Sea (Shabalova et al., 2003). Snow- and glacier melt from the Swiss Alps is superimposed by pluvial flow regimes from major tributaries (Neckar, Main, and Moselle), leading to a complex flow regime (Klein and Meißner, 2016). Maximum flow at the Middle and Lower Rhine River is most commonly experienced in late winter due to high precipitation in the mountain regions of Germany and France, and low levels of evaporation (Klein and Meißner, 2016). The most relevant bottlenecks (shallows) for transport along the international waterway are experienced during low flow at the Middle and Lower Rhine River in late summer and autumn due to high levels of evaporation and reduced contributions from snow- and glacier melt from the Swiss Alps (Klein and Meißner, 2016).

However, climate change is altering flow regimes in the Rhine River due to changing precipitation patterns in combination with increased evaporation, reduced snow storage and an intensification of early snow- and glacier melt (Shabalova et al., 2003). An increase in the frequency of floods is often one of the main climate change impacts cited (Linde et al., 2010). The potential for economic damage along the densely populated areas adjacent to the Rhine River is significant, and flood damage estimates are commonly undervalued (Moel and Aerts, 2011).

Low flows can lead to significant economic losses. Various extreme low-flow events have occurred in recent decades, and projected changes indicate an increase in the frequency and intensity of droughts in the Rhine River basin (RRB) with a high degree of confidence (Huang et al., 2015; Lanen et al., 2016). Climate change impact studies therefore need to also consider the risk of drought, as well as the impact of low-flow periods (Linde et al., 2010).

One of the activities impacted by low-flow periods is Inland-Waterway-Transport (IWT), for which the River Rhine has long been the most important river in Europe (Shabalova et al., 2003). The importance of the River Rhine as an integral part of the *trans*-European waterway system is outstanding: with almost 200 million tons transported along the River Rhine per year (approximately 2/3 of the European IWT volume), it isn't solely Germany's, but also Europe's most important inland waterway. The intense navigation, on which the German energy supply still depends, takes place mainly along the 800 km stretch of shippable river from Rotterdam to Basel (Klein and Meißner, 2016). IWT is an attractive mode of transport due to its ability to distribute large quantities of goods per vessel, resulting in low transport costs and low environmental impact compared to other forms of cargo transport (Klein and Meißner, 2016). It is also considered one of the safest modes of transport, in addition to low infrastructure costs and low restrictions on capacity (Klein and Meißner, 2016).

IWT is particularly advantageous on good navigable fairway conditions, with available water depth determining the loading capacity of vessels (Klein and Meißner, 2016). The close correlation between operating efficiency and water depth implies a high vulnerability to low flow conditions. Low flows can be caused in free-flowing river stretches by a combination of climatic factors, primarily low precipitation, but also high evaporation and dry catchment conditions. Therefore climate change could affect the ease, safety, efficiency and reliability of IWT in the Rhine River (Klein and Meißner, 2016). Past climate change studies with focus on future conditions of IWT (Nilson et al., 2014a; Nilson et al., 2014b) and recent results of IMPREX (Falloon et al., 2019) showed no clear climate change signal of relevant sector-specific low flow days for the near future (2021–2050) compared to the current variability. However, for the distant future (2071–2100) the number of low flow days was projected to increase, revealing the need for climate change adaptation strategies. The direct impacts of severe low flow in late summer and autumn 2018 on shipping companies, as well as indirect impacts on consumers due to increased gas and fuel oil prices caused by increased transportation costs, were extensively reported by national and international media outlets (e.g. NYT, 2018; Spiegel, 2018; Zeit, 2018).

Again, the IKI approach was applied through participatory modelling workshops with actors from the IWT sector, comprised of energy supply companies, shipping and logistic companies, industrial enterprises, and transmission network operators, as well as administrative authorities and ministries. A total of five stakeholders were consulted, producing five individual models which were then synthesized to a group model. The synthesized group model was presented and validated back to the stakeholders during a user workshop hosted by the Bundesanstalt für Gewässerkunde (BfG) in Koblenz in March 2019. For more detailed information on the stakeholders, the process, and the synthesized group model, please refer to Kovalevsky et al. (2019b).

The participatory modelling workshops revealed the added value of improving the accuracy or performance of a particular forecast system, also at longer lead-times. Short-to-medium-range, monthly, and seasonal forecasts could assist in anticipating low flow periods and supporting risk-based decision-making (Hargreaves, 2010; Klein and Meißner, 2016). Further desires for innovations were a clear display of uncertainty in future products, which enhances transparency and underlines that deterministic forecasts are not always accurate (Klein and Meißner, 2017). Actors also preferred river water-level as the forecast variable to focus on, and were supporting the consideration of monthly to seasonal forecasts for anticipating the late summer and autumn water-levels in advance (Klein and Meißner, 2017). This would support decision-making around vessel load optimization, timing of transport mechanisms, scheduling of complete transport cycles, as well as stock and production management along the entirety of the River Rhine (Klein and Meißner, 2017).

A typology of RRB stakeholders was developed in participatory stakeholder modelling sessions, and their decision-making criteria and strategies were derived from stakeholder interviews. These served as a basis for development of an SD model of cargo transportation by IWT supported by navigation-related probabilistic forecasts (Kovalevsky et al., 2018). In particular, the model assesses the benefits of probabilistic forecasts for the decision-making on optimal loading of the vessels and for maintaining the sustainability of supply chains in RRB.

Additionally, based on the vulnerability analysis and user feedback from various IWT actors during the participatory modelling workshops, pre-operational water level and flow forecasting services were developed to mitigate the vulnerability of IWT against hydrological impacts. To support medium-term decision making, 10-day probabilistic water level forecasts have been provided pre-operationally to the users (Klein & Meißner 2019) in addition to the operationally published deterministic 4-day water-level forecast for the River Rhine. Pre-operational means the service is limited to the project duration and does not have the same service level guaranteed as for current operational water level forecasts. Nonetheless, providing this information for the first time enhances medium-term decision making on load optimization, including the estimate of forecast uncertainty.

To support long-term planning of inland waterway transport, monthly to seasonal forecast products have been developed and analyzed in IMPREX (Klein & Meißner 2019). Due to the limited skill of seasonal forecasts in Central Europe with a predictability of 1–2 months at maximum, it was decided to focus on a 6-week flow forecast provided to the users on a weekly basis during the course of IMPREX. The approach developed might inform operations of water transport, particularly under low-flow events, under the current climate conditions. It may also inform the development of proactive adaptation measures for water transport and other sectors dependent on low-flow events under future anticipated climates, in which their frequency and intensity are projected to increase.

On the whole, a high degree of implementation and operationalization of the developed climate services in the RRB could be observed. The observation was confirmed during the aforementioned user workshop hosted by the Bundesanstalt für Gewässerkunde (BfG) in Koblenz in March 2019. This is an indication not only of robust scientific results as well as adequate consideration of user needs, both within the remit of IMPREX, but also strong user capacities to translate and incorporate climate information into decision-making processes, resulting in the successful provision of climate services. The question which arises therefore is when a similar process of climate service development is carried out in two case studies, to what extent do differences in user capacity lead to stronger or weaker climate service implementation and operationalization?

2.3. Shortcoming of climate service prototype development

While the work undertaken in the river basins can be considered a success, climate service prototypes developed for the two case studies represent a tendency to view climate change adaptation as a predominantly technical issue. The underlying conceptual approach, as presented in Fig. 2, focuses on spatial and temporal scales of forecasts and projections, illustrative of a reliance on linear models of climate service delivery (Webber, 2019). It neglects the contestation that in fact political economy also significantly shapes the contextualization of climate information (Nost, 2019).

A pressing area of research is for science-society interfaces to become more responsive to users by contextualization with social, political, and cultural settings (Webber, 2019). This relates to findings made by Vaughan et al., (2018), who emphasize the importance of capacity development for enhancing the effectiveness of climate services. Hence, research into exploring methods for assessing user capacities to enhance the effectiveness of climate services is seen by several international organizations as urgent (IPCC, 2018; WMO, 2019a).

3. A method for assessing user capacities to enhance successful climate service provision and maximize impact

The recent IPCC 1.5 °C report states that effective climate change adaptation requires consideration of “institutional climate change capacities along multiple dimensions”, highlighting low institutional capacity as a key barrier for climate service implementation, preventing the application of climate information for climate-smart decision-making (IPCC, 2018). This is reiterated by the World Meteorological Organization, stating that “training the recipients of climate services is important to ensure capacity to translate and incorporate climate services in their decision-making” (WMO, 2019b). Thus, a focus shift from the producers to the users of climate services in the RRB and JRB is necessary.

The users in the RRB are predominantly private companies, which traditionally are able to mobilize considerable financial, technical, and human resources in-house, including meteorologists, hydrologists, and technicians (Altenburg, 2005). Incentives for cost reduction have also found to be stronger in the private sector due to budget constraints from private shareholders (Altenburg, 2005). Examining policy incentives which drive actions may therefore help in understanding the differences in degree of implementation and operationalization between the RRB and the JRB (Burgess and Ratto, 2003). Contrasting work-loads and resource planning may also be a factor. However, without a strong scientific evidence base, these theories are merely conjecture, calling for analytic tools or methods for assessing user capacities for implementing climate services.

The implementation of climate services will to a large degree depend on the capacity of users, either individuals or institutions (Jacobs et al., 2016; Klinke and Renn, 2012; Munang et al., 2010; Vaughan et al., 2016). Increasing the capacity of users to translate and incorporate climate information has therefore been highlighted as crucial for effective climate service provision (Vaughan et al., 2016). Conversely, the capacity of users to translate and incorporate climate information is an essential aspect of climate services commonly overlooked (Adams et al., 2015), particularly in the context of coping with and adapting to hydrological extremes (Höppner et al., 2012; Lorenz et al., 2017; Williams et al., 2020b; Williams et al., 2018). Tailoring climate services to climate change capacities by adjusting to the degree a user group is able to adapt to climate change could enhance the effectiveness of climate services as a mechanism for climate change adaptation and sustainable development.

Aspects of the capacity of users to translate and incorporate climate information is a requirement included in various indicator-based frameworks for measuring adaptive capacity to cope with climate change (Siders, 2019). Most frameworks follow the notion of a set of necessary conditions for successful adaptation planning being present which are determined by various institutional settings and dimensions (IPCC, 2018; Walker et al., 2019). Climate change adaptation frameworks, commonly based on organisational and development practice theory, also include multiple dimensions, including but not limited to social; political; human; financial; and environmental criteria (Gupta et al., 2010; Siders, 2019; Máñez Costa et al., 2014; Shakya et al., 2018).

A capital approach (Scoones, 1998) has been proposed to examine adaptation capacities. Capitals can be understood as resources upon which action depends (see examples below). When tailoring climate service products to sector-specific user needs, this approach offers a method for including the consideration of the capacities of users. This could not only be useful for high-income institutional contexts, but particularly for middle- to low-income institutional contexts, where the capacity to use climate information in responding to hydrological extremes is often low (Shakya et al., 2018). The strengths and weaknesses of climate change capacities can be measured by evaluating qualitative and/or quantitative indicators for each capital (Carmona et al., 2017; Gupta et al., 2010; Ojwang et al., 2017; Williams et al., 2018). These can then be aggregated to capital level to determine the effectiveness of each capital, understood as the degree to which a desired or intended result can be achieved.

The Capital Approach Framework (CAF) has been applied to various case studies (Carmona et al., 2017; Celliers et al., 2020; Máñez Costa et al., 2014; Ojwang et al., 2017; Williams et al., 2018; Williams et al., 2020a,b). It can be adapted to varying contexts, and can identify strengths and weaknesses of users, institutions, and communities in responding to climate change, in particular hydrological extremes (Carmona et al., 2017; Ojwang et al., 2017; Williams et al., 2018; Máñez Costa et al., 2014). A key strength of the CAF setting is that apart from the wealth of indicator-based adaptation frameworks users from various sectors are active in co-developing and co-producing the various factors upon which resilience-enhancing measures depend (Carmona et al., 2017; Siders, 2019). Here we will discuss social, political, human, financial and environmental capital and their relevance for increasing the effectiveness of climate services. Their application to the IMPREX case studies is discussed below.

3.1. Social capital

Implementing and operationalizing climate services requires appropriate institutional settings, designing patterns which encourage and ensure mutual respect and trust (Gupta et al., 2010; Mackenzie et al., 2019). Further important aspects of social capital include effective risk communication (Haynes et al., 2008), access to useful, salient, and credible sources of climate information (Feldman and Ingram, 2009; Weichselgartner and Kasperson, 2010), continuity and reliability of climate information (Gupta et al., 2010), as well as deeply-rooted societal norms and cultural values (Pahl-Wostl, 2007). Transparent decision-making processes, clear delineation of roles and responsibilities, and accountability with regards to climate change action are essential (Klinke and Renn, 2012; Williams et al., 2018). Social capital also includes the ability to self-organize, as well as mobilization and participation, either of other institutions and networks, or of the wider public (Williams et al., 2018). Users do not act as isolated agents on complex issues, and cooperation can overcome barriers of information sharing for increased climate-smart decision-making and policy planning (Nkiaka et al., 2019; Vincent et al., 2018).

3.2. Political capital

Institutional mechanisms play a key role for political capital. Climate change is a wicked problem (Vogel et al., 2016), and due to power asymmetries and political agendas, as well as the beliefs and values of citizens determining the urgency to act, appropriate institutional constitution is key (Shakya et al., 2018). Political capital for climate services includes the institutional ability to act with foresight, willingness to learn and adapt, and to build coalitions for action and collaborative decision-making, as well as access to new forms of finance to deal with the most pressing needs, and the creation of incentives triggering system-wide change (Shakya et al., 2018). Political leadership also needs to allow room for long-term visions and to ensure a high degree of flexibility to respond to uncertain but high-impact climate change needs, whilst at the same time being open to collaboration between different actors and sectors (Gupta et al., 2010).

3.3. Human capital

Human capital necessary for the implementation and operationalization of climate services includes the people’s expertise, knowledge, level of skill and technological ability to deal with climate data (Gupta et al., 2010; Williams et al., 2018). Climate services therefore need to carefully consider not only which climate data to provide, but also to whom climate data is being provided. Increasing the technological ability of users can contribute to closing the climate information usability gap (Lemos et al., 2012). There is however significant variability in the technological ability of users and institutions for accessing climate data to improve decision-making (Aitsi-Selmi et al., 2016). Customizing climate information to the technological capacity of the user could facilitate the move from useful to usable climate information (Lemos et al., 2012). Technological ability is further key for linking and facilitating research-based knowledge and action (van Kerkhoff and Lebel, 2006).

3.4. Financial capital

Financial capital includes the availability of financial resources to support and enhance policy measures and financial incentives (Gupta et al., 2010), as well as flexible budget reallocation, access to new climate finance, and mobilising private investment (Shakya et al., 2018). It also extends to the establishment of financial incentives for climate services, as well as the diversification of financial resources (Gupta et al., 2010; Pahl-Wostl, 2007). Financial capital further encompasses marketability, an eminent issue in upscaling context-specific climate services. The understanding of the potential demand for climate information is currently undefined and fragmented, and is in need of improving (Street, 2016). The European Commission has acknowledged the importance of further understanding and strengthening the market for climate-dependent products and services (Hewitt et al., 2013). This enhances the ability of decision-making not only on adaptation issues, but also mitigation policies, resilient infrastructures, and future investments (European Commission, 2015). A strong and stable market is crucial to enhandavid.williams@posteoce the capacity for delivering climate services, and to provide social and economic benefits across Europe (Street, 2016).

3.5. Environmental capital

Environmental capital for the implementation of climate services refers to the management strategies and planning processes for the natural environment, including binding legal frameworks for environment and nature protection (Carmona et al., 2017; Williams et al., 2018). Contexts in which legislative instruments and mechanisms ensure environment and nature protection enhance the likelihood of implementing climate services is higher. Environmental capacity also includes general awareness of environmental impacts of climate change, as well as the importance of ecosystem services (Williams et al., 2018), along with actions and decisions favoring quality of land and water, such as crop productivity, water consumption, and environmental care (Carmona et al., 2017).

4. Capital Approach Framework applied to JRB and RRB

The capacity of users of climate services developed in IMPREX has previously been assessed in the JRB using the CAF (Carmona et al., 2017). Social capital was evaluated as moderately effective, mainly due to a lack of platforms and networks for the exchange of information, resulting in poor communication with the wider society. A high level of transparency and trust was inherent to decision-making processes in the JRB, leading to a positive evaluation of political capital. Human capital was also deemed highly effective due to the developed skill-level and wide-ranging competencies, as well as a high degree in terms of innovation for climate service application. Financial capital was evaluated as moderately effective, with deficiencies in terms of inadequate insurance policies affecting public and private investments, as well as a perception of economic impacts being most severe. Finally, environmental capital was deemed highly effective, primarily due to actions taken to restore the environment after climatic hazards have occurred, and strict adherence to timeframes of environmental action (Carmona et al., 2017).

For the RRB, no formal assessment of capital effectiveness has been conducted, and thus the evaluation is made ex ante, and derived provisionally based on qualitative observations as well as the expertise and experience of the authors in accordance with (Bremer et al., 2019). As the users of climate services for the Rhine River are primarily private companies, there is a lack of transparency around decision-making processes. Yet, the access to useful, salient, and credible sources of climate information ensures a sufficient incorporation of the climate information into decision-making systems, leading to a moderate evaluation of social capital. Institutionally, there is a considerable emphasis on efficient streamlining for innovation and uptake of new knowledge and information, leading to a positive evaluation of political capital (Figs. 3 and 4).

Concerning human capital, the skill-level and expertise of users of

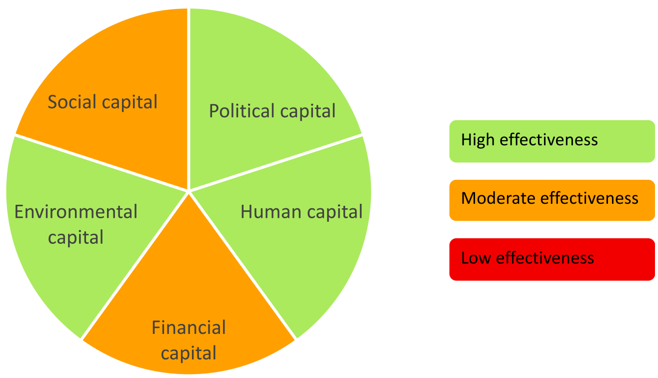

Fig. 3. Capital effectiveness in JRB.

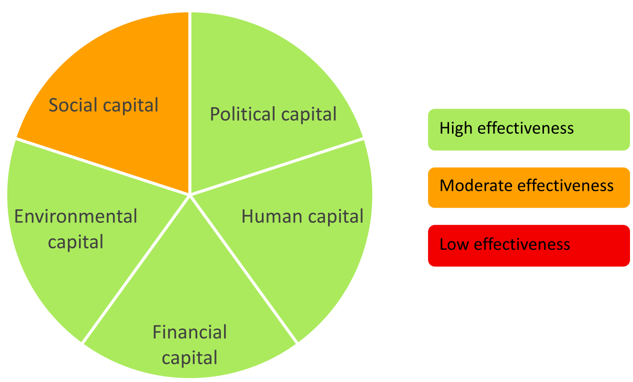

Fig. 4. Capital effectiveness in RRB.

climate services for the Rhine River is high, with an abundance of technicians and meteorologists. Similarly, users also have access to financial capital in terms of resources through efficient financial incentivisation and flexible investment mobilization. Finally, environmental capital has been deemed highly effective due to strict environmental legislation and protection, as well as monitoring and evaluation mechanisms.

The added value of the CAF is illustrated when considering that it is not so much the quality of information hindering the use of climate services (Lemos and Rood, 2010; Nkiaka et al., 2019). Rather, it is the capacity of users to effectively evaluate and base decisions and policies around the range of projections that are available (Vincent et al., 2017). While in the presented case studies the capacity for climate services is considerable, this form of assessment could yield markedly different results when applied in alternative contexts, particularly in low income regions (Harvey et al., 2019; Nkiaka et al., 2019).

Factors enabling climate change adaptation are highly scale- and context sensitive, varying significantly from user to user (Dilling et al., 2019). Drawing direct comparisons between the RRB and the JRB is not nevessarily desirable as adaptation is always informed by local conditions. The high level of both scale- and context-sensitivity require different methods of data interpretation. It is also important to note that the determinants of capacity to translate and incorporate climate information into decision-making and policy-planning systems may vary depending on the diversity of users and the institutional setting (Siders, 2019).

5. Extending the scope of climate services

In highlighting limited user and institutional capacity to implement and operationalize climate services, the IPCC 1.5 °C Report offers an explanation as to why no discernible link between improved climate projection systems and climate-smart decision-making or action could be identified (IPCC, 2018; Lemos and Rood, 2010; Naustdalslid, 2011). For climate services to be effective mechanisms for climate change adaptation and sustainable development, not only tailoring climate services to user needs is required, as described in Section 2, but far more to also consider user capacities in the development phase.

Strengthening regional and local meteorological networks could play a key role in enhancing the capacity of users for translating and incorporating climate information into decision-making and policy planning systems by improving expertise on climate change dynamics, risk and vulnerability framing, climate change modeling, climate change scenarios, climate change adaptation frameworks, downscaling methods, and adaptation planning (United Nations Institute for Training and Research, 2008). It is clear however that understanding climate information is not the sole determinant of success for the translation and incorporation of climate information into decision-making and policy planning systems. Decisions are not only based on availability and quality of information, and it is important to understand how hierarchy, power, political will, and institutional politics prevent the translation and integration of climate information to create policy paralysis and inaction (Lemos and Rood, 2010; van Kerkhoff and Lebel, 2006). The CAF has been demonstrated as a useful tool in elucidating the strengths and weaknesses of users and institutions for implementing climate change adaptation.

Commitment to creating and developing user capacities for translating and incorporating climate information, as well as broad and horizontal stakeholder participation, have been found to encourage the uptake of climate information into policy planning processes (Huntjens et al., 2012). Thus, the likelihood of uptake and implementation of climate information is significantly increased if climate services are co-developed with sector-specific actors, and tailored to the capacities of users. It is therefore essential for climate service providers to extend the current understanding of climate services to assessing and enhancing the capacity of users for integrating and operationalizing climate services. This research is timely, as an increasing number of countries are setting up organized climate service streams to inform development planning and other climate change adaptation and sustainable development actions (WMO, 2019b).

6. Conclusion

This article presents adaptation options for two European river basins affected by hydrological extremes developed within the IMPREX project. It illustrates how IMPREX co-produced climate services by applying participatory modelling techniques to tailor climate information to user needs. The climate services developed in the JRB and RRB demonstrate the added value of participatory approaches, enhancing the quality and relevance of the generated climate information, forging synergistic relationships between providers and users.

During the process of climate service development, it became clear that the ability of users and institutions to translate and incorporate climate services into decision-making and policy planning was key to implementing and operationalizing climate services. Therefore, this article proposes an analytical approach for identifying strengths and weaknesses of users and institutions for climate service providers not only to consider during the climate service development phase, but also to offer capacity-enhancing measures as a climate service for adaptation. We argue that further research in examining methods for tailoring climate services to the capacity of users and institutions will significantly increase the uptake of climate information into decision-making and policy planning processes. We feel these considerations are necessary for enhancing the impact and value of climate services as mechanisms for climate change adaptation and sustainable development.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was conducted under IMPREX, a research project supported by the European Commission under the Horizon 2020 Framework programme (grant nr 641811). The authors would further like to thank the reviewers and editors for their valuable comments, and the numerous stakeholders for participating in this research.

References

Adams, P., Eitland, E., Hewitson, B., Vaughan, C., Wilby, R., Zebiak, S., 2015. Toward an ethical framework for climate services. Doi: 10.13140/RG.2.1.1029.0645.
Aitsi-Selmi, A., Blanchard, K., Murray, V., 2016. Ensuring science is useful, usable and used in global disaster risk reduction and sustainable development: a view through the Sendai framework lens. Palgrave Commun. 2, 1–9. https://doi.org/10.1057/palcomms.2016.16.
Altenburg, T., 2005. The private sector and development agencies: How to form successful alliances. German Development Institute. Available at: https://www.die-gdi.de/uploads/media/The_private_sector_and_development_agencies.pdf.
Andreu, J., Ferrer-Polo, J., Pérez, M.A., Solera, A., 2009. Decision Support System for Drought Planning and Management in the Jucar River Basin, Spain, in: 18th World IMACS/MODSIM Congress. Cairns, Australia.
Andreu, J., Ferrer-Polo, J., Pérez, M.A., Solera, A., Paredes-Arquiola, J., 2013. Drought Planning and Management in the Júcar River Basin. In: Schwabe, K., Albiac, J., Connor, J., Hassan, R., Meza González, L. (Eds.), Drought in Arid and Semi-Arid Regions, a Multi-Disciplinary and Cross-Country Perspective. Springer, Dordrecht, pp. 237–249. https://doi.org/10.1007/978-94-007-6636-5.
Andreu, J., Solera, A., Suárez, S., Pedro-Monzonís, M., Pulido-Velazquez, M., Macián-Sorribes, H., Rubio-Martin, A., 2018. Prototype hydrologic module. Deliverable for IMPREX Project. Available at: https://imprex.eu/deliverables.
Antunes, P., Santos, R., Videira, N., 2006. Participatory decision making for sustainable development - The use of mediated modelling techniques. Land Use Policy 23, 44–52. https://doi.org/10.1016/j.landusepol.2004.08.014.
Azhoni, A., Jude, S., Holman, I., 2018. Adapting to climate change by water management organisations: Enablers and barriers. J. Hydrol. 559, 736–748. https://doi.org/10.1016/j.jhydrol.2018.02.047.
Berkhout, F., van den Hurk, B., Bessembinder, J., de Boer, J., Bregman, B., van Drunen, M., 2014. Framing climate uncertainty: Socio-economic and climate scenarios in vulnerability and adaptation assessments. Reg. Environ. Chang. 14, 879–893. https://doi.org/10.1007/s10113-013-0519-2.
Bremer, S., Wardekker, A., Dessai, S., Sobolowski, S., Slaattelid, R., van der Sluijs, J., 2019. Toward a multi-faceted conception of co-production of climate services. Clim. Serv. 13, 42–50. https://doi.org/10.1016/j.cliser.2019.01.003.
Buontempo, C., Hanlon, H.M., Bruno Soares, M., Christel, I., Soubeyroux, J.M., Viel, C., Calmanti, S., Bosi, L., Falloon, P., Palin, E.J., Vanvyve, E., Torralba, V., Gonzalez-Reviriego, N., Doblas-Reyes, F., Pope, E.C.D., Newton, P., Liggins, F., 2018. What have we learnt from EUPORIAS climate service prototypes? Clim. Serv. 9, 21–32. https://doi.org/10.1016/j.cliser.2017.06.003.
Burgess, S., Ratto, M., 2003. The Role of Incentives in the Public Sector: Issues and Evidence. Oxford Rev. Econ. Policy 19, 285–300. https://doi.org/10.1093/oxrep/19.2.285.
Carmona, M., Máñez Costa, M., Andreu, J., Pulido-Velazquez, M., Haro-Monteagudo, D., Lopez-Nicolas, A., Cremades, R., 2017. Assessing the effectiveness of Multi-Sector Partnerships to manage droughts: The case of the Jucar river basin. Earth's Futur. 5, 750–770. https://doi.org/10.1002/2017EF000545.
Celliers, L., Rosendo, S., Costa, M.M., Ojwang, L., Carmona, M., Obura, D., 2020. A capital approach for assessing local coastal governance. Ocean Coast. Manag. 183, 104996. https://doi.org/10.1016/j.ocecoaman.2019.104996.
Confederación Hidrografica del Júcar, 2015. Júcar River Basin Management Plan. Available at: https://www.chj.es/es-es/medioambiente/planificacionhidrologica/Paginas/Indice-Planificacion-hidrologica.aspx.
Dilling, L., Lemos, M.C., 2011. Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. Glob. Environ. Chang. 21, 680–689. https://doi.org/10.1016/j.gloenvcha.2010.11.006.
Dilling, L., Prakash, A., Zommers, Z., Ahmad, F., Singh, N., de Wit, S., Nalau, J., Daly, M., Bowman, K., 2019. Is adaptation success a flawed concept? Nat. Clim. Chang. 9, 572–574. https://doi.org/10.1038/s41558-019-0539-0.
Eisenack, K., Moser, S.C., Hoffmann, E., Klein, R.J.T., Oberlack, C., Pechan, A., Rotter, M., Termeer, C.J.A.M., 2014. Explaining and overcoming barriers to climate change adaptation. Nat. Clim. Chang. 4, 867–872. https://doi.org/10.1038/nclimate2350.
Estrela, T., Pérez-Martin, M.A., Vargas, E., 2012. Impacts of climate change on water resources in Spain. Hydrol. Sci. J. 57, 1154–1167. https://doi.org/10.1080/02626667.2012.702213.
European Commission, 2015. A European research and innovation: Roadmap for Climate Services. doi: 10.2777/702151.
Falloon, P., Williams, K., Andreu, J., Solera, A., Suárez-Almiñana, S., Klein, B., Meissner, D., 2019. Estimation of hazards based on improved representation of highly vulnerable water resources of strategic importance on the climate scale. Deliverable for IMPREX Project. Available at: https://imprex.eu/deliverables.
Feldman, D.L., Ingram, H.M., 2009. Making Science Useful to Decision Makers: Climate Forecasts, Water Management, and Knowledge Networks. Weather. Clim. Soc. 1, 9–21. https://doi.org/10.1175/2009WCAS1007.1.
Gupta, J., Termeer, C., Klostermann, J., Meijerink, S., Van Den Brink, M., Jong, P., Nooteboom, S., Bergsma, E., 2010. The Adaptive Capacity Wheel: a method to assess the inherent characteristics of institutions to enable the adaptive capacity of society. Environ. Sci. Policy 13, 459–471. https://doi.org/10.1016/j.envsci.2010.05.006.
Hargreaves, J.C., 2010. Skill and uncertainty in climate models. Wiley Interdiscip. Rev. Clim. Chang. 1, 556–564. https://doi.org/10.1002/wcc.58.
Harvey, B., Jones, L., Cochrane, L., Singh, R., 2019. The evolving landscape of climate services in sub-Saharan Africa : What roles have NGOs played. Clim. Change 157, 81–98.
Haynes, K., Barclay, J., Pidgeon, N., 2008. The issue of trust and its influence on risk communication during a volcanic crisis. Bull. Volcanol. 70, 605–621. https://doi.org/10.1007/s00445-007-0156-z.
Hewitt, C., Buontempo, C., Newton, P., 2013. Using climate predictions to better serve society's needs. Eos 94, 105–107. https://doi.org/10.1002/2013EO110002.
Höppner, C., Whittle, R., Bründl, M., Buchecker, M., 2012. Linking social capacities and risk communication in Europe: A gap between theory and practice? Nat Hazards 64, 1753–1778. https://doi.org/10.1007/s11069-012-0356-5.
Hovelynck, J., Dewulf, A., François, G., Tailieu, T., 2010. Interdisciplinary Knowledge Integration through group model building: recognizing dualities and triadizing the conversation. Environ. Sci. Policy 13, 582–591.
Hovmand, P., 2014. Community Based System Dynamics. Springer, New York doi: 10.1007/978-1-4614-8763-0.
Huang, S., Krysanova, V., Hattermann, F., 2015. Projections of climate change impacts on floods and droughts in Germany using an ensemble of climate change scenarios. Reg. Environ. Chang. 15, 461–473. https://doi.org/10.1007/s10113-014-0606-z.
Hunink, J., Tomás, A. De, Li, Y., Castelletti, A., Giuliani, M., Giudici, F., Suárez, S., Andreu, J., Koutroulis, A., Grillakis, M., Solera, A., 2017. Prototype design of drought Decision Support Systems. Deliverable for IMPREX Project. Available at: https://imprex.eu/deliverables.
Huntjens, P., Lebel, L., Pahl-Wostl, C., Camkin, J., Schulze, R., Kranz, N., 2012. Institutional design propositions for the governance of adaptation to climate change in the water sector. Glob. Environ. Chang. 22, 67–81. https://doi.org/10.1016/j.gloenvcha.2011.09.015.
IPCC, 2018. Strengthening and implementing the global response. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter4_Low_Res.pdf.
Jacob, D., Kotova, L., Teichmann, C., Sobolowski, S.P., Vautard, R., Donnelly, C., Koutroulis, A.G., Grillakis, M.G., Tsanis, I.K., Damm, A., Sakalli, A., Vliet, M.T.H., 2018. Climate Impacts in Europe Under + 1.5°C Global Warming. Earth's Future. 6, 264–285. https://doi.org/10.1002/eft2.286.
Jacobs, K., Lebel, L., Buizer, J., Addams, L., Matson, P., McCullough, E., Garden, P., Saliba, G., Finan, T., 2016. Linking knowledge with action in the pursuit of sustainable water-resources management. Proc. Natl. Acad. Sci. 113, 4591–4596. https://doi.org/10.1073/pnas.0813125107.
Klein, B., Meißner, D., 2019. Semi-operational forecasting system for Rhine, Danube and Elbe to support improved transport cost planning. Deliverable for IMPREX Project. Available at: https://imprex.eu/deliverables.
Klein, B., Meißner, D., 2017. Framework for the assessment of forecast quality and value in the navigation sector. Deliverable for IMPREX Project. Available at: https://imprex.eu/deliverables.
Klein, B., Meißner, D., 2016. Vulnerability of Inland Waterway Transport (IWT) and water management on hydro-meteorological extremes. Deliverable for IMPREX Project. Available at: https://imprex.eu/deliverables.
Klinke, A., Renn, O., 2012. Adaptive and integrative governance on risk and uncertainty. J. Risk Res. 15, 273–292. https://doi.org/10.1080/13669877.2011.636838.
Kovalevsky, D., Kriegsmann, A., Williams, D.S., Máñez Costa, M., 2019. Integrated risk maps. Deliverable for IMPREX Project. Available at: https://imprex.eu/deliverables.
Kovalevsky, D., Mañez Costa, M., 2019. Modelling the demand for weather index-based insurance products in regions prone to agricultural droughts, in: 59th ERSA Congress "Cities, Regions and Digital Transformations: Opportunities, Risks and Challenges." Lyon, France.
Kovalevsky, D., Máñez Costa, M., 2019. Dynamics of water-constrained economies affected by climate change: nonlinear and stochastic effects. In: Volchenkov, E. (Ed.), The Many Facets of Complexity Science: In Memory of Valentin Afraimovich (1945-2018). Higher Education Press/Springer.
Kovalevsky, D., Mañez Costa, M., Williams, D.S., Klein, B., 2018. System dynamics modelling of inland waterway transportation of cargos for energy sector supported by navigation-related probabilistic forecasts, in: The 9th International Congress on Environmental Modelling and Software. Fort Collins, USA.
Kovalevsky, D., Williams, D.S., Máñez Costa, M., 2019b. Impact on adaptive management of transport sector. Deliverable for IMPREX Project. Available at: https://imprex.eu/deliverables.
Krueger, T., Page, T., Hubacek, K., Smith, L., Hiscock, K., 2012. Environmental Modelling & Software: The role of expert opinion in environmental modelling. Environ. Model. Softw. 36, 4–18. https://doi.org/10.1016/j.envsoft.2012.01.011.
Lanen, H.A.J.V., Laaha, G., Kingston, D.G., Gauster, T., Ionita, M., Vidal, J., Vlnas, R., Tallaksen, L.M., Stahl, K., Hannaford, J., Delus, C., Fendekova, M., Medeiro, L., Prudhomme, C., Romanowicz, R., Rets, E., Gailliez, S., Wong, W.K., Adler, M., Blauhut, V., Caillouet, L., Chelcea, S., Frolova, N., Gudmundsson, L., Hanel, M.,

Haslinger, K., Kireeva, M., Osuch, M., Sauquet, E., Stagge, J.H., Van Loon, A., 2016. Hydrology needed to manage droughts : the 2015 European case. Hydrol. Process. 30, 3097–3104. https://doi.org/10.1002/hyp.10838.

Larosa, F., Mysiak, J., 2019. Mapping the landscape of climate services. Environ. Res. Lett. 14. https://doi.org/10.1088/1748-9326/ab304d.

Lehner, B., Oll, P.D., Henrichs, T., Kaspar, F., 2006. Estimating the impact of global change on flood and drought risks in Europe: a continental integrated analysis. Clim. Change 75, 273–299. https://doi.org/10.1007/s10584-006-6338-4.

Lemos, M.C., Kirchhoff, C.J., Ramprasad, V., 2012. Narrowing the Climate Information Usability Gap. Nature Climate Change 2, 789–794. https://doi.org/10.1038/nclimate1614.

Lemos, M.C., Rood, R.B., 2010. Climate projections and their impact on policy and practice. Wiley Interdiscip. Rev. Clim. Chang. 1, 670–682. https://doi.org/10.1002/wcc.71.

Linde, A.H., Aerts, J.C.J.H., Bakker, A.M.R., Kwadijk, J.C.J., 2010. Simulating low probability peak discharges for the Rhine basin using resampled climate modeling data. Water Resour. Res. 46, 1–19. https://doi.org/10.1029/2009WR007707.

Lorenz, S., Dessai, S., Forster, P.M., Paavola, J., 2017. Adaptation planning and the use of climate change projections in local government in England and Germany. Reg. Environ. Chang. 17, 425–435. https://doi.org/10.1007/s10113-016-1030-3.

Mackenzie, B., Celliers, L., de Freitas Assad, L.P., Heymans, J.J., Rome, N., Thomas, J.O., Anderson, C., Behrens, J., Calverley, M., Desai, K., DiGiacomo, P., Djavidnia, S., dos Santos, F., Eparkhina, D., Ferrari, J., Hanley, C., Houtman, B., Jeans, G., Landau, L., Larkin, K., Legler, D., Le Traon, P.Y., Lindstrom, E.J., Loosley, D., Nolan, G., Petihakis, G., Pellegrini, J., Roberts, Z., Siddorn, J., Smail, E., Sousa-Pinto, I., Terrill, E., 2019. The role of stakeholders and actors in creating societal value from coastal and ocean observations. Front. Mar. Sci. 6, 137. https://doi.org/10.3389/FMARS.2019.00137.

Máñez Costa, M., Carmona, M., Gerkensmeier, B., 2014. Assessing governance performance. Climate Service Centre Germany (GERICS). Available at: https://www.climate-service-center.de/imperia/md/content/csc/report_20.pdf.

Máñez Costa, M., Kovalevsky, D., 2018. Participatory system dynamics modelling for adaptation to extreme hydrological events under conditions of climate change, in: The 36th International Conference of the System Dynamics Society. Reykjavik, Iceland.

Máñez Costa, M., Osorio, J., Kovalevsky, D., 2017. Generic Integrative Modeling Approach Guideline. Deliverable for IMPREX Project. Available at: https://imprex.eu/deliverables.

Marcos-Garcia, P., Lopez-Nicolas, A., Pulido-Velazquez, M., 2017. Combined use of relative drought indices to analyze climate change impact on meteorological and hydrological droughts in a Mediterranean basin. J. Hydrol. 554, 292–305. https://doi.org/10.1016/j.jhydrol.2017.09.028.

Marcos-Garcia, P., Pulido-Velazquez, M., 2017. Cambio climático y planificación hidrológica: ¿es adecuado asumir un porcentaje único de reducción de aportaciones para toda la demarcación? Ing. del agua 21, 35. https://doi.org/10.4995/ia.2017.6361.

Moel, H.D., Aerts, J.C., 2011. Effect of uncertainty in land use, damage models and inundation depth on flood damage estimates. Nat. Hazards 58, 407–425. https://doi.org/10.1007/s11069-010-9675-6.

Munang, R., Rivington, M., Takle, E.S., Mackey, B., Thiaw, I., Liu, J., 2010. Climate information and capacity needs for ecosystem management under a changing climate. Procedia Environ. Sci. 1, 206–227. https://doi.org/10.1016/j.proenv.2010.09.014.

Naustdalslid, J., 2011. Climate change – the challenge of translating scientific knowledge into action. Int. J. Sustain. Dev. World Ecol. 18, 243–252. https://doi.org/10.1080/13504509.2011.572303.

Nilson, E., Krahe, P., Klein, B., Lingemann, I., Horsten, T., Carambia, M., Larina, M., Maurer, T., 2014. Auswirkungen des Klimawandels auf das Abflussgeschehen und die Binnenschiffahrt in Deutschland. KLIWAS.

Nilson, E., Krahe, P., Klein, B., Lingemann, I., Horsten, T., Carambia, M., Larina, M., Maurer, T., 2014. Auswirkungen des Klimawandels auf das Abflussgeschehen und die Binnenschiffahrt in Deutschland. KLIWAS. Available at: https://www.bafg.de/KLIWAS/DE/03_Vorhaben/04_vh4/01_401/DOI10.5675-Kliwas_43-2014_4.01.html.

Nkiaka, E., Taylor, A., Dougill, A.J., Antwi-Agyei, P., Fournier, N., Bosire, E.N., Konte, O., Lawal, K.A., Mutai, B., Mwangi, E., Ticehurst, H., Toure, A., Warnaars, T., 2019. Identifying user needs for weather and climate services to enhance resilience to climate shocks in sub-Saharan Africa. Environ. Res. Lett. 14. https://doi.org/10.1088/1748-9326/ab4dfe.

Nost, E., 2019. Climate services for whom? The political economics of contextualizing climate data in Louisiana's coastal Master Plan. Clim. Change 157, 27–42. https://doi.org/10.1007/s10584-019-02383-z.

NYT, 2018. The Rhine, a lifeline of Germany, is crippled by drought. https://www.nytimes.com/2018/11/04/world/europe/rhine-drought-water-level.html.

Ojwang, L., Rosendo, S., Mwangi, M., Celliers, L., Obura, D., Muiti, A., 2017. Assessment of Coastal Governance for Climate Change Adaptation in Kenya. Earth's Futur. 5, 1119–1132. https://doi.org/10.1002/eft2.261.

Olazabal, M., Ruiz de Gopegui, M., Tompkins, E.L., Venner, K., Smith, R., 2019. A cross-scale worldwide analysis of coastal adaptation planning. Environ. Res. Lett. 14, 124056. https://doi.org/10.1088/1748-9326/ab5532.

Pahl-Wostl, C., 2007. Transitions towards adaptive management of water facing climate and global change. Water Resour. Manag. 21, 49–62. https://doi.org/10.1007/s11269-006-9040-4.

Pahl-Wostl, C., Holtz, G., Kastens, B., Knieper, C., 2010. Analyzing complex water governance regimes: The Management and Transition Framework. Environ. Sci. Policy 13, 571–581. https://doi.org/10.1016/j.envsci.2010.08.006.

Palutikof, J.P., Street, R.B., Gardiner, E.P., 2019. Decision support platforms for climate change adaptation : an overview and introduction. Clim. Change 153, 459–476.

Pulido-Velazquez, M., Peña-Haro, S., García-Prats, A., Mocholi-Almuveder, A.F., Henriquez-Dole, L., Macián-Sorribes, H., Lopez-Nicolas, A., 2015. Integrated assessment of the impact of climate and land use changes on groundwater quantity and quality in the Mancha Oriental system (Spain). Hydrol. Earth Syst. Sci. 1677–1693. https://doi.org/10.5194/hess-19-1677-2015.

Rubio-Martin, A., Pulido-Velazquez, M., Macian-Sorribes, H., Garcia-Prats, A., 2020. System dynamics modelling for supporting drought-oriented management of the Jucar River system, Spain. Water 12 (5), 1407. https://doi.org/10.3390/w12051407.

Schleussner, C.F., Lissner, T.K., Fischer, E.M., Wohland, J., Perrette, M., Golly, A., Rogelj, J., Childers, K., Schewe, J., Frieler, K., Mengel, M., Hare, W., Schaeffer, M., 2016. Differential climate impacts for policy-relevant limits to global warming: The case of 1.5°c and 2°c. Earth Syst. Dyn. 7, 327–351. https://doi.org/10.5194/esd-7-327-2016.

Scoones, I., 1998. Sustainable rural livelihoods: a framework for analysis, IDS Working Paper. Doi: 10.1057/palgrave.development.1110037.

Sedlacko, M., Martinuzzi, A., Røpke, I., Videira, N., Antunes, P., 2014. Participatory systems mapping for sustainable consumption: Discussion of a method promoting systemic insights. Ecol. Econ. 106, 33–43. https://doi.org/10.1016/j.ecolecon.2014.07.002.

Shabalova, M.V., Deursen, W.P.A.V., Buishand, T.A., 2003. Assessing future discharge of the river Rhine using regional climate model integrations and a hydrological model. Clim. Res. 23, 233–246.

Shakya, C., Cooke, K., Gupta, N., Bull, Z., 2018. Building institutional capacity for enhancing resilience to climate change: an operational framework and insights from practice. Available at: https://reliefweb.int/sites/reliefweb.int/files/resources/GIP01916-OPM-Strengthening-institutions-Proof4-web.pdf.

Siders, A.R., 2019. Adaptive capacity to climate change: A synthesis of concepts, methods, and findings in a fragmented field. Wiley Interdiscip. Rev. Clim. Chang. 10. https://doi.org/10.1002/wcc.573.

Spiegel, 2018. Rhein-Pegel sinkt auf 33 Zentimenter. http://www.spiegel.de/video/duerre-rhein-pegel-sinkt-auf-33-zentimeter-video-99021722.html.

Street, R.B., 2016. Towards a leading role on climate services in Europe : A research and innovation roadmap. Clim. Serv. 1, 2–5. https://doi.org/10.1016/j.cliser.2015.12.001.

United Nations Framework Convention on Climate Change, 2017. World energy system not on track to meet Paris climate goals. https://unfccc.int/news/world-energy-system-not-on-track-to-meet-paris-agreement-goals.

United Nations Institute for Training and Research, 2008. Capacity Development for Adaptation to Climate Change & Greenhouse Gas Mitigation. Available at: https://unitar.org/ccp/sites/unitar.org.ccp/files/c3d_brochure.pdf.

van den Hurk, B., Bouwer, L.M., Buontempo, C., Döscher, R., Ercin, E., Hananel, C., Hunink, J.E., Kjellström, E., Klein, B., Máñez Costa, M., Pappenberger, F., Pouget, L., Ramos, M.H., Ward, P.J., Weerts, A.H., Wijngaard, J.B., 2016. Improving predictions and management of hydrological extremes through climate services. Clim. Serv. 1, 6–11. https://doi.org/10.1016/j.cliser.2016.01.001.

van den Hurk, B., Hewitt, C., Jacob, D., Bessembinder, J., Doblas-reyes, F., Döscher, R., 2018. The match between climate services demands and Earth System Models supplies. Clim. Serv. 12, 59–63. https://doi.org/10.1016/j.cliser.2018.11.002.

van Kerkhoff, L., Lebel, L., 2006. Linking Knowledge and Action for Sustainable Development. Annu. Rev. Environ. Resour. 31, 445–477. https://doi.org/10.1146/annurev.energy.31.102405.170850.

Vaughan, C., Buja, L., Kruczkiewicz, A., Goddard, L., 2016. Identifying research priorities to advance climate services. Clim. Serv. 4, 65–74. https://doi.org/10.1016/j.cliser.2016.11.004.

Vaughan, C., Dessai, S., Hewitt, C., 2018. Surveying climate services: What can we learn from a bird's-eye view? Weather. Clim. Soc. 10, 373–395. https://doi.org/10.1175/WCAS-D-17-0030.1.

Vennix, J., 1996. Group Model Building: Facilitating Team Learning Using System Dynamics. John Wiley & Sons Ltd., Chichester.

Videira, N., Antunes, P., Santos, R., 2009. Scoping river basin management issues with participatory modelling: The Baixo Guadiana experience. Ecol. Econ. 68, 965–978. https://doi.org/10.1016/j.ecolecon.2008.11.008.

Vincent, K., Daly, M., Scannell, C., Leathes, B., 2018. What can climate services learn from theory and practice of co-production? Clim. Serv. 12, 48–58. https://doi.org/10.1016/j.cliser.2018.11.001.

Vincent, K., Dougill, A.J., Dixon, J.L., Stringer, L.C., Cull, T., 2017. Identifying climate services needs for national planning: insights from Malawi. Clim. Policy 17, 189–202. https://doi.org/10.1080/14693062.2015.1075374.

Vogel, C., Scott, D., Culwick, C.E., Sutherland, C., 2016. Environmental problem-solving in South Africa: harnessing creative imaginaries to address 'wicked' challenges and opportunities. South African Geogr. J. 98, 515–530. https://doi.org/10.1080/03736245.2016.1217256.

Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. Environ. Model. Softw. 25, 1268–1281. https://doi.org/10.1016/j.envsoft.2010.03.007.

Walker, Warren E, Marchau, Vincent A W J, Kwakkel, J.H., 2019. Dynamic Adaptive Planning, in: Marchau, V.A.W.J., Walker, W.E., Bloemen, P.-J.T.M., Popper, S.W. (Eds.), Decision Making under Deep Uncertainty. Springer International Publishing, pp. 53–69. Doi: 10.1007/978-3-030-05252-2.

Webber, S., 2019. Putting climate services in contexts: advancing multi-disciplinary understandings: introduction to the special issue. Clim. Change 157, 1–8. https://doi.org/10.1007/s10584-019-02600-9.

Weichselgartner, J., Kasperson, R., 2010. Barriers in the science-policy-practice interface: Toward a knowledge-action-system in global environmental change research. Glob. Environ. Chang. 20, 266–277. https://doi.org/10.1016/j.gloenvcha.2009.11.006.

Williams, D.S., Mañez Costa, M., Celliers, L., Sutherland, C., 2018. Informal Settlements and Flooding: Identifying Strengths and Weaknesses in Local Governance for Water Management. Water 10, 871–892. https://doi.org/10.3390/w10070871.

Williams, D.S., Máñez Costa, M., Sutherland, C., Celliers, L., Scheffran, J., 2019. Vulnerability of informal settlements in the context of rapid urbanization and climate change. Environ. Urban. 31, 157–176. https://doi.org/10.1177/0956247818819694.

Williams, D.S., Celliers, L., Unverzagt, K., Videira, N., Máñez Costa, M., Giordano, R., 2020a. A method for enhancing capacity of local governance for climate change adaptation. Earth's Future 8, 1–16. https://doi.org/10.1029/2020EF001506.

Williams, D.S., Rosendo, S., Sadasing, O., Celliers, L., 2020b. Identifying local governance capacity needs for implementing climate change adaptation in Mauritius. Clim. Policy. Doi: 10.1080/14693062.2020.1745743.

WMO, 2019a. 2019 State of Climate Services: Agriculture and Food Security. https://library.wmo.int/doc_num.php?explnum_id=10089.

WMO, 2019b. The future of climate services. https://public.wmo.int/en/resources/bulletin/future-of-climate-services.

Zeit, 2018. Auf dem Trockenen. https://www.zeit.de/2018/47/rohstoffpreise-rhein-wasser.