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Supporting climate change adaptation worldwide: A web application for exploring uncertain future changes in water resources

Petra Döll[1,2], Guillaume Attard[3,4], Fabian Kneier[1], Laura Müller[1]

[1]Institute of Physical Geography, Goethe University Frankfurt, 60348 Frankfurt/Main, Germany
[2]Senckenberg Leibniz Biodiversity and Climate Research Centre (SBiK-F) Frankfurt, 60325 Frankfurt/Main, Germany
[3]AGEOCE, 69003 Lyon, France
[4]Earth Blox, EH12 9EG Edinburgh, Great Britain

Correspondence to: Petra Döll (p.doell@em.uni-frankfurt.de)

Abstract. While adaptation to changing water resources due to climate change is necessary everywhere, information about their potential future changes has not been easily accessible to most climate change adaptation processes. The free interactive web application Climate Change Impact of Water Resources (CCIWR) Explorer presents the output of a multi-model ensemble of global hydrological models. It provides state-of-the-art information to support participatory climate change adaptation processes worldwide. What makes the CCIWR Explorer unique is its ability to inform climate change adaptation decisions that account for stakeholder risk aversion. It not only shows the projected median future change in total water resources, groundwater resources, and evapotranspiration in the four seasons or annually, but also which fraction of the ensemble members project a change that stakeholders consider hazardous. Three visualizations are provided: Two map views as well as "Local Insights", percentile boxes showing the range of future changes in individual 0.5° grid cells. The Explorer was evaluated regarding effectiveness, efficiency, operability, user engagement, and beneficialness. This was achieved through an online user survey, in which 21 pilot users familiarized themselves with the web application by completing two tasks before evaluating various aspects of the Explorer. On average, user satisfaction was high. Satisfaction and the number of correct answers are positively correlated with user expertise. Based on experiences with using multi-model ensemble projections to inform stakeholders in three participatory processes, we recommend that experts, such as water engineers and climate managers, consult the CCIWR Explorer to inform stakeholders. The Explorer is also suited to direct use by university students and researchers.

1 Introduction

Worldwide, strategies for adapting to climate change need to be developed through local participatory processes, particularly to minimize risks associated with changing water resources. To identify suitable adaptation measures, quantitative information about potentially hazardous future changes in local water resources is required. However, future changes in water resources can only be projected with large uncertainties (e.g., Tabari et al., 2021). For one specific future greenhouse gas emissions

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scenario, different climate models calculate rather different future changes in climatic variables, in particular in precipitation (Tarrin-Carrasco et al., 2025), and different hydrological models will translate the same time series of climatic input variables into rather different time series of, e.g., groundwater recharge (Reinecke et al., 2021). Therefore, decisions on climate change adaptation need to consider the uncertainty of future hazards of climate change (Döll and Romero-Lankao, 2017).

It is generally not possible to know whether a specific climate or hydrological model is superior to the other models in climate change studies. Even if a hydrological model has been shown to simulate historical streamflow or other hydrological variables well, it cannot be assumed to be superior to others when computing future climate change impacts. Most local or basin-scale hydrological models, for example, do not take into account the response of the vegetation to increased CO_2 and the changing climate when computing evapotranspiration. Therefore, it is state of the art to assess the potential future changes of hydrological variables using the output of multi-model ensembles (MMEs) (Hagemann et al., 2013). These consist of the output of multiple hydrological models, each of which is forced by the bias-adjusted output of global climate models (GCMs) (Döll et al., 2015). The output of each model combination is considered to be equally likely, and the distribution of the changes calculated by each model combination of the MME approximates the uncertain range of future changes.

Most participatory climate change adaptation processes will not have access to multi-model local or regional studies on future changes in water resources due to financial and other constraints. Therefore, they are best served by the output of existing MMEs of global hydrological models (GHMs) that are driven by the bias-adjusted output of global climate models, as provided by ISIMIP (www.isimip.org; Müller and Döll 2024). Suppose a well-established local hydrological model can be applied to project future hydrological changes by forcing it with the bias-adjusted output of several global climate models. In that case, the local model ensemble changes should be contrasted with the changes of the GHM MME to embrace the uncertainty of translating climatic changes into hydrological changes. The spatial resolution of GHMs of 0.5° latitude by 0.5 longitude (55 km x 55 km at the equator) may seem, at first glance, unsuitably coarse for informing local climate change adaptation. However, given the even coarser spatial resolution of global climate models and their large uncertainty in translating greenhouse gas emissions scenarios into changes in climate variables, in particular precipitation, information on potential future changes in water resources in 0.5° grid cells is appropriate for informing on climate-driven changes in areas smaller than a 0.5° grid cell.

The output of the most recent ISIMIP3b GHM MME (https://www.isimip.org/protocol/3/) is freely available for many model output variables as daily or monthly time series of 0.5° by 0.5° gridded values for the time period 1985-2100 in the form of NetCDF files, as described by Müller and Döll (2024) for the previous GHM MME developed under the ISIMIP2b protocol. As processing many large data files using, e.g., Python or R requires specialized skills and effort, we wanted to provide information on hydrological changes important for understanding climate change impacts on water resources and their uncertainty in an easily accessible format. To this end, we analyzed the available model runs and output variables of the ISIMIP3b GHM MME and processed the variables runoff, groundwater recharge, and actual evapotranspiration. We then provided and visualized the changes between a reference period and various future periods via a freely accessible map-based web application, the interactive data explorer (Neset et al., 2016) “Climate Change Impact on Water Resources Explorer”

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(https://ee-gwp.projects.earthengine.app/view/cciwr-explorer), hereafter CCIWR Explorer. A link to the Explorer is provided on the ISIMIP website (https://www.isimip.org/outcomes/data-visualization/).

The development of the CCIWR Explorer was guided primarily by the question: How can information on potential future changes in water resources, derived from a GHM MME, be optimally provided on a web portal, with a focus on supporting local climate change adaptation processes worldwide? The focus was on how to best communicate the uncertainty of the quantitative estimates of future changes, i.e., the range of potential future changes. The uncertainty stems from 1) the uncertain future greenhouse gas emissions, 2) the uncertainty of translating emissions scenarios into climate scenarios by global climate models, and 3) the uncertainty of translating climate scenarios into water resources scenarios by global hydrological models. It is the innovative way in which uncertainties are visualized that distinguishes the CCIWR Explorer.

When developing the CCIWR Explorer, we envisaged that scientists and experts involved in local to national climate change adaptation processes around the world would use it and disseminate the information it offers. Additionally, multidisciplinary scientists from fields such as hydrology, ecology, agricultural sciences, and economics may wish to be informed about potential future changes in water resources in their study regions. Furthermore, the web application can serve as a valuable tool for teaching on climate change and sustainability.

The CCIWR Explorer was developed by bringing together expertise in global hydrological modeling, communication of climate change hazards, and geoscientific web application development. Two of the authors were involved in the development of a global-scale web application on freshwater-related hazards of climate change in the framework of the large research project CO-MICC (www.co-micc.eu). The CO-MICC web application (data portal) was co-designed with meteorologists, hydrologists, and water resources managers from Spain, Morocco, Algeria, and Tunisia and involved more hazard indicators and visualization options than the CCIWR Explorer (Döll et al., 2021; https://www.co-micc.eu/data/data-portal/). Unfortunately, due to technical and organizational issues, the data portal was only accessible for a few months. Different from the CO-MICC web application, which was technically developed by a large company funded within a research project, the CCIWR Explorer was developed without any third-party funding on a very low budget. The CCIWR Explorer was also inspired by more recent experiences of two co-authors in communicating uncertain climate change hazards in participatory processes concerning the adaptation to climate change in the water sector (Müller and Döll, 2024; Söller et al., 2026). We also reviewed existing web applications that present future climatic changes and their impacts. In this paper, we present the CCIWR Explorer and show the results of its evaluation by pilot users. We also discuss its application in participatory processes and how it represents uncertainty, as well as the suggestions made by pilot users for improving it.

2 Methods and data

2.1 Data

Monthly time series of total runoff, diffuse groundwater recharge, and actual evapotranspiration, which were computed by GHMs in experiment 2015soc in the framework of ISIMIP3b (https://protocol.isimip.org/#/ISIMIP3b/water_global), were

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downloaded from the ISIMIP repository. While the three GHMs WaterGAP 2.2e, CWatM, and MIROC-INTEG-LAND provided all three variables, JULES-ES-VN6P3 did not provide diffuse groundwater recharge. Each GHM had been driven by the bias-adjusted output of five CMIP6 global climate models, each of which had computed climate variables impacted by three greenhouse gas emission (or rather concentration) scenarios (Table 1). Thus, the different results of 20 model combinations, i.e., ensemble members, could be analyzed in the case of GHM total runoff and actual evapotranspiration, but of only 15 ensemble members in the case of diffuse groundwater recharge. GHM model output is provided as 0.5° longitude by 0.5° latitude grid cell values (55 km by 55 km at the equator) and covers the time period 1985-2100. The reference period for computing future percent changes of the three variables is 1985-2015, as the simulation runs with three different greenhouse gas emissions cover the period 2016-2100. In the 2015soc experiment (Table 2.3 in https://protocol.isimip.org/#/ISIMIP3b/water_global), the impact of temporally varying water use and artificial reservoirs is considered in the reference period. However, in simulations for 2015–2100, direct human impacts on water resources and land cover are held constant at 2015 levels. This ensures that changes between the reference and future periods reflect climate change impacts only.

All data presented in the CCIWR Explorer were downloaded from the ISIMIP repository (https://data.isimip.org/). For the reference period, the experiments with the specifier "historical_histsoc_default" were selected, for the period 2015-2100, the experiments with the specifiers "ssp12670_2015soc-from-histsoc_default", "ssp370_2015soc-from-histsoc_default", and "ssp585_2015soc-from-histsoc_default", the latter distinguishing the three implemented greenhouse gas emissions scenarios (https://www.isimip.org/outputdata/).

Table 1: Data presented by the CCIWR Explorer as obtained from ISIMIP3b (Gosling et al., 2024). All combinations of variables, season, future time period, and greenhouse gas emissions scenario are provided, where each relative change is quantified by a GHM MME of (a maximum of) 20 ensemble members. Each of the four global hydrological models is driven by the bias-adjusted output of five global climate models.

Variables	Total water resources, groundwater recharge, actual evapotranspiration
Annual or seasonal aggregation	Annual, December to February, March to May, June to August, September to November
Percent changes from 1985-2014 until	2016-2045, 2041-2070, 2071-2100
Greenhouse gas emissions scenarios	SSP1-2.6 (low), SSP3-7.0 (high), SSP5-8.5 (very high)
Global climate models	mpi-esm-2-hr, ukesm1-0-ll, mri-esm2-0, gfdl-esm4, ipsl-cm6a-lr
Global hydrological models	JULES-ES-VN6P3, WaterGAP 2.2e, CWatM, MIROC-INTEG-LAND

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2.2 Implementation of web application with Google Earth Engine

The CCIWR Explorer was developed using Google Earth Engine (GEE), a cloud-based platform for scientific analysis and visualization of geospatial datasets that provides APIs and other tools to enable the analysis of large datasets (Gorelick et al., 2017). A primary advantage of GEE is its free availability for academic and research purposes. This allowed for the development of a high-performance tool without a dedicated server infrastructure.

The CCIWR Explorer leverages GEE's high-performance distributed computing to process the GHM MME output on-the-fly. The logic, primarily contained in the back.js module, performs the following functions:

- The platform filters collection of images based on user-defined climate scenarios (SSPs), variables, and time horizons to compute first mean values of the three variables for the reference period 1985-2014 and future periods 2016-2045, 2041-2070 and 2071-2100, and then relative changes of the three variables between the reference period and the three future periods.
- To avoid misleadingly large relative changes arising from very small absolute values, an MME member is excluded from the ensemble if its variable value for the reference period is smaller than 5 mm/year for the yearly analysis and 1 mm/season for the seasonal analysis.
- Using server-side reducers, the application extracts the ensemble distribution for a selected 0.5° grid cell to generate percentile box charts that indicate certain percent changes that are not exceeded by a certain percentage of the ensemble members.

The user interface was built with the front.js module, using GEE's user interface library, allowing for real-time interaction with the data. The application features a linked dual-map interface. The top map displays the median relative change of a variable, while the bottom map indicates the percentage of models simulating a change above or below a user-selected threshold. When a user clicks on the map, the application dynamically renders "Local Insights" with percentile boxes showing P10, P30, P50 (median), P70, and P90 values for the selected grid cell. The P10, for example, indicates the future percent change that is not exceeded by 10% of all ensemble members. While GEE is a powerful tool for global-scale analysis and visualization, its architecture introduces specific constraints in the context of easy-to-deploy public web applications like the CCIWR Explorer. The GEE ui library is relatively specialized. This hindered the implementation of more advanced web features, such as custom CSS styling or a more flexible layout. The code of the web application is freely available (see Section Data availability).

2.3 Pilot user survey

We evaluated the quality of the web application CCIWR Explorer with an online survey using the software SoSci Survey (www.soscisurvey.de). The survey questions were inspired by the international standard for evaluating the quality-in-use of software ISO/IEC 25019:2023 (2023), where quality-in-use is defined as the "extent to which the system (…), when it is used in a specified context of use (…), satisfies or exceeds stakeholders' (….) needs to achieve specified beneficial goals or outcomes" (topic 3.1.15, https://www.iso.org/obp/ui/en/#iso:std:iso-iec:25019:ed-1:v1:en). Characteristics of quality-in-use

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include beneficialness and usability. Beneficialness is the "extent of benefit resulting from the use of a (…) system" (topic 3.2.1), while usability is defined as the "extent to which a system (…) can be used by specified users (…) to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use" (Topic 3.2.1.1). This definition of usability was also used in the more specific quality-in-use model for web portals developed by Herrera et al. (2010). In our context, effectiveness and efficiency are related to learnability, the degree to which the functions of a system can be learnt by specified users within a specified amount of time, which is also recognized as a criterion for the quality-in-use (ISO25000, https://www.iso25000.com/index.php/en/iso-25000-standards/iso-25010). User satisfaction was evaluated regarding two criteria formulated on ISO25000: user engagement ("degree to which a user interface presents functions and information in an inviting and motivating manner, encouraging continued interaction") and operability ("degree to which a product or system has attributes that make it easy to operate and control").

The survey consisted of four parts (see survey text in Supplement 1). To be able to evaluate the Explorer, the survey participants first needed to become acquainted with the web app. Therefore, after a short introduction in part 1 of the survey, the survey participants were given two tasks in part 2 of the survey to perform using the web app and were asked to report the number of minutes needed to complete them. The first task asked the user to explore renewable groundwater resources in Central America, which required the users to first select the appropriate variable, temporal aggregation (annual averages), time period, emissions scenarios, and map extent. They then needed to analyze the top map with the median changes to correctly answer question 1.1 and the bottom map to answer questions 1.2 and 1.3. The second task was to explore the changes in total runoff in the city of Ulaanbatar both annually and in the summer months. In order to correctly answer five questions, the user had to find the city on the map, click on it, and interpret the percentile boxes in the "Local insights" section of the page. All questions in part 2 were multiple-choice questions (see Supplement 1). The user's performance in solving these tasks served to evaluate effectiveness and efficiency. Effectiveness was operationalized as the fraction of correct answers to the eight questions in the two tasks. Efficiency was quantified by dividing the number of correct answers by the time it took users to complete the task, as reported by the users themselves.

In part 3 of the survey, user satisfaction, with its sub-criteria operability, user engagement, and beneficialness, was elicited through 10 Likert-scale statements (Supplement 1). Operability was elicited with statements 1 and 2 of part 3, user engagement with statements 4, 5, 7, and 10, and beneficialness with statements 3, 6, 8, and 9. Finally, two open questions asked for missing information in the documentation that is provided on the web page and for suggestions to improve the Explorer. The last part of the survey elicited the user background and included four Likert-scale questions. On a Likert scale, the users rated their knowledge of climate change and climate scenarios as well as of water resources (questions 4.1 and 4.2), as well as their experience with hydrological modeling and the quantification of climate change impacts (questions 4.3 and 4.4). Finally, they were asked whether, before this survey, they had understood the meaning of percentile and whether they had known about MMEs and their application in estimating future climatic changes or climate change impacts.

The survey was open from July 7 to October 31, 2025. It was advertised via various professional and student mailing lists, LinkedIn, and personal contacts. 21 pilot users completed the survey.

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3 The CCIWR Explorer

When calling the URL of the CCIWR Explorer, the user sees the landing page depicted in Fig. 1. It encompasses two map windows on the right-hand side, the user interface on the upper part of the left-hand side, and, below it, the Local Insights
195 percentile boxes showing changes between the reference period and three future time periods for a grid cell on which the user has clicked on one of the maps. By interacting with the computer via the user interface, the user selects the variable, the emissions scenario, the time horizon, and the season (or the annual aggregation of the monthly values) (Table 1). These specifications determine what is shown on the two maps and the Local Insights graph.

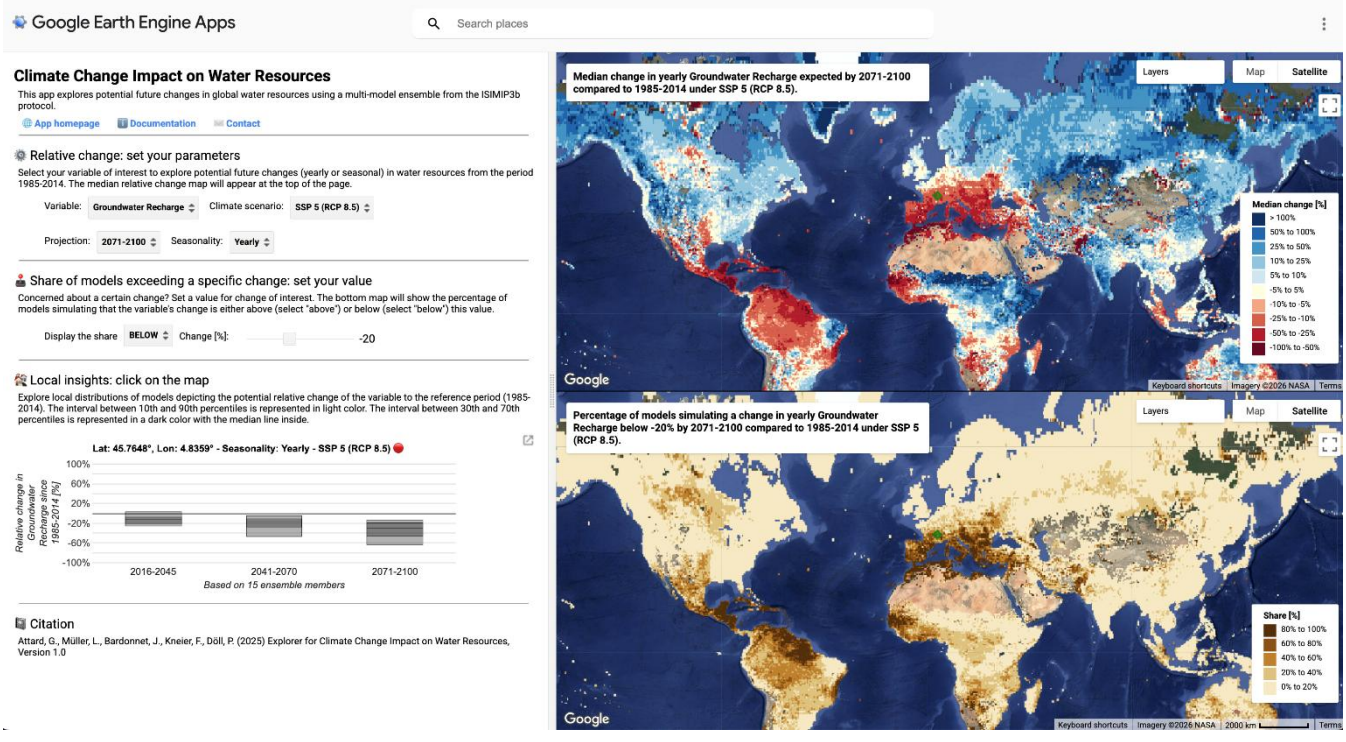


Figure 1: Screenshot of the landing page of the CCIWR Explorer (https://ee-gwp.projects.earthengine.app/view/cciwr-explorer).

The upper map window shows the median percent change of the variable, i.e., the change that is not exceeded by half
205 of the MME members. The bottom map shows the percentage of MME members simulating that the variable`s change is either above or below a certain threshold that the user selects (default setting: below the threshold of -20% change). By consecutively varying the threshold, the user can obtain a comprehensive impression of the spatially distributed hazards of climate change. For example, the spatial patterns of the number of models that exceed a certain decrease in groundwater recharge inform about the spatial pattern of (approximate) likelihood for exceeding problematic decreases. This is an informative addition to the

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median future change shown simultaneously in the top map window, which, without the bottom map, may hide a problematic change, as some MME members may project a problematic change even though the MME median indicates a non-problematic change. Both map windows permit zooming and panning, and the user can increase the transparency of the data layer to see the base layer with city names.

The percentile boxes in the Local Insights plots are designed like those introduced by Müller and Döll (2024). This publication compares percentile boxes to four alternative methods for visualizing cumulative distributions in the form of percentiles, letter-value plot, violin plot, box plot, and the bar chart as used by GERICS, the Climate Service Center Germany. GERICS bar charts and percentile boxes are easier to understand than the other three alternatives. Both indicate just five percentiles, i.e., they show five values of change of the variable of interest, where, e.g., P10 refers to the change that is not exceeded by 10% of the MME members. A percentiles box shows P10, P30, P50 (median), P70, and P90, while a GERICS bar chart shows the minimum change, P20, P50, P80, and the maximum change (e.g., https://www.gerics.de/imperia/md/content/csc/projekte/klimasignalkarten/gerics_klimaausblick_germany_version1.2_deutsch.pdf). Showing the minimum and maximum may reduce the readability of the GERICS bar chart, as outliers may increase the box size strongly. Not including all MME members in the percentile box, but only 80%, increases the precision with which the three central percentile values can be identified from the visual. In addition, showing P10 and P90 in percentile boxes often fits the notion of both scientists and stakeholders of excluding extreme values from consideration. When clicking on the Local Insights graph, the graph opens in a separate page, from where either the graph can be downloaded as png file, or the data behind it as csv file. The gridded data shown on the maps cannot be downloaded.

Before engaging with the user interface, the user can easily detect, at the top left of the page, the word “documentation”. By clicking on this word, the documentation of the CCIWR Explorer opens. The original documentation available to the participants of the pilot user survey is included as Supplement 3. The current version was updated in response to the user survey and is included as Supplement 4 (see Section 5.2). The documentation introduces the purpose of the web application, and then answers the following questions: What type of information is provided by the CCIWR Explorer? How is the information provided? How is the provided information best utilized for informing local climate change adaptation processes? After having read this short documentation of about three pages, the user understands the purpose, applicability, and content of the web app and knows how to operate the interface in a meaningful way. The revised version also includes a tutorial.

To utilize the CCIWR Explorer to inform stakeholders about potential future changes in water resources, even if there is no internet access during the stakeholder engagement, a user may print parts of the screen to pdf files in advance and then combine them. As an example, Fig. 2 shows potential future changes in renewable water resources in Southern Africa. While the two top panels are the same and show the median changes, the lower panels enable them to grasp the uncertainty of the projections by showing, on the left side, the share of MME members that project a general decrease in total renewable water resources, and on the right side, the share that projects a decrease of at least 25%. For many but not all grid cells with a projected median increase in water resources (blue cells in the top maps of Fig. 2), more than 20% of the MME members

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project a decrease, but less than 20% a decrease of more than 25%. In some grid cells with a median increase, e.g., in southern Tanzania, more than 20% of the MME members predict a decrease of more than 25%.

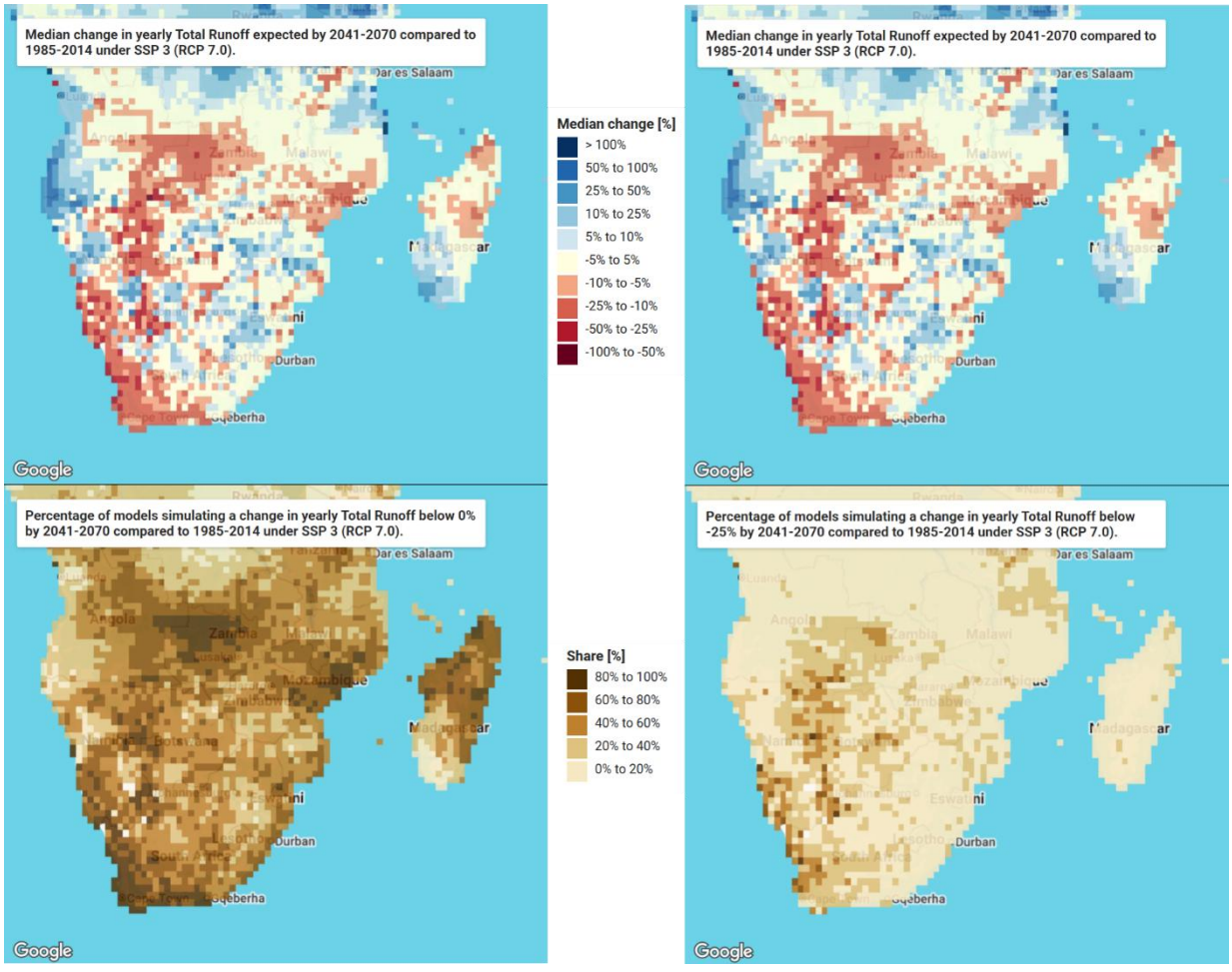


Figure 2: Arrangement of screenshots made to inform stakeholders about potential future changes of renewable water resources until 2041-2070 under the high emissions scenario SSP 3 (RCP 7.0) in southern Africa. While the upper maps both show the median change of the MME, the lower left map shows the share of MME members that project a decrease in renewable groundwater resources, while the lower right map shows the (smaller) fraction of models that project a decrease of at least 25%. © Google Earth Engine.

After showing the larger regional pattern of future changes in water resources using maps, local participatory processes for climate change adaptation are best informed by Local Insights plots. These plots show the range of potential changes in a selected 0.5° grid cell using percentile boxes. Müller and Döll (2024) provide information how the interpretation of percentile plots can be explained to stakeholders, and the revised documentation also provides guidance. The Local Insights plots offer,

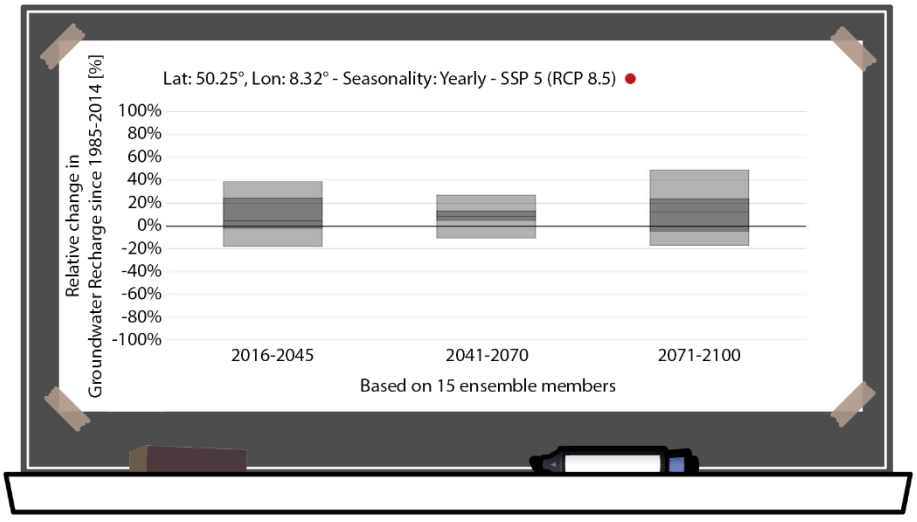
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for instance, concise information on projected seasonal changes in the variable of interest. As an example, Fig. 3 shows seasonal and annual changes of diffuse groundwater recharge between the reference period and the near, intermediate, and far future for a grid cell in the mountains north of the city of Frankfurt, Germany. While most MME members project an increase in annual groundwater recharge, i.e., renewable groundwater resources, 10% project a decrease of more than 20% until the far future (lower end of box), which may motivate risk-averse stakeholders to undertake adaptive water management measures. The predominantly projected increases in annual groundwater recharge until the far future are due to rather stable values in winter (December to February) and strongly increasing values in spring (March to May), the two seasons that dominate annual groundwater recharge in the region. These projections are suitable for countering fears of a lack of drinking water supply from groundwater if waterworks have access to large groundwater reservoirs. However, if waterworks rely on groundwater bodies with a small storage capacity, they may be negatively affected by the projected decrease in groundwater recharge in the summer (June to August) and fall (September to November) seasons (Fig. 3). 30% of the MME members project a decrease in summer groundwater recharge of more than 40% until the end of the century (lower end of dark yellow box), while 10% of the MME members project declines of more than 70%. Figure 3 shows a clear decreasing tendency in summer groundwater recharge during the 21st century.

The first author has already integrated the CCIWR Explorer into her hydrogeography class. In this class, students successfully used the CCIWR Explorer to characterize the impacts of climate change on water in selected large river basins. They took several screenshots after zooming in on the basin and then juxtaposed them on a PowerPoint slide. They also used Local Insights to show their classmates the potential future temporal development of water resources at a specific location within the basin.

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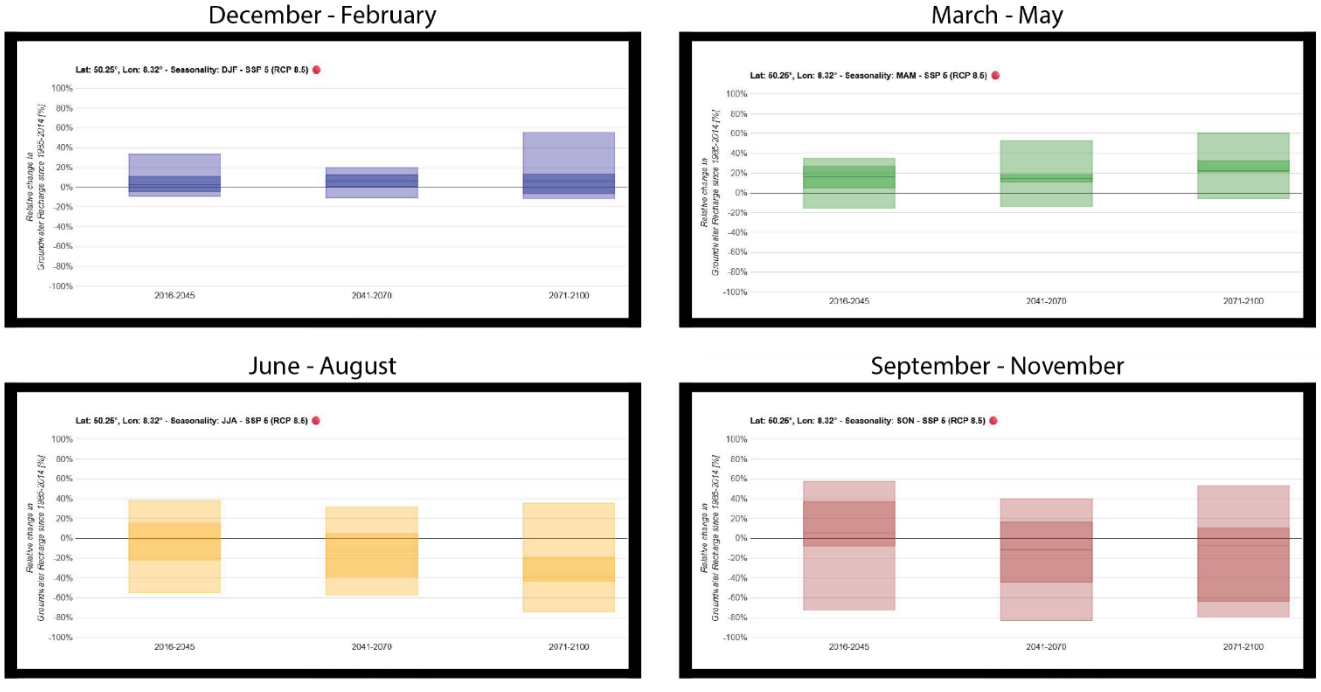


Figure 3: Arrangement of five downloaded png files with Local Insights plots for the 0.5° grid cell north of Frankfurt (Germany), where the municipality of Waldems is located. It may serve to inform local stakeholders about potential future changes in groundwater recharge. The arrangement shows, at the top, the changes in annual groundwater recharge between the reference period and three future time periods, and, below, the projected changes in seasonal groundwater recharge.

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4 Evaluation results

4.1 Effectiveness and efficiency

The effectiveness of the CCIWR Explorer is quantified by the correct number of answers to questions related to the two tasks that the pilot users had to perform to become acquainted with the web application. On average. i.e., over all 21 pilot users, 5 out of the 8 questions were answered correctly. Only three users answered all the questions correctly. Relating the number of correct answers to the time required to do the tasks, including potentially reading the documentation, quantifies the efficiency of use. The reported times ranged from 4 minutes to 55 minutes, with a median of 21 minutes. Assuming that the reported "4 minutes" represents a typo, as three questions were answered correctly, the efficiency ranges between 0.9 and 7.5 correct answers per 10 minutes, with a median of 2.4 correct answers per 10 minutes. The number of correct answers is positively correlated with user expertise, but only weakly (Fig. 4b). The level of user expertise was quantified by averaging, for each user, the Likert-scale (1-5) answers to four questions regarding the user's climate change and water resources knowledge, and their experience with hydrological modeling and the quantification of climate change impacts (Supplement 2). We did not include, in the level of user expertise, the previous user knowledge about percentiles and the application of MMEs in climate change studies, as all survey participants except one indicated that they had this knowledge before taking the survey.

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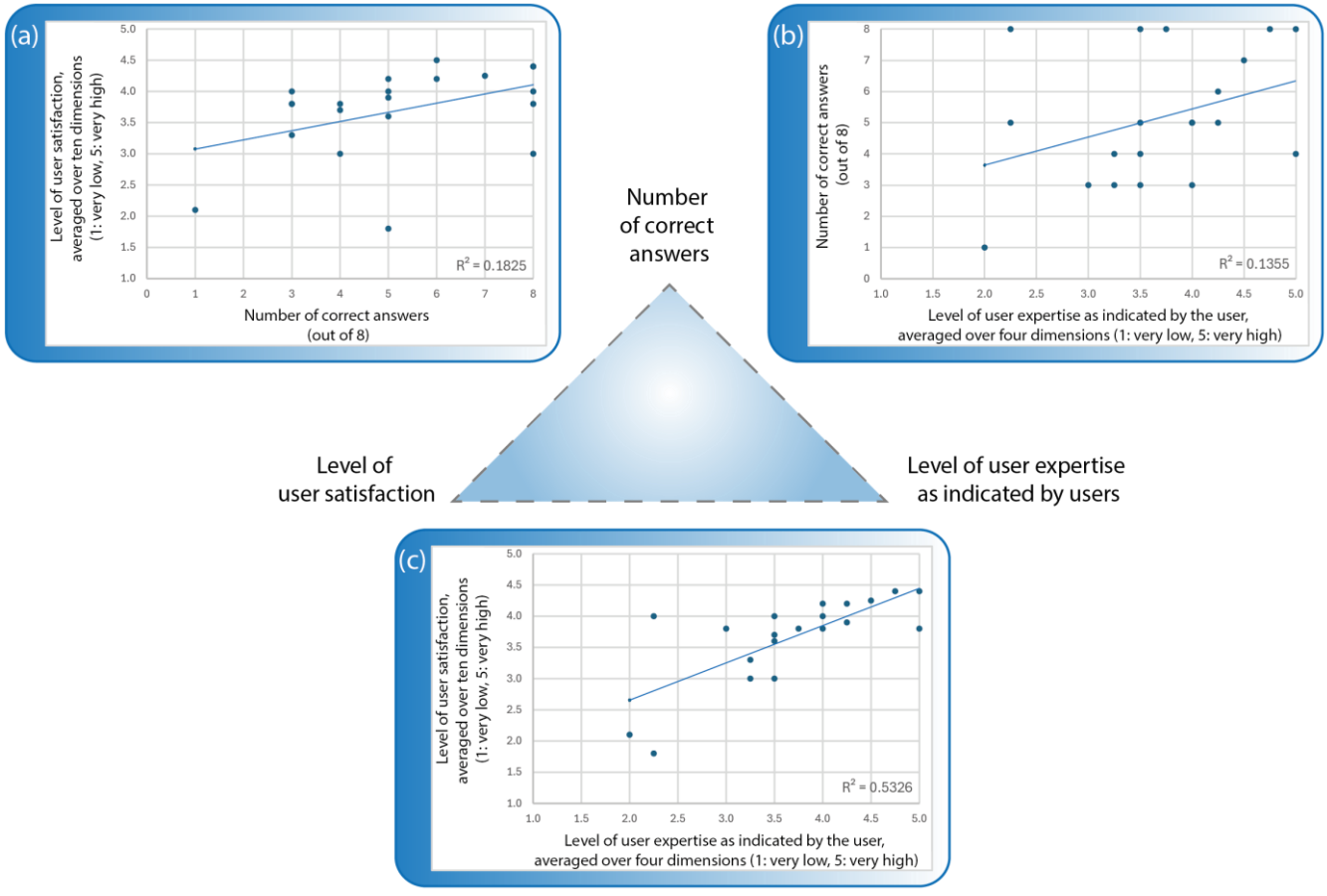


Figure 4: Relations between the number of correct answers in tasks 1 and 2, user satisfaction, and user expertise. Relation between the level of user satisfaction and the number of correct answers (a), the number of correct answers and level of user expertise (b), and the level of user satisfaction and the level of user expertise (c).

Evaluating the sub-criterion of user satisfaction operability (statements 1 and 2 in Fig. 5) separately, more than 60% of the users agreed or strongly agreed with the statements. Statements 4, 5, and 7 were included to evaluate user engagement, specifically the clear and informative presentation of median changes (top map), MME member agreement (bottom map), and the Local Insights plots. The presentation of the top map obtained a better evaluation than the other two, which may be explained by the fact that this is the most typical and simplest presentation of climate change impacts, while the bottom map and the Local Insights plot visualize the distribution of MME results, which is something that most users might not have seen before. In terms of beneficialness (statements 3, 6, 8, and 9), only 10-20% of the participants did not see a benefit in the CCIWR Explorer. Many survey participants evaluated the bottom map more negatively than the top map and the Local Insights plot, both in terms of user engagement and beneficialness. The level of user satisfaction correlates positively with the number of correct answers (Fig. 4a), but only weakly. However, with an R^2 of 0.53, it correlates rather strongly with the level of

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expertise (Fig. 4c). Only 3 out of the 21 survey participants did not intend to consult the CCIWR Explorer again in the future (statement 10).

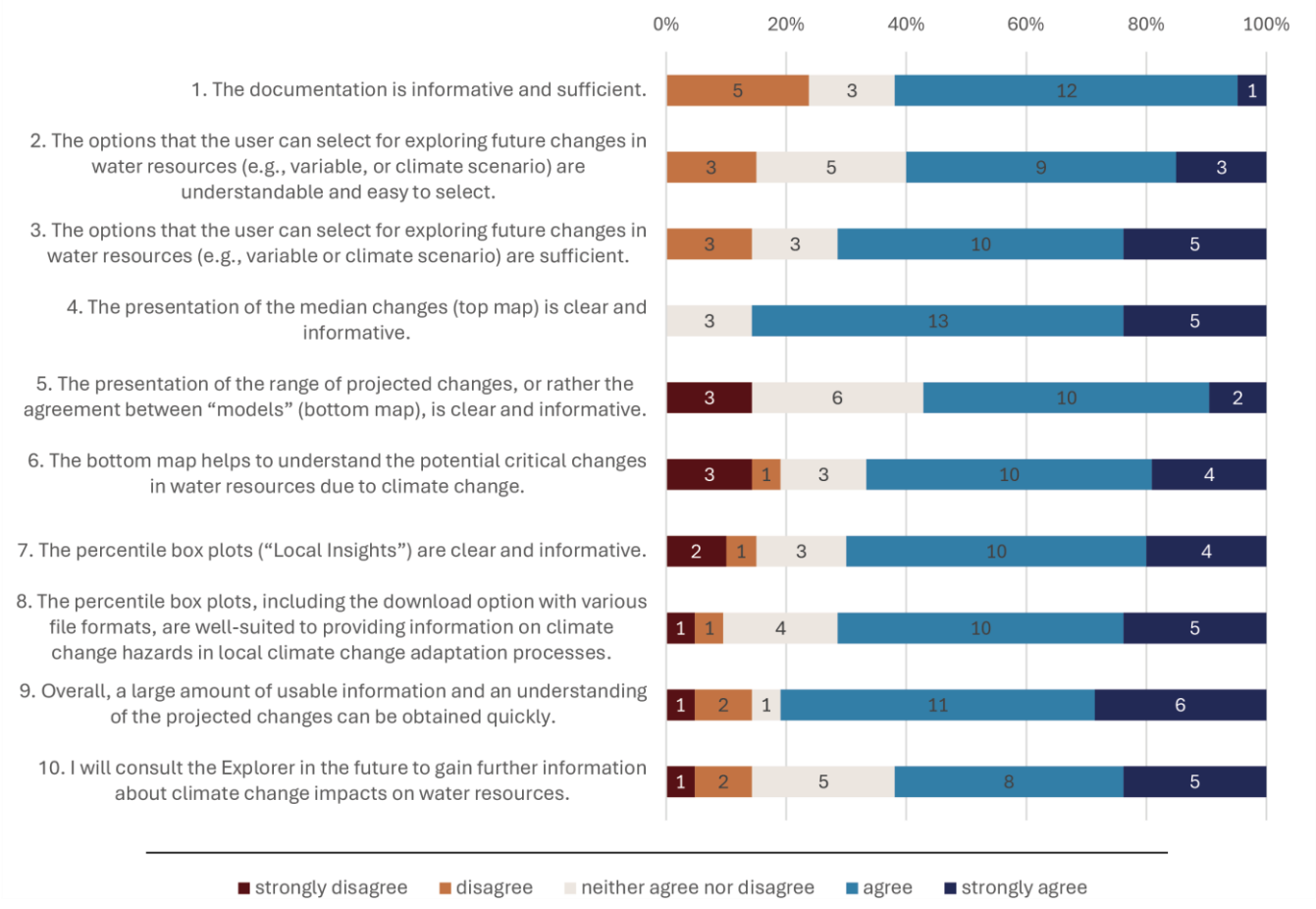


Figure 5: Evaluation of 10 statements describing user satisfaction, based on a total of 21 or 20 answers.

5 Discussion

5.1 Usage of information provided by the CCIWR Explorer in local participatory processes for climate change adaptation

GCM-GHM MME data based on ISIMIP model runs, such as that visualized by the CCIWR Explorer, were communicated and discussed in three participatory processes for water management under climate change in which two of the co-authors were involved. In all cases, stakeholders were informed on the range of potential future changes in their area of interest by percentile boxes, like those provided as "Local Insights" by the CCIWR Explorer. We experienced that, when communicated

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adequately (as described in detail in Müller and Döll, 2024), knowledge of potential changes in future water resources in the form of distributions of potential changes helped stakeholders to better understand what is and is not known about the future and consider their level of risk aversion. This provided a solid foundation for identifying options of management under uncertainty.

The participatory process KlimaRhön aimed at identifying ways for adapting to climate change in the biosphere reserve Rhön in central Germany in the two stakeholder-selected problem fields “water supply of households, agriculture and industry, mainly from groundwater” and “aquatic ecosystems, with a focus on springs and small streams” (Müller et al., 2024). Already in the first workshop, which was preceded by interviews with stakeholder representatives, we, as hydrological researchers familiar with climate change impacts on water resources, communicated the potential changes of total water resources and groundwater resources by percentile boxes, after explaining what MMEs are and how to read the percentile boxes (Müller and Döll, 2024). The 31 stakeholders participating in the first workshop, except for two, were not accustomed to working with climate change information and were not familiar with assessing uncertainties using MMEs (Müller and Döll, 2024). Afterwards, supported by a written summary of the climate change hazards, the stakeholders discussed the question, 'Which future impacts of climate change — the extent of which can only be estimated with uncertainty — do we want to prepare for?', at one of three tables in a World Café. All but one of the stakeholders advocated adapting to the worst-case scenario, guided by the precautionary principle. However, concerns were raised regarding costs and other issues (see Müller and Döll, 2024, for more details). Presenting potential future decreases in water resources in summer, alongside the stakeholders’ experiences of recent unusually dry summers, led to the participatory process focusing on adapting to potential water scarcity in the summer months. At the end of the first workshop, the stakeholders were asked to rate their agreement on the statement “Through the scientific input, I gained a better understanding of the potential changes to water resources due to climate change in the biosphere reserve Rhön”, where the scientific input relates to the information on potential future hydrological changes as derived from the MME. More than 60% of the stakeholders strongly agreed or rather agreed with this statement. More than 75% of the stakeholders strongly agreed or rather agreed with the statement “Through the scientific input, I gained a better understanding of the uncertainties of the estimated changes in the biosphere reserve Rhön” (Müller and Döll, 2024).

The projected change in water resources, albeit in a simplified way, also became part of the participatorily derived Bayesian Network that estimates the implementation probability of certain climate change adaptations (Müller et al., 2024). In the KlimaRhön participatory process, uncertainty, as introduced by the MME-based climate change hazard projections, served as a boundary concept for both the stakeholders and the sociologists in the team conducting the participatory process (Müller et al. 2025).

In a project on groundwater management, MME-based information stemming from the same MME as that used for the participatory process in the biosphere reserve Rhön was communicated in two participatory processes by a hydrologist with the help of the percentile box visualization shown in Figure 2 of Söller et al. (2026). In both processes, one in a region south of the Harz in Germany and the other on the Croatian island of Krk, these presentations enabled stakeholder discussions

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on robust groundwater management strategies that respond to the overall location-specific future trends in water resources as computed by the MME and are robust under the range of potential future changes. In the German case, the presentation of the range of potential future changes with percentile boxes, instead of the often communicated average projected changes, together with the uncertainty regarding the complex hydrogeology but also water abstractions, led the participants to develop a groundwater management concept including management measures that was explicitly geared at dealing with these uncertainties (Söller et al., 2024a). While most MME members project strong seasonal but not annual decreases in water resources for Germany, this is different for the Mediterranean island of Krk, where annual water resources are projected to decline significantly by most ensemble members (Söller et al., 2026). In the face of the strong interdependence between the main income source in Krk, tourism, and the available water resources, the projections of declining water resources all around the year supported the stakeholders in identifying a large number of adaptation measures regarding both the optimization of water supply and the reduction of tourism-related water demand (Söller et al., 2024b).

There was no local information on groundwater recharge, and only very few streamflow observations, if at all, for the areas covered by the three participatory processes. There were also no regional hydrological models or projections of hydrological changes. Therefore, stakeholders considered the MME-based projections to be valuable information that was, until then, not available to them. Identification of specific water management options was only roughly based on the distribution of the MME-based hydrological changes, but rather led by finding measures that are robust under a wide range of plausible hydrological changes (e.g., decreases in the summer or decreases year-round). This is an appropriate way of utilizing MME projections at the early stage of identifying climate change adaptation options; all three participatory processes were the first processes on water management under climate change that were performed for the areas. Whenever more specific adaptation planning, together with financing adaptation measures, needs to be done at a later stage, e.g., decisions on investments in new groundwater wells, then the information on the percentage of MME members that, e.g., project a decrease in groundwater recharge of more than a critical percentage value, is more decision-relevant than in early climate change adaptation processes. Then, the stakeholder will decide on the specific hydrological change to which they plan to adapt based on their risk aversion.

Based on our experiences in the above participatory processes, we recommend that someone with expertise in climate change impact assessment, e.g., a water resources specialist or a local climate change manager, extracts the information on climate change hazards from the CCIWR Explorer that is pertinent to the specific participatory process. This person should then communicate the information to the stakeholders at the beginning of the participatory process. This includes an explanation of how an MME quantifies hydrological changes and how to read the maps and percentile boxes. The projected potential hydrological changes may then be communicated by showing the visualizations, either only the percentile boxes (Fig. 3) or additionally the map views (Fig. 2), depending also on the size of the area of interest. It is important to clearly verbalize the information that can be derived from the visualizations, saying, e.g., “10% of the models of the multi-model ensemble project a decrease in average groundwater recharge of more than 20%”. In the final step, the expert should summarize the

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specific hazards relevant to the subsequent stakeholder discussion and explain to what extent the coarse-scale modelling results are relevant to the local situation.

5.2 Representation of the uncertainties of future climate change and its impacts

There are a few map-based web applications that provide model output regarding future climate change and its impact at the global scale. As with the CCIWR Explorer, they represent uncertainty regarding future greenhouse gas emissions by asking the user to select one SSP-RCP scenario. Uncertainties of future changes under any emissions scenario caused by the climate or impact models and quantified by multi-model ensembles are represented in different ways. We will first compare how the range of model results is displayed for a single spatial unit, such as a grid cell or a country, and later, how it is represented in or as maps with multiple spatial units.

5.2.1 Temporal development in single spatial units

Since 2021, the Intergovernmental Panel on Climate Change (IPCC) has offered the Interactive Atlas (https://interactive-atlas.ipcc.ch/) for flexible spatial and temporal analyses of much of the observed and projected climate change information that underpins the Working Group I contribution to the Sixth Assessment Report. This web application is based on a large MME of CMIP6 global climate models and only shows climate variables, but no information on climate change impact on water resources. It provides many ways for presenting the uncertainty of future climatic changes and allows the user to select, on the map, world regions for which the temporal development of the selected variable is presented, in particular as time series. For each year, the median, P5, P25, P50, P75, and P95 are shown by a thick line for the median and different shadings for the P25-P75 and P5-P95 ranges. In addition, the results of the individual global climate models are shown with lines. The more recent European Copernicus Interactive Climate Atlas (https://atlas.climate.copernicus.eu/atlas) has been inspired by the IPCC Interactive Atlas and uses the same approaches for representing uncertainties. The Climate Impact Explorer by Climate Analytics and The International Institute for Applied Systems Analysis (https://climate-impact-explorer.climateanalytics.org/) provides projections for future climate impacts at different warming levels and for several policy-relevant greenhouse gas emission scenarios. Like the CCIWR Explorer, it is based on ISIMIP3b MME output. However, it is not documented which impact models (e.g., GHMs) are included. Regarding water resources, streamflow and surface water runoff (not total runoff as in the case of the CCIWR Explorer) are made available. The original 0.5° model outputs are aggregated such that the user can explore the temporal evolution of the relative change of the variable in continents, countries, or provinces with time series graphs that are similar to those of the IPCC Interactive Atlas. However, only P5, P50, and P95 are shown.

The CCIWR Explorer does not show time series of yearly future changes with respect to a reference period, but three percentile boxes that aggregate changes over three 30-year time periods. This simplification makes it easier for the user to grasp and communicate future changes as it does not overwhelm with temporal variations. The information content provided is similar to “table summaries” provided by the IPCC Interactive Atlas, also with five percentiles, but adds visualization as percentile boxes.

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5.2.2 Map views

When perusing map views of the IPCC Interactive Atlas, the user can select different ways to show uncertainty on the global maps of projected percent change (e.g., precipitation) that is caused by the global climate models, "simple" or "advanced". If "simple" is selected, no overlay indicates high model agreement, where at least 80% of models agree on the sign of change; diagonal lines indicate low model agreement, where fewer than 80% of models agree on the sign of change. Model agreement is computed at a grid cell level. If "advanced" is selected, three levels of uncertainty are distinguished. No overlay indicates that the change is robust and likely emerges from internal variability, with at least 66% of the models showing a change greater than the internal-variability threshold, and at least 80% of the models agreeing on the sign of change; diagonal lines indicate no change or no robust change (fewer than 66% of the models show change greater than the internal-variability threshold); crossed lines indicate conflicting signals where at least 66% of the models show change greater than the internal-variability threshold but fewer than 80% of all models agree on the sign of change. On the maps of the Climate Impact Explorer, grid cells with "insufficient model agreement" are marked in grey color with diagonal lines, but it is not documented how this category was defined. No further information on model uncertainty is provided on maps.

The Hypeweb web application of the Swedish Meteorological and Hydrological Institute (https://hypeweb.smhi.se/explore-water/climate-change-data/global-climate-change/) provides global-scale information on changes in total runoff and streamflow due to future climate change. Different from the CCIWR Explorer, it is based on only one GHM that is driven by the output of multiple global climate models (from CMIP5, the older generation of global climate models). In the map view, the uncertainty is presented, according to user selection, either as the agreement on the sign of change or as the range of relative changes that is projected if the GHM is driven by the MME of global climate models. In addition, the output of the GHM driven by each of the 20 global climate models can be shown. Hypeweb and the CCIWR Explorer thus provide in the map view quantitative data on the range and distribution of potential future changes, while the first two web applications only provide one change value per grid cell, the MME median change, and only mark grid cells without robust median values. In addition to the MME mean, Hypeweb shows the grid cell-specific range of percent changes as computed by the MME, e.g., 50% if the minimum value of the MME is -20% and the maximum value is 30%, which is a suitable way of quantifying model-based uncertainty. However, different from the bottom map view of the CCIWR Explorer, it does not enable the user to explore the distribution of changes (this could be done by looking at the changes projected by using each of the 19 considered global climate models as input to the single GHM). The advantage of showing the fraction of the MME members with changes below (or above) a user-defined threshold change, in the bottom map of the CCIWR Explorer, is that it allows the user to see the (approximate) likelihood, as the share of MME members, with which a user-defined hazard level may be exceeded (Fig. 2). Evaluating the bottom map, the user can relate different hazard levels, e.g., decreases in groundwater recharge of more than 5, 20, or 40%, to different model shares, e.g., more than 80%, 40-60%, and 0-20%. Such maps show spatially distributed information about the potential range of projected future changes in a differentiated way that fits the information content of the MME. It enables a combined representation of the (approximate) likelihood of future changes

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and their spatial heterogeneity, which can neither be achieved by plots showing the temporal evolution of single spatial units nor by maps of median or mean MME changes in which only the robustness of the mean or median is indicated.

5.3 Pilot user suggestions for improving the CCIWR Explorer

16 pilot users provided suggestions for improving the CCIWR Explorer when asked about missing information and suggestions for improvement. The most relevant suggestions, together with our responses to them, are listed in Table 2. Seven pilot users suggested providing a step-by-step tutorial and more detailed information on how to interpret what is displayed in the CCIWR Explorer. Referring to the tasks set out in the survey, one user wrote, “Overall, the documentation gives mainly context (which is good) but gives little guidance. Since your tasks are very well chosen, I'd suggest to simply add those to the documentation”. We have implemented this user’s advice and some other suggestions in the revised version of the documentation of the CCIWR Explorer (Supplement 4). It is not possible to implement many suggestions for improving the user interface and its flexibility (see bottom row of Table 2) due to the characteristics of the Google Earth Engine used to set up the web application, which does not facilitate an easy implementation of some user-friendly features.

Table 2: Pilot user suggestions for improving the CCIWR Explorer and our responses. The number of pilot users making a specific suggestion is included in the first column in parentheses.

Suggestion	Response
Provide a step-by-step tutorial, possibly a video tutorial, and provide examples of how to interpret the results (for users who are new to climate data analysis). (7)	The tasks given in part 2 of the survey have been added as a tutorial to the revised documentation, where, as an alternative, the link to a corresponding interactive online tutorial is also provided.
Documentation: Provide a table with model names, scenarios, periods, and other relevant data. (1)	Table 1 of this paper has been included in the revised documentation.
Documentation: Provide equations used to make the bottom map and the percentile boxes. (1)	We prefer not to include these equations in the documentation, as the approach is well explained verbally in the documentation, and the equations are available in the provided app code.
Maps: Make colors better identifiable, even if the data layer is selected to be transparent. (3)	This is not possible. After the survey, the default opacity of both maps was set to 100% to provide optimal color-based class identification. In the revised documentation, we have advised the user to use transparency for finding specific locations, but to set it to zero for optimal identifiability of classes.
Local Insights plot: Explain better how to read percentile boxes, e.g., in a legend for the plot. (1)	There is no space on the screen to do this. We have enhanced the explanation in the documentation

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Local Insights plot: Show the maximum and minimum of each variable and enable downloading of more metrics, such as mean and standard deviation. (1)	Currently, only the median, P10, P30, P70, and P90 of relative changes are provided for each of the three time periods in the downloadable csv file. As in GEE, the generated csv files are based on the plot, the suggestion is not easily implementable.
Local Insights plot: Show exact values of the percentiles when hovering over lines in the percentile boxes. (1)	Currently, this is only done for the median, as we did not manage to do it for the other percentiles using GEE. Exact values can be read from the csv file that can be exported.
Include more variables. (2)	We would have liked to include streamflow, but due to the different river networks used by the available GHMs, this was not possible. Streamflow could be included if more GHMs with the same river network submit their output to ISIMIP.
Decrease grid size to 10 km x 10 km to make it suitable for local cases. (1)	This will not be possible in the near future, as there are not enough GHMs with this higher spatial resolution. Besides, given the spatial resolution of global climate models, which is lower than the GHMs, the added value of the requested grid size is expected to be small.
Provide an option to export the maps. (1)	This would only be possible in the commercial GEE version.
Provide small question marks next to buttons that offer explanatory text when clicked, and provide explanatory text when hovering over, e.g., the seasons JJA, etc. (2)	It would be very time-consuming to implement these suggestions because Google Earth Engine is not designed for the easy production of user-friendly web applications.
Provide more interactive features, such as a comparison tool to overlay different scenarios side by side. (2)	
Maps: Enable turning of either the top or bottom map, and to arrange the two maps horizontally side by side. (1) Enable the user to select not only a grid cell but a user-defined region. (2)	
Local Insights plot: Mark the median line more clearly. (2) Enable the user to set their own percentiles. (1)	

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6 Conclusions

The CCIWR Explorer is a low-budget web application for supporting climate change adaptation in the water sector under uncertainty. The development process focused on facilitating effective communication regarding the plausible range of potential future changes in water resources. The objective was to enable users to understand and embrace the uncertainty information provided by MMEs, and to use this information to identify adaptation measures. With the provided knowledge about the proportion of the ensemble members that project a change they consider hazardous, stakeholders can make informed adaptation decisions based on their risk aversion.

While the Explorer was evaluated very favorably by most pilot users, the evaluation, as well as our own experience with presenting multi-model ensemble projections in participatory processes for climate change adaptation, indicates that some hydrological and climate change expertise is required for a meaningful interpretation of the provided information. Therefore, we recommend including experts such as water engineers or climate managers in participatory climate change adaptation processes dealing with water resources. These experts can use the CCIWR Explorer to compile information to communicate to stakeholders, using the maps and plots provided by the web application. We also believe that the CCIWR Explorer is suitable for direct use by university students and researchers, as well as for informing the public about the impact of climate change on water resources. The CCIWR Explorer may inspire a future integrated, interactive cross-Working Group IPCC Atlas, which, according to Alegria et al. (2024), should be developed to support comprehensive AR7 climate change risk assessments. Alegria et al. (2024) propose that ISIMIP MME output, like the one presented in the CCIWR Explorer, becomes a primary source for global climate impacts in key WGII-relevant sectors such as health, water, forests, agriculture, and fisheries. Unfortunately, even very prominent web applications on climate change have not been formally evaluated by their users. To the best of our knowledge, this is not even the case of the IPCC Interactive Atlas (Cimadevilla et al., 2025). In line with the recommendations of VanderMolen et al. (2019), we advise the implementation of comprehensive user surveys, especially for current and future IPCC interactive atlases.

Data availability

The questionnaire (Supplement 1), the survey results (Supplement 2), the original documentation of the CCIWR Explorer available to the survey participants (Supplement 3), and the revised documentation (Supplement 4) are provided as supplements to this paper. *Supplement link.* The code of the web application is available at https://drive.google.com/file/d/1FZvI9sufoQ7LhkUyZ0Ani8xLHywX9iGL/view?usp=drive_link.

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Author contributions

PD and GA developed the concept and methodology of the CCIWR Explorer with the support of LM and FK. GA performed the technical implementation. PD developed and evaluated the user survey and prepared the manuscript and the figures with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

Ethical statement

The online evaluation of the CCIWR Explorer and the respective questionnaire was approved by the Ethics Board of the Geosciences/Geography Department of Goethe University Frankfurt on June 27, 2025. The first page of the survey included the following: “By continuing, you confirm that you understand that your participation is entirely voluntary. You understand that your responses will be kept strictly confidential and anonymous. You agree that the data collected may be published anonymously. You have the option to withdraw from this study at any time, without penalty, and you also have the right to request that your responses not be used”.

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The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.

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