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An integrated climate and water resource climate service prototype for long term water allocation in the Upper Yellow River region of China

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ABSTRACT

Water Resourcing in China has historically been a complex issue requiring the ability to deal with regular floods, droughts and diverse water needs. Climate change represents another challenge to this sector, albeit one that is not traditionally considered by water managers. In this sector in China water management is predominantly based on historic, seasonal and annual forecast data while multi-annual and (multi-)decadal data are seldom used. In this paper, we present the co-development of a climate service prototype designed to provide water managers with insights into the impacts of climate change on the Upper Yellow River region for the next century. The paper is an outcome from our project that encouraged water resource planners and water resource managers to utilise long-term climate information to understand the uncertainties and the challenges our changing climate is likely to have in the region. Using an interdisciplinary team and adopting a user-centred, co-production approach, a prototype web-based data visualisation tool was developed. The development of the prototype was based on a design specification constructed from the findings of detailed interviews that allowed it to be developed and tested under SARS-CoV-2 pandemic restrictions that prevented the typical development process to be undertaken. The developed prototype presents climate information and communicates uncertainties regarding climate change in the remainder of the century through data sets that are typically used by the water sector in China in a simple, easy to understand style. Models that estimate river levels under different extraction scenarios and results about estimated river level and flow, and flood risk are also presented. The prototype was shown to be successful, as key messages relating to the impact of climate change and the challenges for water resource management could be effectively communicated through the tool interface.

Practical implications: Understanding the impacts of climate change on water resourcing is complicated and multifaceted. There is a need for better data about what water there is and how it is moving around between and within catchments. Estimates of past, present and future climate variables along with historical measurements of river flow can be used to help visualise some of the uncertainties and changes that may happen in the next 50 years. In addition, there is a need to understand changing water demands and water resource management practices. Current water resource management practices are based on historical conditions and assumptions that are less likely to hold true in a more variable and warmer climate. Communicating how future changes will impact future water resourcing is critical to water resources in a changing climate (Belcher et al. 2018).

This research outlines the construction of a tool to visualise the impacts of climate change on water availability in part of China that is typically water scarce, using models developed using the Soil Water Assessment Toolkit (SWAT). A model of the Upper Yellow River (UYR) was developed to demonstrate the impact of climate change on river levels in the catchment based on climate variables. The rainfall-runoff model was based on climate predictions from the CMIP5 assessment HadGEM3-GC3.05 climate model and incorporated information about

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water resource allocations for different administrative regions of the catchment The general climate trend for the region is that it is expected to become significantly warmer. The total amount of precipitation is likely to be about the same, and yet it is expected that overall, the catchment will become significantly drier over time as winter shortens and summer lengthens. The outputs from the model reflect the changes in climate variables. The uncertainties were communicated via a Web based tool. Water resource managers in China helped to coproduce the tool by participating in workshops and providing feedback on prototypes. The workshops helped scientists and water resource managers to communicate about climate change impacts on water resources and water resource management.

Introduction

Managing water resources is a critical challenge of the 21st century due to increasing and competitive demands – growing populations, urbanisation, more affluent lifestyles, and intensification of agriculture and industrial uses – coupled with decreasing supply in many areas (Srinivasan et al., 2012; WWAP (United Nations World Water Assessment Programme) (2015), UNESCO 2019). The reasons behind dwindling supplies are complex, ranging from pollution to increasing climate variability and change. The expected climate change in the next 100 years – a general picture of global warming with localised and large-scale increase in the frequency and severity of extreme events – is likely to exacerbate water scarcity and water quality and resource management issues because of droughts and floods (IPCC, 2014; Kirchhoff, 2013; Zhang et al., 2019, Wang et al., 2021). China experiences a variable climate and uneven distribution of water resources with the North and West receiving less precipitation and the South and East being generally wetter. China is a land of great rivers that mostly flow from the mountainous regions of the Tibetan Plateau and Himalayas. More southern and eastern regions are less prone to issues of water scarcity as precipitation is generally higher and more regular. Whilst there is a general migration of people to these already more populated regions, there is both a considerable population to support in the drier areas and a political desire to make these regions populous and productive. Water scarcity, flood risk and a growing reliance on hydroelectric power are major challenges for water resource management (Zhou et al., 2009; Wang et al., 2013; Wu et al., 2014; Li et al., 2016; Wang et al., 2017; Xi et al., 2018; Wang et al., 2021). In order to ensure that the economic outputs of the Yellow River region remain strong and the long-term safety and wellbeing of the population can be preserved, a large-scale transfer of water from the South to the North is happening (Kattel et al., 2019).

Water resource management is an active process that operates on a range of temporal and spatial scales, with a range of strategic planning to support those activities (Shaw et al., 2011; United Nations Water, 2018). For Chinese water managers, this includes: daily to weekly activities – including monitoring river levels, and issuing flood warnings; monthly and seasonal activities – such as planning infrastructure maintenance and upgrade and reviewing water allocation plans; and, long term activities such as planning for new infrastructure developments (Goulding et al., 2017; Wang et al., 2020). Climate information is critical to the successful implementation of resourcing strategies and plans (Hewitt et al., 2012; Kirchhoff, 2013; WMO, 2014). In China, climate information for daily to seasonal forecasts is predominantly obtained through the China Meteorological Administration (CMA) (Goulding et al., 2017; Khosravi et al., 2021), which is then distributed to the water sector, through the Ministry of Water Resources (MWR). The MWR comprises multiple institutes at the basin level and provincial level, including the River Basin Commissions, which are a significant contributor to the water allocation planning process (Opitz-Stapleton et al., 2016).

A critical issue has been the dominant use of historical data by Chinese water managers to inform both short term decisions (daily to weekly timescale) and long term decisions (seasonal, to annual timescales) and processes, such as dam construction (Khosravi et al., 2021). Historical data is often preferred because it provides a reference point and forms an important point of similarity in the interactions between climate information providers and water managers (Goulding et al., 2017). This relationship, and the delivery of climate information in a series of meetings and informal settings is an important part in providing relative descriptions to forecasts (Taylor et al., 2021), which allow water managers to relate to previous experiences in order to provide daily to seasonal forecasts. As such, historical data is often used in preference to data from climate projections, which are simulations of the possible future climate, based on assumptions about future concentrations or emissions of future greenhouse gases. This is further enforced through the length of time that most critical water resource management decisions are made or considered such as 6–12 month timeframes (Opitz-Stapleton et al., 2016). Furthermore, climate projection data are often obtained through other climate information providers, where the relationship between resource manager and data provider is not as well developed and where needs and requirements are not as well understood, further reducing uptake of this information (Khosravi et al., 2021; Taylor et al., 2021). A lack of confidence in projection datasets due to associated uncertainty and a lack of legal or technical motives to use this data further reduce the uptake of climate projection data and reinforce the use of 6–12 month timeframes of typical resource management approaches (Feldman and Ingram, 2009).

Climate services, defined as the provision of climate data to assist decision making, have the ability to bridge the gap between climate information and decision making (Hewitt et al., 2012). In China, the Climate Science for Services Partnership (CSSP) has helped to establish the connection between water managers, their needs and the ability of current climate science to bridge these gaps (Belcher et al., 2018). An example of the ability of this programme to deliver high quality climate services has been established through the creation of a seasonal forecast service for the Yangtze River basin (Goulding et al., 2019).

The co-development approach to the development of climate service and environmental visualisation tools has been shown to be an effective method for the long-term adoption of software and prototypes (Lorenz et al., 2015; Grainger et al., 2016; Hewitt et al., 2020). In this process, a collaboration is made with end users throughout the prototype development phase. This is to both refine the end product and to ensure usability and ultimately product adoption, and is an integral part of creating the service. The success of this approach has been noted in the development of other climate services, such as Project Ukko, part of the EUPORIAS design study (Buontempo et al., 2018, Christel et al., 2018).

In this research, we apply an interdisciplinary, co-developed approach to create a climate service tool – the **I**ntegrated **C**limate-**W**ater **R**esource **M**anagement tool (iC-WRM) as part of the CSSP programme. Using a user-led design approach, the prototype was constructed in collaboration with climate scientists and from the findings of research that established Chinese water managers' needs and requirements, as reported by Khosravi et al. (2021). The aim of this study is to apply the results from the Soil and Water Assessment Tool (SWAT) hydrological model of the Upper Yellow River, into a climate service prototype, and to assess its effectiveness in promoting to water resource managers the issues related to climate change. As shown by Khosravi et al. (2021), long term planning in the sector is limited to 12-month time frames, and the application of climate change datasets or knowledge is not typically used. By applying proven tools, models and techniques to create an online climate service, we aim to highlight to water resource managers the potential issues that climate change can cause, and to influence long term planning processes. The assessment of this study focuses on how effective the application of these established processes are in creating this change, and how far the services created can help support decision makers with regards to issues surrounding water management and climate change.

As a result of the restrictions of international and domestic travel caused by the SARS-CoV-2 pandemic, the traditional tools used in co-development, such as in-person meetings and group feedback sessions, were modified to include online workshops and evaluation forms to provide a number of approaches for users to participate in the process (New et al., 2020). Using a wide, interdisciplinary and multidisciplinary approach that uses expertise from climate science, hydrology, data visualisation and social sciences (as outlined in Khosravi et al., 2021) the co-development of the climate service utilises a wide range of knowledge and experience to facilitate the development of the tool within the current scientific capability. Using the Upper Yellow River region as a case study, the climate service prototype translates climate information into a readily useable format to support long-term water resource decisions through the use of 'what if?' scenario testing. This approach engages the major stakeholders – the water managers and the intermediaries – along familiar enquires relative to their day-to-day operations and interaction with forecast and projection data.

Study area

The focus of the iC-WRM model was the Upper Yellow River region in China. This catchment is used as it is a climatically sensitive region of China with high occurrences of drought, flooding and increasing water resource pressure (Wang et al., 2008). As a demonstration of potential trends in the climate, in the period from 1970 to 2010, there has been a noted drying trend in the catchment with a reduction in discharge levels along the Yellow River as a result of increasing water extraction and changing precipitation patterns (Feng and Zhu, 2022). The majority of

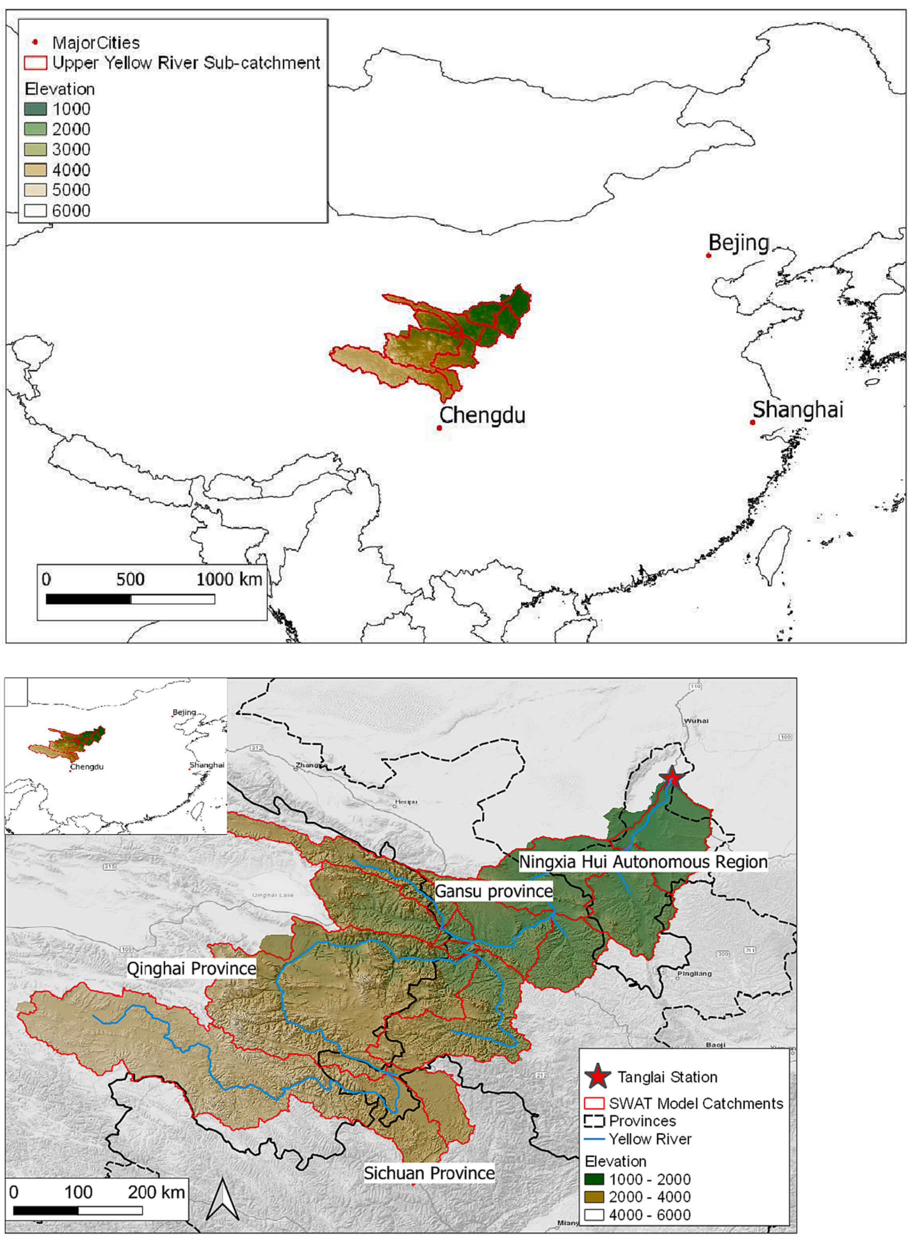

Fig. 1. Location of the Upper Yellow River test case catchment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

water allocation plans developed in China are predominately for this region, to support agriculture, consumption and industry (Optiz-Stapleton et al., 2016). The South North Water Transfer Project (SNWTP) has been created to alleviate these issues. Further, problems in the catchment in terms of runoff have been identified with a predicted decrease of 9 % identified by 2050 as a result of climate change (Wang et al., 2017). The area of interest is displayed in Fig. 1.

Climate service co-development methodology

In order to create a climate service prototype that will provide users with valuable insight, a multi-stage development approach involving user interaction was followed, based on the procedures set out by Grainger et al., (2018). First, a broad climate service specification was developed from the interviews with Chinese water managers that had taken place previously (Khosravi et al., 2021). An initial phase of interaction with interested users was then undertaken through one-to-one discussions, an approach that allowed for a degree of openness amongst participants, to help refine the key elements of the prototype (Golding et al., 2017, 2019). The prototype was developed on the simulation outputs of a hydrological model of the area of interest, with visualisation of the data established based on the user's needs, and on similar data representations typically used by the water resource managers. The approach of selecting key outputs from climate models based on user's knowledge provides a mechanism for adoption of climate services (Vincent et al., 2020). A workshop was then conducted which introduced participants to the prototype tool, the processes and computation behind the tool, and allowed feedback to be given. From this, an online survey was then prepared to allow more detailed feedback to be given (cf. Bruno Soares and Dessai, 2015). As part of this feedback, the participants were also questioned on the level of awareness of climate change that the prototype had provided them. This would help to establish if the prototype, and the data visualisation techniques used within, had helped to overcome some of the issues in using climate change data and considering projection data which had been identified from the interviews reported by Khosravi et al. (2021). The feedback from the user's evaluation workshop through an online survey questionnaire was then used to refine both the prototype and the design specification for the climate service, introducing more features and clarifying aspects of the prototype. From this, and with further interviews and feedback (an iterative process), an improved version of the prototype was then developed which forms the foundation for a full working climate service. This process is demonstrated in Fig. 2.

The co-development and evaluation steps were considered with respect to ensuring a high degree of participation, interest and usefulness to prospective users (i.e. water managers and the intermediaries). This approach was designed to reduce the possibility of 'respondent fatigue' – where overexposure of participants to the development process can increase tensions in the development of climate services (Mahon et al., 2019). The approach adopted was agile which allowed a greater deal of flexibility as a result of the restrictions on travel and interactions caused by the SARS-CoV-2 pandemic.

Translating the user needs – Development of the specification for the climate service for the water sector in China

The main source of data to create a specification for the climate service prototype tool is the research outlined by Khosravi et al. (2021). This research had established the water manager's needs and requirements, and more significantly established the reasons behind the lack of adoption from this sector for long term climate projection data. It also determined how climate information is converted and used to perform the essential tasks of the water sector in the context of China. This information, in combination with ad-hoc discussions with sector workers, helped establish the key points to be addressed by the climate service.

Primarily, the climate information required by the water sector from climate information providers or climate services is data for precipitation, temperature, solar radiation, relative humidity and near surface wind values which is provided at daily, weekly, seasonal and annual timeframes. This climate information is used as the input to institution specific hydrological and rainfall-runoff models to predict river water levels, volumes and surface runoff. This converted data is the main component for determining the water allocation plan; the legislative mechanism by which each province can extract water, whilst ensuring suitable levels of water remain in the main Yellow River channel (Wang et al., 2008; Opitz-Stapleton et al., 2016). The seasonal water allocation plan is an essential part of resource management, with a large amount of activity of the managers based on properly assessing potential levels of water as well as monitoring current levels. Flood and drought control are also important considerations in this process, and as part of the remit of the water managers; hence, understanding and planning for extremes of

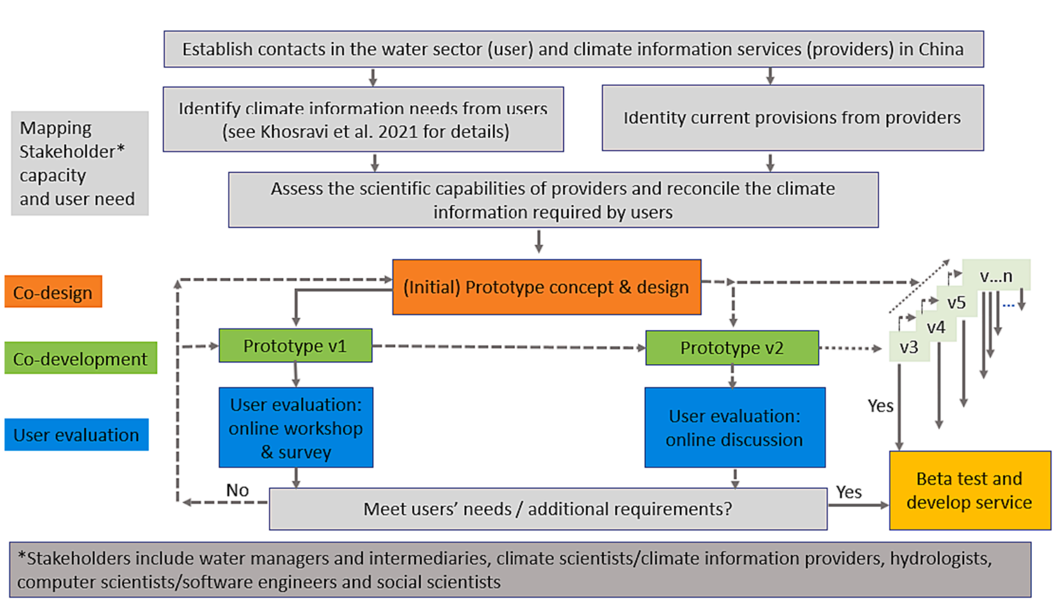

Fig. 2. Schematic diagram of the co-design approach for the development of the iC-WRM climate service prototype.

river levels is therefore a significant component of the management process. Specific examples of this include understanding low flow scenarios (flows that occur 95 % of the time), which will determine if any compensation flows are released for rivers from reservoirs, and high flows (5 %) which will determine if any additional capacity is required in the river to prevent flooding. Understanding how these values changes will be important in understanding how the operations of water resourcing might change under different climate predictions.

From Khosravi et al. (2021) and Kreibich et al. (2022), it was apparent that the majority of water decision making, including dam construction and flood defence infrastructure, is based on historical data, which is enforced in the legislation for the water sector. Problems with a long-term timescale are therefore evaluated based on current conditions and historic information, rather than climate projection information. A clear specification for the prototype was to frame the climate information in these terms, presenting future river levels and flow, and demonstrating the impact of climate change on these values. It is noted that whilst water managers did not adopt climate projection information directly, this data was used by hydrological researchers a majority of whom are water managers' intermediaries that work in Government institutes, such as the Research Centre for Climate Change. The translation of climate information and the use of climate projection were therefore specific to institutions, and rather than repeat the functions that existing institutes use, but do not widely share, the tool was aimed more at providing key insights to support decision making, rather than directly establish new datasets. The same principle helped to establish the presentation of the climate service prototype, with visualisations of data and projections being favoured over further numeric datasets (i.e. daily rainfall amount) or forecast and projection summaries, which is a task currently undertaken by the CMA as part of its climate service deliverables.

The importance of the provincial water allocation plan to water resource managers also raised another key specification point; understanding how water levels may evolve at the regional and provincial scale. The outputs should provide some level of detail of changes at this scale. Further, the ability to control the levels of water allocation should also be controlled by the user, with options to select how varying extraction rates, which are an issue in current conditions, may impact river levels. These two aspects would provide insight into understanding if particular parts of the basins or provinces may suffer as a result of future climate patterns. Furthermore, this would also allow the climate service to explore 'what if?' scenarios; options which would allow the user to explore how current water extraction values might impact river levels in changing climate.

A key finding of Khosravi et al.'s (2021) work was that low uptake of climate projection data was related to lack of confidence in the data as a result of the associated uncertainties, as well as the level of detail in the data (specifically too little detail, as the large scale Global Climate Models, GCM, require downscaling of the data to make it relevant at the water manager operational level), low accessibility, and an absence of legal obligation to consider projection data. Earlier research focussing on the characterisation and communication of uncertainty in climate information provision in China, indicated that there is currently limited interaction between providers and recipients of multi-decadal climate projections, meaning providers may speculate on how uncertainty could be communicated, but not have direct feedback from users (Taylor et al., 2021). The presentation of uncertainty was therefore considered an important component of this climate service prototype. A seven-point specification for the climate service prototype was established, which is presented in Table 1.

Table 1
Climate service prototype design specification, established through interviews and discussions with water managers and sector workers.

Specification number	Requirement	Background
1	The climate service has to present river level and flow information	River level data is the main information presented to water managers, rather than climate variables such as precipitation.
2	The prototype should present the impact of climate change on multi-annual and multi-decadal river levels and flow to assist in long-term planning	Providing data and information on multi-annual and multi-decadal time frames helps fill the current strategy and data gap.
3	The climate service will be predominantly visual and will include figures and displays currently used and favoured by water resource managers.	Rather than provide numeric or text-based information, the main element of the climate service will be data visualisation, using graphics similar to the ones used by water managers in their reports and analysis.
4	Water allocation planning data and typical outputs used by water resource managers should be used to improve understanding of climate change, with respect to current conditions.	The climate service should provide a component of water allocation within it to allow an understanding of current water abstraction and climate change to be made.
5	Scenarios and climate data should be options that can be explored by the user	Each water allocation and climate scenario variable for the climate service can be adjusted by the user to answer 'what if?' questions.
6	Options to explore regional information on the impact of climate change	As the impact of climate change will vary across wide geographical area
7	Uncertainty of the climate data should also be included and displayed	In order to address the issues of uncertainty in climate information, an option for displaying or exploring the data uncertainty should be available.

Development of the prototype

Using the climate service specification, a prototype was developed which provides an initial means to evaluate and discuss both the layout of the tool, the information presented, the implications of the results, and to ultimately evaluate if the tool provided a change in attitudes towards climate data. This development was split into 2 key phases – the development of the data for the climate service, and the development of the climate service 'front end' – the data visualisation tool which would be the main component for end users to deal with.

The interdisciplinary nature of the project team provided the means to create, evaluate and visualise the data. A wide range of tasks were required which broadly include developing a rainfall-runoff model to convert rainfall to river flow data, selecting climate data scenarios, determining water allocation values and displaying and presenting data in a clear and intuitive manner.

Development of the climate service data

A hydrological model of the Upper Yellow River catchment was created using the physically based hydrological model the Soil and Water Assessment Tool (SWAT), which uses a semi-distributed model setup (i,e, uses sub-catchments as the basis of the numeric model) to determine runoff produced from a rainfall input, based on physical properties of the underlying land useA full description of the model can be found at https://swat.tamu.edu/This model has been successfully applied in this region before (Wu et al., 2019), and has the advantage that water allocation options can be used in the model, incorporating one of the design specifications. Water allocation can be divided down into individual hydrological response units (HRU) which represent the discrete sub-components of the model at which overland flow and river flow are calculated. The ability to include water allocation as a component within the model is an important consideration in the selection of a hydrological model where this process is a key component of the output. The SWAT model has been used to investigate water resourcing in the Han River basin (Tian et al., 2021), and in the absence of the in-house models that are used by water resource managers, this model provides a useful and well-known comparison point for the climate service prototype and output.

The model requires terrain data, climate data, including precipitation, maximum and minimum daily temperatures, relative humidity values and near surface wind speed. In order to calibrate the model, daily river flow data is also required. The 90 m Multi-Error-Removed Improved-Terrain Digital Elevation Model (MERIT DEM) data was used as the terrain data input (Yamazaki et al., 2019). This information is processed by SWAT to establish sub basins and drainage pathways that form the basis of the hydrological calculations. The model catchment boundary was established using the location of the Tanglai river gauge which forms the downstream boundary of the model domain (Fig. 3). Climate data, used as the input boundary conditions to the simulations, were taken from the HadGEM3-GC3.05 perturbed parameter ensemble (PPE) (Yamazaki et al., 2021, Rostron et al., 2020). The PPE members provide meteorological data at 5/9 degree × 5/6 degree resolution, which is around 60 km × 75 km in mainland China, and have been used in similar applied studies in understanding the impact of climate change on shifting climate zones (Li et al., 2021). In the absence of observed rainfall gauge data, the climate data is applied as a boundary condition by selecting the 13 PPE model cells which are closest to the 13 sub-basin centroids, which follows the SWAT internal method for allocating weather gauge locations. The lack of available gauge data prevents a more robust downscaling approach from being applied.

Calibration of the model was based on comparing model discharge output against the daily discharge data for the Tanglai station obtained from the Global Runoff Data, which has data ranging from 1978 to 1997. Two data time slice periods were taken for calibration (1980 – 1985) and validation (1990 – 1995). Climate Variable Input was taken from the historical period of the PPE4 member, which is forced with CMIP5 data, PPE4 was selected for the calibration of the SWAT model as it provided the best performance in comparison to observed gauge data (Jiang et al., 2022). The discharge model output for the calibration period is displayed in Fig. 4. Broadly, the model can be considered robust with a Nash Sutcliffe efficiency value of 0.68 established in the calibration period, and a corresponding value 0.47 for the validation period. Whilst the validation value is quite low and the model underestimates of the peak value, and overestimates the minimum flow value for the validation period, the emphasis for the model is correctly matching the timing of the peak which provides a useful starting point for the water resource managers to evaluate the prototype. The model correctly matches the seasonal flow patterns, which are important in determining the water allocation plan and water abstraction from the river. This provides a useful starting point for the water resource managers to evaluate the prototype.

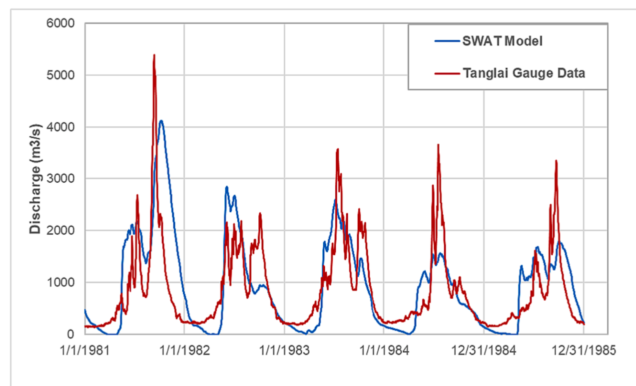

Fig. 4. Upper Yellow River SWAT model output data vs observed data for the Tanglai gauge for the 1980–1985 calibration period. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

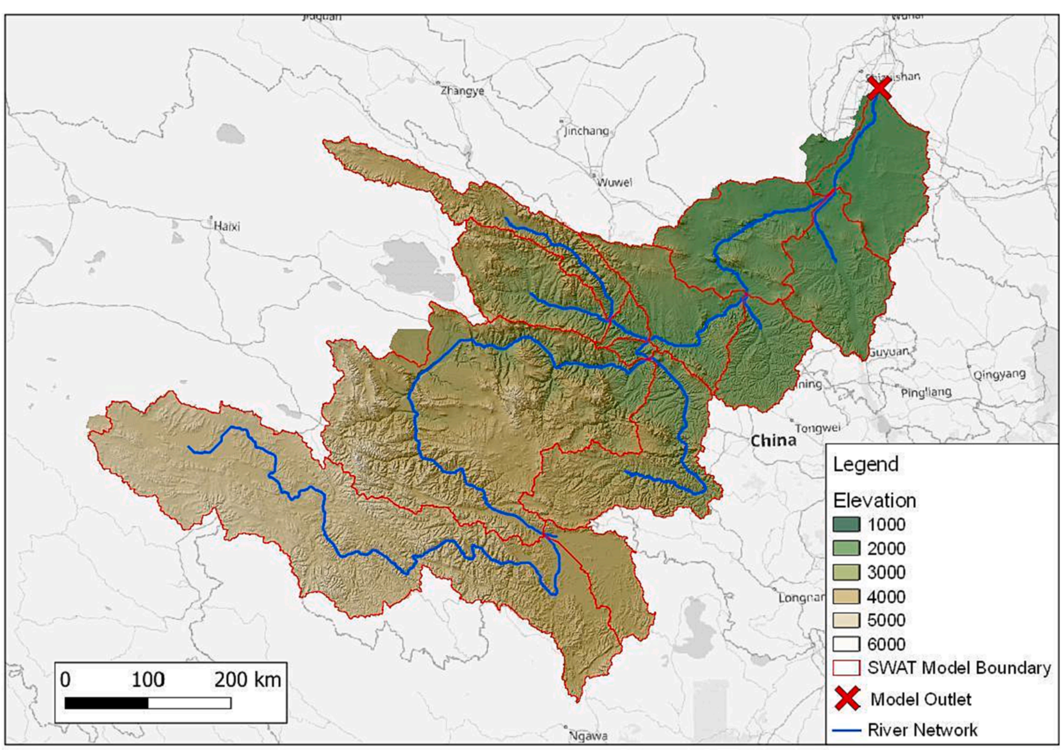

Fig. 3. Upper Yellow River model domain, terrain, and boundary locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

By developing a hydrological model with this data, the model is more indicative of a more naturalised catchment where the link between climatic drivers and river flow is more direct and before significant alterations to the hydrology were made. The model is therefore not meant to reflect current or future conditions where river flow will be altered by the need to maintain water levels for consumption but to demonstrate the direct impact of climate change on river flow. This limits the ability of the model to create accurate predictions based on current management approaches but does show the impact of climate change more directly. As a result, the model should be considered indicative of the trends of future flow but not absolute values. They are sufficient for the development of the prototype presented here.

Data for the future climate projections was taken from three members of the HadGEM3-GC3.05 under the Representative Concentration Pathway (RCP) 8.5 emissions scenario. Three PPE members (PPE4, PPE7 and PPE13) were selected based on their performance against historical rainfall and maximum and minimum temperature patterns across China (Zhao, et al., 2023; Jiang et al., 2022). Using multiple PPE outputs created an emphasis on the possible range of likely outcomes from global climate model simulations without producing more complex datasets, such as multiple ensemble based results that would have the potential to produce more detailed, but more complex displays. A single RCP scenario was used to present a worst-case scenario of both increasing and decreasing variability in precipitation. This could lead to increased periods of drought and more frequent flooding and emphasize the potential long-term impacts of climate change on river levels. Further RCP emission scenarios were not considered in order to limit the number of presentation options required in the prototype, and to provide a simpler narrative in the climate service. This is important for prototype development, but for the final climate service, multiple RCP options should be incorporated in order to provide a comprehensive overview of the impact of climate change.

Four 10-year periods were selected to demonstrate the changing levels of the river over the next century, using 1999–2009 as the baseline – which includes both historic and future forecast data – and modelling the outflow for 2019–2029, 2049–2059 and 2089–2099. These periods are referred to in the climate service as 'time slices' to enable a granulated view of the changes to river levels to be compared within the climate service outputs. The time slice dates were selected to provide a wide range of coverage of the next century, with sufficient spacing between the time slices to establish and understand variations in river level trends. The step change in water resources provided by the time slice approach provided a clearer understanding of the model results in the prototype.

With a baseline model established, provincial level water extraction for each sub basin was incorporated into the model. Using an annual extraction plan from Ke (2003) for the 5 provinces that overlap the model catchment boundary, a simple extraction plan was devised using the water pricing mechanism of Wang et al. (2008) to represent the consumption of water for the region. In this water allocation plan, the majority of water extraction occurs during the dry spring season months of March to May, and no extractions occur during the dry winter months from December to February. These values remain static across the various time slices and are therefore independent of possible temperature increases and population and economic growth. In order to explore the impact of water extraction in future climates, these basic values were varied by 20 %. This is to understand the impact of over and under extraction of water, which is a common problem for the water authorities in China. Preliminary discussion with participants of the workshop emphasised this issue when understanding how the water allocation plans are used. The value of 20 % represents an approximation to the levels of resource use as the full extent of the problem is difficult to establish and was determined through discussions with participants of the workshop to represent an approximation to the variations of water resourcing for individual provinces as well as factoring a small increase in consumption through time. The use of more definitive future trends for water consumption is difficult to establish, so the value used here should be considered conservative and indicative. The water is extracted using the consumptive water use process in SWAT. This removes water based on the water allocation plan from the reach section of each water basin at each time step, and is lost to the system. Whilst some of the water extracted is likely to end up in the atmosphere or in products stored or transported from the region, some extracted water might end up back in the river. Considering the lack of data available about how water allocated is used and the inherent uncertainty of how that water may return to the hydrological system a key assumption within the model is that extracted water is consumed from the system and removed. For the initial climate service development, these extraction values are designed to provide broad insights into the potential impacts of both water extraction and climate change, rather than projected water demand and extraction values. In effect the tool is designed to demonstrate the implications of current water management processes in future climates scenarios. It is envisioned that later versions of this service will contain greater detail in regard to this, with the possibility of improving the link between increasing water demand as a result of a larger population and economic activity and increasing temperatures.

The output of the model indicated a clear drying trend across all 3 climate model simulations by the end of the century. At the 2019–2029 and 2049–2059 time slices, there are some variations, with two of the PPE simulations predicting lower discharge levels, and one predicting higher levels. This is due to variations in rainfall leading to higher peak values across the 10-year time slice periods, but with a noticeable increase in the variation of rainfall, with notable periods of lower than the baseline discharge levels. Despite the overall reduction in river levels, the risk of flooding remains high with increased Q10 levels for all 3 time slice periods compared to the baseline, and higher maximum discharge values. These results indicate the increased pressure on water resourcing in terms of both water allocation and flood control and are similar to results seen in Zhu et al., 2016.

Using this calibrated model, daily discharge data for each time slice, climate model simulation and water extraction scenario were calculated to form the dataset of the climate service. It is important to note that this approach is not a definitive method for presenting the impact of climate change on river flow but is designed to allow an evaluation of the prototype, using figures and outputs familiar to the water resource managers. The results of the model should be viewed in this context.

Developing the climate service prototype frontend

Following the environmental visualisation development processes of Grainger et al. (2018), the simulation outputs were converted to a working prototype through an interdisciplinary approach.

In order to develop a climate service from the 7-point specification, a multi-graphical display layout was chosen to provide a suitable approach to encoding the key climate data, without relying on a single, and perhaps overly complex display (Grainger et al., 2018; Taylor et al., 2021). Using a wireframe approach, an initial layout was created by visualisation experts, and refined to produce a working prototype which retained key working components of the tool (Sedlmair et al., 2012). Four key visual outputs were selected to present the data, with three options to select and explore the data. These user input selections provide a narrative to the data and create a method to allow for data decoding (Cairo, 2013) as well as providing the means to understand the data (Kosara, 2013). The layout for Version 1 can be seen in Fig. 5.

The 3 user inputs selections were a time slice, climate simulation input and water allocation option. These 3 selection options represented the key inputs that were altered in the SWAT simulations that were determined from the climate service prototype specification. Using the 1999–2009 period as a baseline period, the time slice option allowed the user to explore data from the 2019–2029, 2049–2059 and 2089–2099 simulations and compare those time slices to the baseline through the graphical outputs. The user option was presented as a set number of

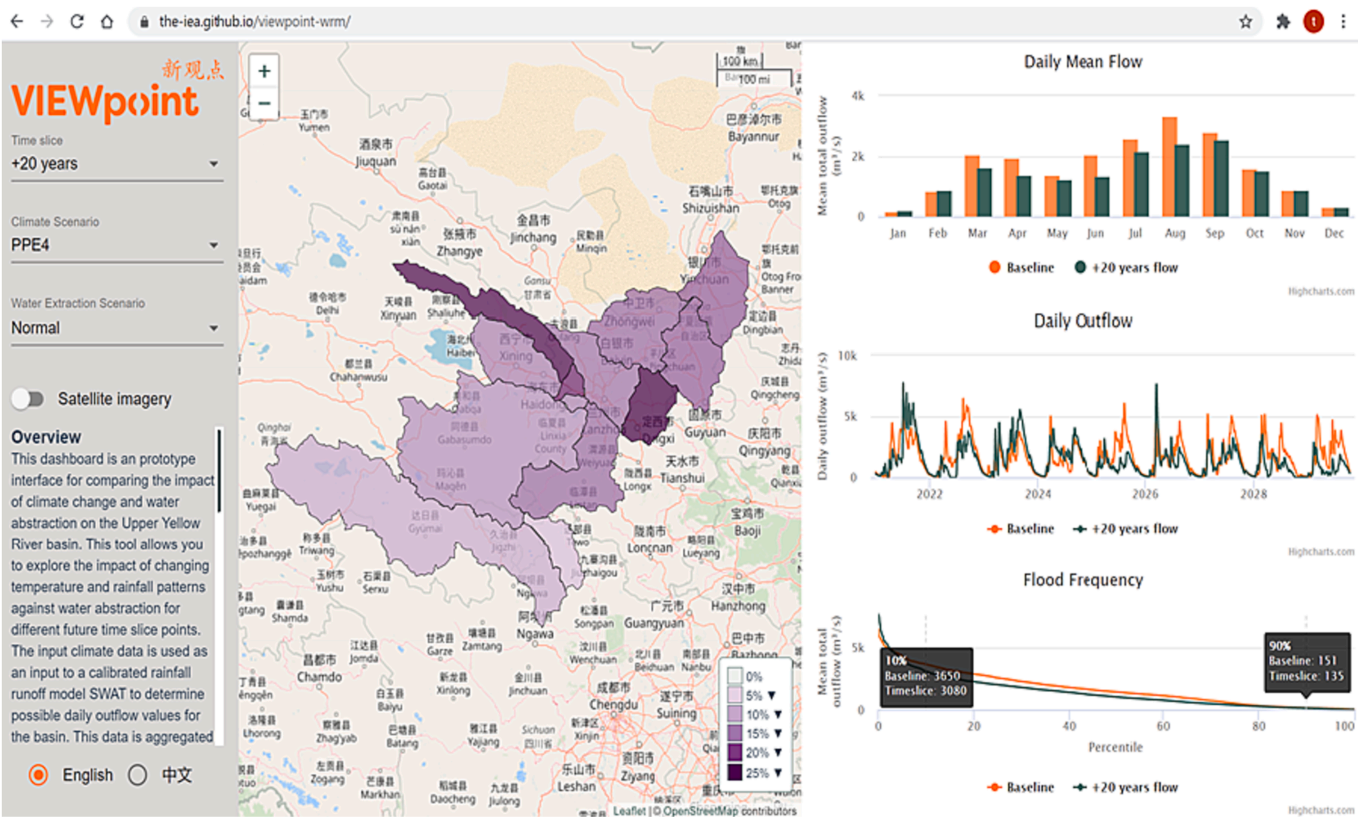

Fig. 5. The first version of the iC-WRM Prototype, adopting a multi-graphical display layout.

years from baseline conditions to match the context of water resource planning time frames. The 1999–2009 was selected as a baseline to provide users with a reference for understanding with recent conditions. Whilst 'baseline' may suggest a more definitive set of conditions with which to compare possible changes, in this context it represents a set of recent conditions in which the water management procedures and decisions would be similar for water managers to understand and relate to, rather than defining the baseline as along climatic metrics such as average discharge or rainfall amounts. Establishing a baseline along these lines may be more important in future developments of the climate service. Climate projection uncertainty could be explored by examining the results from each PPE simulation separately. Water extraction representing the consumption of water within each province could be varied by the user by ±20 % and ±10 % across the catchment. For Version 1 of the prototype, this was static across all provinces – i.e. the simulations were based on all provinces modifying their water extraction above or below the standard values simultaneously.

The main graphical display is adjusted based on these user input selections. The main frame contains a map of the main catchment, which is broken down by the 13 sub-catchments of the Upper Yellow River SWAT model. In this display (main panel Fig. 5), the colour of each sub-catchment was represented by the difference between the total river flow for the sub-catchment over the baseline compared to the user input selection and expressed as percentage difference. Three graphs are presented on the left-hand panel, each panel provides a comparison between the baseline value displayed in orange, and the selected user inputs displayed in green. The top graph displays the daily mean flow for each month, where the daily average for each month is displayed to give an indicator of general river volumes and flows for each month. This is an output typically used in water allocation resource plans and was included here to provide comparison with current datasets. A more direct comparison of the model output was created for the middle 'Daily Outflow' panel. This was the direct river flow data for the bottom of the test case catchment and allowed a more complete understanding of the monthly flow figures in the top panel. Further, it could be seen if there were potential years of droughts or floods throughout the baseline and time slice period. The bottom panel displayed flood duration frequency or cumulative frequency curves from across the decade of the time slice and baseline value. Understanding the Q90 (low flow rate, or the flow rate that a river will flow at for 90 % of the time) and Q10 (high flow rate, or the flow rate that a river will flow at for 10 % of the time) values – quantile threshold flow values that are used to understand the potential low flow and high flow values that will dictate processes such as dam operations, potential flood event occurrences, water storage volumes and reservoir dimension – is critical to water resource managers (Khosravi et al., 2021). Understanding how these values change over the next century will be vital in creating appropriate compensatory strategies.

First evaluation workshop

The first evaluation and presentation of the iC-WRM climate service prototype took place via a virtual workshop. This workshop served three goals: firstly to evaluate the layout and functionality of the climate service, secondly to evaluate the benefit of the service and thirdly to establish if the data presented in the tool helped foster an understanding of the potential impact of climate change on current activities. Attendees were invited from across the Chinese Water Resource sector, including representatives from the MWR and the SNWTP, with further representatives from a number of private sector workers, the Met Office and Nanjing University of Information Science & Technology, project partners for the CSSP work package. 27 participants attended the meeting, with 14 from the SNWTP. The majority of invited attendees have been involved in the project at previous points including the interviews outlined in Khosravi et al. (2021).

A virtual workshop was organised to allow multiple users to attend, regardless of location and was suitable for attendees in both China and the UK. In order to expedite the evaluation process and to ensure that the users could use and engage with the interface and understand the principles behind it, pre-workshop information was provided to all attendees. This included a vi. deo demonstration and documentation for the prototype and underlying models. This provided a level of information that allowed potential users to prepare for the workshop, and to allow greater emphasis in the workshop to be placed on feedback and evaluation. This approach also allowed greater distribution of the material, to other interested parties not currently connected to the project.

The workshop took place in February 2021 using online meeting software, and included a live demonstration of the tool and a focused discussion, during which specific attendees were invited to pass comments. As a result of the SARS-CoV-2 pandemic, the traditional approach of organising and running a workshop could not be undertaken. This is traditionally an important part of the user defined approach, and in the absence of this process, an agile presentation and evaluation method was adopted. The workshop was also used as an opportunity to direct participants to a formal evaluation questionnaire. Further feedback and discussion were enabled through a number of different methods, including the messenger service WeChat to allow informal opinions and to be used. Whilst this approach could not allow for a more formal evaluation, it ensured that all who were interested in providing feedback were able to do so.

User feedback was gained primarily via workshops and an online survey questionnaire after the workshops and focused on evaluation of the interface, functionality and on communicating climate change and the uncertainties presented in the prototype. The feedback consisted of rating scale questions (a graphic and a 5-point rating) to measure the level of comprehension, clarity and agreement of the prototype. There were also open-ended questions to gather general comments and feedback. The questionnaire was intentionally kept brief to ensure that focused feedback was provided. Whilst this reduced the detail in the evaluation process, it ensured that a wide range of opinions could be taken and considered. This decision was taken based on feedback from previous interviews and workshops.

Workshop evaluation analysis – Refining the prototype

Feedback was collated from across the different formats to provide feedback on the use of the tool. 11 attendees responded to the formal questionnaire, with 72 % of these working in the MWR, and 54 % of the attendees listed their daily responsibilities as water resource allocation, which was further split in half by those considering long term water allocation problems. 27 % listed their responsibilities as 'Day to Day Operation/Flood Risk and monitoring'. This represents a suitable spread of roles and responsibilities from the water sector with which to evaluate the first version of iC-WRM.

The website was viewed as being easy to understand and use with an average rating of 3.2/5 for this question, with 45 % rating it 3/5 and 45 % rating it 4/5. In terms of the tool providing users with information and data they would need to do their work, a lower average rating of 2.7/5 was achieved, with 54 % rating the tool as 3/5. However, less than half the respondents would use the data and graphs presented in their current reports. Whilst this may seem a negative result, it also demonstrated the difficulties in producing climate services where strict legislation and defined report structures may restrict general adoption. This is reflected in a question highlighting how important that data displayed in the graphs is, with 90 % of the attendees rating this as 3/5 and above.

The results from the climate prototype improvements are displayed in Fig. 6. An important feature requested to be included within the climate service was additional water resourcing options at the province level, and the option to vary water allocation by each province, with 72 % of respondents wanting additional functions for this within the tool. A significant potential issue is individual provinces extracting water beyond the agreed water allocation amounts and there are currently few legal options for the MWR or the River Basin Commissions to deal with this (Opitz-Stapleton et al., 2016). All respondents from the MWR wanted this option to be included and would provide a level of operational support from the tool which was not available in the first prototype version.

Further options for exploring climate modelling uncertainty were also requested. Rather than only exploring scenarios individually, the option for comparing the PPE climate members in a single visual analytical context was also included. As mentioned in Section 3.1, the three PPE options do not represent probabilistic uncertainty, but scenario uncertainty. Here it is used as a proxy to demonstrate the application of uncertainty in climate data. Further detailed improvements included the options for cross comparing different scenarios, as well as to the existing baseline options, and the ability to extract tabular data for each graph.

Options for also including data relating to the SNWTP were also requested. As the limitations of the project prevents a more extensive hydrological modelling effort from being undertaken, this could not be included in the updated prototype. This is a potential area of further development, which can be included by modelling the corresponding Upper Yangtze River basin, which corresponds to the Western route of the SNWTP. By including this section, and considering the differences in

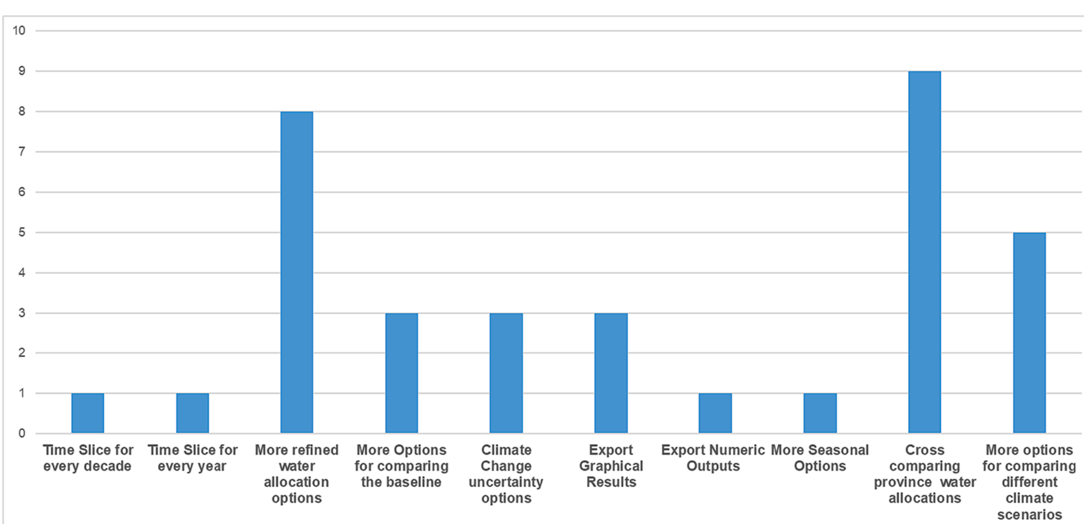

Fig. 6. Summary of the questionnaire results for requested options for improving the climate service prototype.

river levels, a basic comparison could be made of highlighting how much water would need to be transferred to keep river levels at the baseline value and demonstrating this impact in turn on both the Yangtze and Yellow rivers.

Using the feedback provided from the workshop, the prototype was updated to include options for analysing water extraction at the province level, combining the outputs from the climate simulations and comparing multiple time slice options. The data presented in the graphical displays were also modified to allow more options for comparing the climate scenario data. For example, the user could combine the outputs from the 3 PPE scenarios and display error bars on the outputs to visualise the uncertainty related to the climate inputs. More options for comparing baseline scenarios against the selected user inputs were also included. The graphic displays were also changed to allow the user to view each option individually, by selecting the chart on the bottom row tab. The updated prototype is displayed in Fig. 7. This second version still has a number of additional options to include based on the feedback, but provided an improvement compared to the first version.

The impact of climate change on water resourcing

As well as refining the feedback for improving the tool, the workshop also provided the means to evaluate how the data provided in the tool influenced their understanding of the impacts of climate change. When asked if the tool helped the users understand the impact of climate change, 63 % responded by agreeing with the statement, whilst 27 % neither agreed nor disagreed. The results from the questionnaire concerning the potential impact of climate change are summarised in Fig. 8. The main implication for the water resource managers that the prototype highlighted was the need to produce more accurate reports, with more detailed long-term planning. The use of projection data rather than historical data was also highlighted as an important issue.

These results indicate that part of the main development rational has been answered through this prototype, and that some of the issues noted in the interviews and discussions reported by Khosravi et al. (2021) have also been addressed. In terms of raising awareness of the impacts of climate change this climate service has demonstrated both the need for different approaches to future water resource planning and the use of projection data.

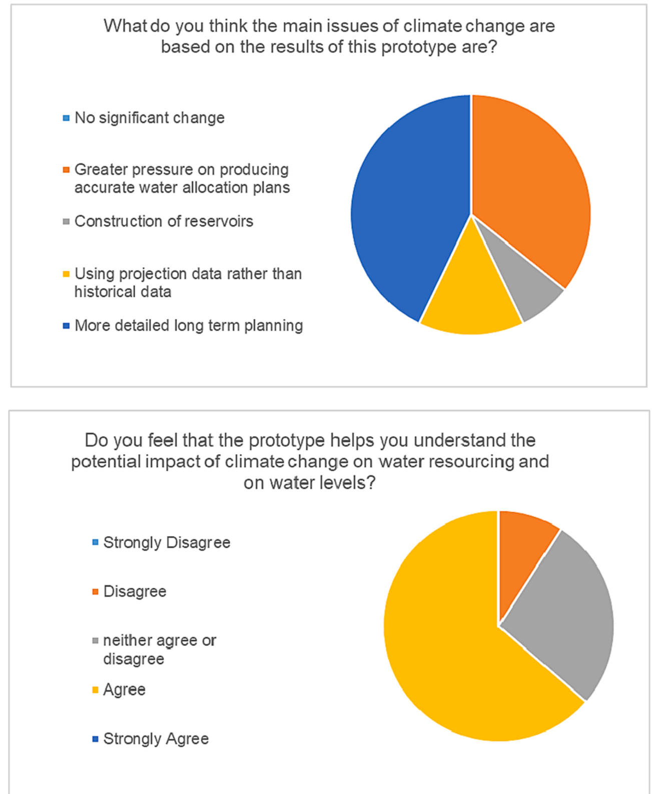

Fig. 8. Summary of the evaluation questionnaire results for establishing the potential main issues of climate change on water resourcing.

There is a clear requirement for further refining the prototype in

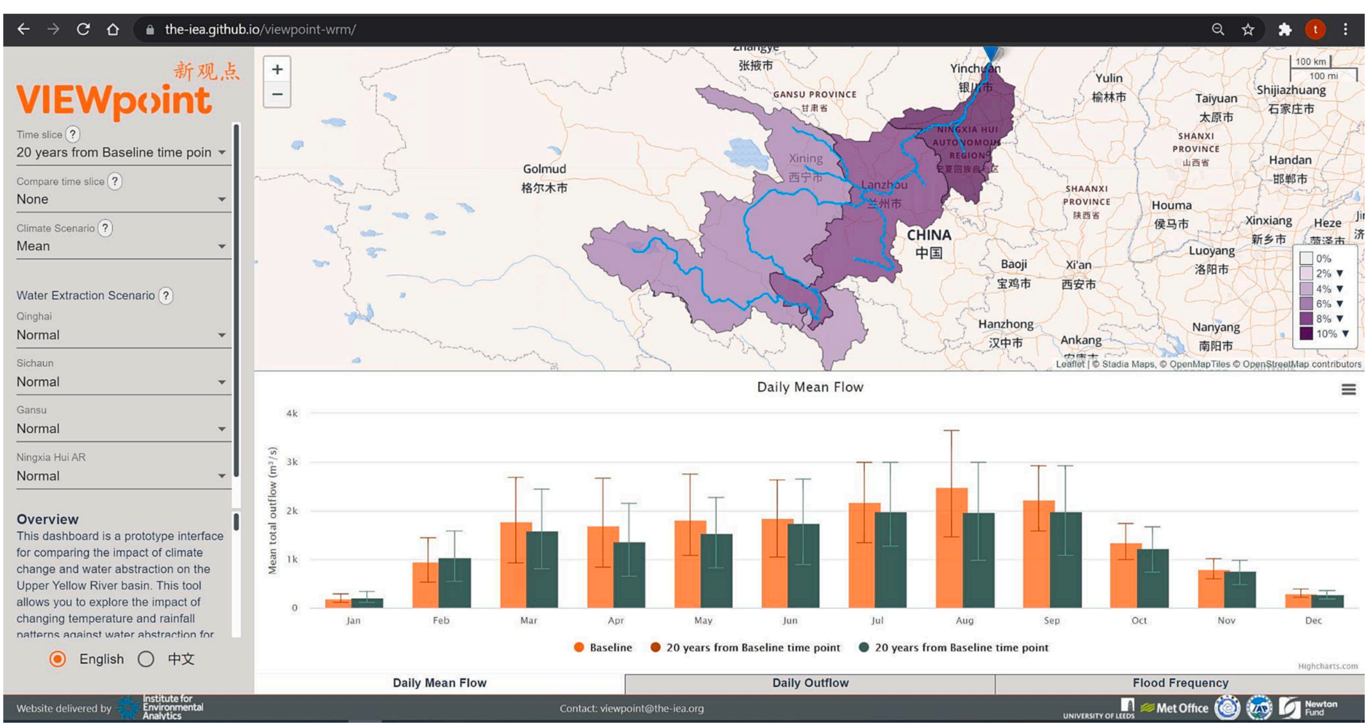

Fig. 7. Version 2 of the iC-WRM Prototype, incorporating more options for comparing the different climate and water extractions, with more graphical options.

order to support water resource managers in decision making and to better support long term management issues, but the initial prototype has demonstrated the ability for this prototype to assist with this. Broadly, the tool helps with understanding the impacts of climate change, although further work is required to refine this to an operational level. The feedback from the evaluation has been used to refine the specification to include these options.

Discussions and conclusions

The construction of the iC-WRM climate service through an interdisciplinary co-production method has been outlined in this research. This approach has helped to successfully determine a climate service specification that can provide real term benefits to users, and to help the adoption of climate projection data in the Chinese water resource sector. The output of the tool has demonstrated the increased pressure on water management in the future with a noticeable trend in decreasing river levels, and more volatile river conditions, with higher peak values and lower Q90 values. The evaluation results of the prototype have established that the key message relating to impact of climate change on water resource is also clear, but further improvements of the prototype are required to enhance and support decision makers in the development of water allocation plans and infrastructure development.

The development of the tool has demonstrated the importance of an interdisciplinary approach. With restrictions to both time and physical meetings, relying on expertise in various fields of science have helped to ensure that the project could be completed, and a working climate service provided. Drawing on expertise from the fields of hydrology, climate science and data visualisation has provided shorter development cycles, with knowledge and experience helping to reduce variables and unknowns at various points in the production of the climate service. This has enhanced the co-developed approach used for this project. In this approach, incorporating the user into the development cycle will always present a challenge. Understanding users' needs, allowing feedback, testing and evaluating the effectiveness of proposed tools and services, will always introduce vital, but time intensive evaluation processes. By using expertise at various points in the project development, this has helped to enhance the limited time available to ensure the maximum could be achieved within notable restrictions. A key point was the development of the design specification. The creation of this demonstrates the benefits of the interdisciplinary approach in creating a climate service. Skills and knowledge from social sciences have provide detailed insights into the needs of the end users, which can be adopted and interpreted by data visualisation specialists, and reduce the number of iterations of prototypes required in a typical user lead design approach.

Restrictions caused by SARS-CoV-2 pandemic also forced the project and development team to adopt agile development processes. This led to the use of more vi. deo and instant messaging chat services and helped to maintain end user interest and maintain momentum in the project. The use of these mechanisms also ensured that users could engage with the development process in their own time, which provided the means to allow evaluation at more opportunistic moments. These approaches could be implemented alongside the more traditional workshop and face-to-face interview approach. Beyond the global pandemic restrictions, the same methods may prove beneficial in other climate service developments and help to increase the potential end user base beyond those that would typically be involved in these development processes. Accessing a wide range of potential users remains a challenge in the co-development approach, and the methodology used here can be a template for other applications.

The choice of location has also proven beneficial in this research. Targeting the Upper Yellow River, a climate sensitive region of the country, where the application of water resource management will become more challenging has helped to headline the importance of using projection data over the traditional historic and seasonal based forecasting. This is an aspect to consider in wider climate service development, where restrictions may reduce the ability to work towards fully developed services and tools. Further, it works within the end users range of experience, and helps to focus both developers and end users on targeted outcomes for the proposed tools.

Whilst the prototype has been demonstrated to be a useful tool, there are a number of limitations to this work which could be improved upon. More comprehensive secondary evaluations should help to identify the extent to which the improvements to the prototype have been effective. Further options of layout and presentation of the climate service were also not considered. For this research, the prototype was based on careful examination of end users' requirements and data visualisation techniques typical for the sector, which provided confidence in the approach taken. In more ideal circumstances, however, a wider range of visualisation techniques could be undertaken to explore new methods of presenting climate information. The limited geographical extent of the modelling has also limited the number of scenarios that could be considered, such as the impact of climate change in water resource management at the national scale. This is particularly important when considering the development and operations of the SNWTP, and further developments of this approach should bear this in mind. Further to this, the hydrological model developed for this study has been designed to provide the necessary inputs for the climate service and has not been compared to the more detailed simulations developed by the water resource managers. Whilst the model results were acceptable in terms of developing a prototype, for further uptake and adoption of such services, the option of using the results in bespoke tools used by the industry or allowing users to insert their own results should be included. The option to compare the results from a wide range of models was not possible in the timeframe of this project, but should be considered for the further refinement of the prototype in order to ensure a high level of quality in the outputs. In addition to improving the hydrological models, the range of climate prediction inputs should also be increased. In this study, 3 simulations from the PPE dataset were used to determine a range of possible climate model outputs. In order to determine more extensively the range of possible water resourcing futures, further permutations and simulations could be used to create a wider ensemble of results than has been used here, in particular using more RCP climate scenarios to develop a wider range of possible future river levels. Further work should also focus on more detailed water allocation plans, in particular understanding how abstracted water is used and how it may feed back into the water cycle, and understanding how changing climate and population dynamics might feedback into this allocation plans. This could also be furthered to include daily and annual activities, such as reservoir operations to understand the impact of these decisions against different climate scenarios. The next steps for the prototype are to further refine and encompass a wider geographic area including the Yangtze River basin in order to evaluate the amount of water required by the SNWTP to compensate flows in the Yellow River basin. Further work will use the co-developed approach to refine both the models and data used to underpin this work. In terms of the co-developed approach, further applications should consider the differences between the use of virtual workshops versus in-person workshops. The advantages of the virtual workshops – greater accessibility, wider potential audience, ability to record and reuse the workshop material – are offset by the limited interaction available through such methods. Understanding how and when to apply these approaches would be useful in evaluating the co-developed approach.

In developing the climate service prototype, a further point gained from this research is that it should be flexible in presentation or in application to accommodate user provided datasets. The effort in the development was focused on the visualisation and presentation of the data with a possible extension of the prototype to allow users to include their own data. This would provide the means for users to include their own options and assumptions into the climate service, further enhancing uptake of the prototype. A number of key questions have been raised in the development of this climate service prototype, one of which is how to present uncertainties related to climate information. Following feedback from the workshop, an effort was made to incorporate the range of climate scenario information into an encoded form – a single graphical display of the data – as well as the option to examine the various outputs individually. From a water resource sector perspective, encoding multiple inputs into a single visualisation provides a more useful insight into climate change, such as presenting the results with a range of potential values represented by minimum and maximum bands, to allow the scope of possible decisions to be understood. From a climate science perspective, this would suggest that the PPE members could be considered probabilistic, but the correct interpretation is that each PPE member is an individual member of a climate projection dataset. This approach, however, provides water resource manager with a clearer understanding of the impact of the climate simulations and the range of possible future scenarios. This aspect of determining the end user of climate service is an important consideration in the long-term adoption of this prototype (Jacobs and Street, 2020). Finally, the development of the prototype has provided an insight into the degree to which climate services provide either detailed analysis or promote awareness and understanding. The feedback from the workshop demonstrated that the iC-WRM has promoted a degree of understanding about the potential impact of climate change in terms of water resources management in China. This will also help to encourage the development of other climate services to understand and implement the key outputs of this climate service prototype to other sectors (e.g. agriculture/food production, regional planning).

CRediT (Contributor Roles Taxonomy) Author Statement.

Thomas Willis and Yim Ling Siu contributed to the design and content of the paper. Thomas Willis was also responsibility for running the SWAT (Soil & Water Assessment Tool) and producing the model results. John Rostron offered his expertise in the long-term climate datasets and forecasts as well as reviewed the draft paper. Guy Griffiths offered his expertise in data visualisation to create a website/webpage for the developed climate service prototype/tool and he also helped to design the graphical and map displays of the model outputs. Andrea Taylor, Suraje Dessai and Andrew Turner provided comments and edits of the draft paper. Buda Su and Tong Jiang offered their expertise in using SWAT model in the context of China and they also reviewed the draft paper. Yim Ling Siu is also responsible for leading and supervising the research activities as well as carrying out project administration.

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.

Data availability

Data will be made available on request.

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