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Applying a climate information distillation framework to support a climate resilient hydropower sector in Nepal

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Co-production of climate services is widely recognised as a valuable way to integrate relevant and reliable climate information into decision-making contexts. Yet the extent of information and evidence that may be relevant to a climate-sensitive decision can be very large, and it is not always feasible to involve all stakeholders throughout the process of constructing climate information. Pragmatic approaches are required, particularly in resource-constrained contexts to ensure scientifically defensible climate information can be provided to guide adaptation decisions. The Climate Information Distillation Framework (CIDF) is a multidisciplinary approach that builds on recent research with the aim of supporting climate service development across a range of applications, sectors and contexts. Here we apply the theoretical framework to the Nepal hydropower sector. Focusing on present day uncertainties and projected future changes to extreme rainfall, we show that a CIDF can be applied in situations where opportunities for co-production are limited but where there is a need to consider diverse perspectives and objectives. The benefits and challenges of using this framework are discussed, highlighting that while climate information rarely dominates in adaptation decision-making processes, appropriate framing, synthesis, transparency and communication of uncertain climate information can valuably support adaptation decisions and policy. Providing the case study of hydropower development in Nepal, within a complex economic and development context, we find that applying the theoretical framework must be done with humility and flexibility to support real-world decision-making.

KEYWORDS
climate services, co-production, extreme rainfall, hydropower, Nepal

1 Introduction

1.1 Climate change impacts on hydropower in Nepal

Nepal is highly exposed and vulnerable to climate change (Amadio et al., 2023; Nepal and Kadayat, 2024), ranked 122 out of 183 countries worldwide on its vulnerability and level of adaptation readiness (ND-GAIN, 2026). The country's energy sector is exposed to a diverse range of climatic and non-climatic hazards (Sharma et al., 2023; Adhikari et al., 2024) and Nepal's

National Adaptation Plan (NAP) recognises the need for the sector to develop appropriate adaptation strategies (MoFE, 2018). Achieving climate resilience in the energy sector, and electricity generation in particular, means reducing exposure to present-day hazardous weather and investing in long-term adaptation measures to cope with altered and emerging risks from climate change, while balancing other challenges including social, technological and policy drivers (Adhikari et al., 2024).

The hydropower sector dominates electricity supply in Nepal yet is particularly exposed to climate hazards associated with a lack or excess of rainfall (Bhattarai et al., 2025); drought conditions impact energy production and intense rainfall leads to damaging and dangerous impacts on energy production and hydropower infrastructure, with knock-on downstream impacts if this fails (Shrestha et al., 2021; Wasti et al., 2022). As climate change affects the spatial and temporal variability and intensity of rainfall (e.g., Douville et al., 2021; Fowler et al., 2021), hydropower companies, governments and local communities all have a role in ensuring the sector adapts to the changing risks using the best available climate information.

Nepal generates around 94% of its electricity from hydropower (Vaidya et al., 2021), with a total installed capacity of 3 GW (NEA, 2024) and rapid growth in new capacity. Ranked globally, in 2024 Nepal made the sixth largest addition to their installed hydropower capacity of 700 MW (IHA, 2025), and the Investment Board of Nepal predicts there is potential hydropower capacity of 43 GW (IHA, 2025). With surplus electricity during the wet season months, Nepal has started to export energy to the Day-Ahead Market (DAM) of Indian Energy Exchange (NEA, 2022a; Shrestha, 2021).

The impacts of climate change on the hydropower sector in Nepal are varied but uncertain (Bhattarai et al., 2025), due to the lack of reliable long-term hydro-meteorological data and high uncertainty associated with future climate trends (Basnyat and Watkiss, 2017). Devkota et al. (2025) highlight the considerable uncertainties in future temperature and precipitation changes, distinguishing that snow-fed rivers exhibit greater discharge and variability compared to spring-fed rivers, and adaptive hydropower design. Climate-induced hazards, such as extreme rainfall, typically initiate cascading hazards including high sediment loads, landslides, and glacial lake outburst floods (GLOFs) that can be economically costly to hydropower and energy transmission infrastructure, as well as having broader social and national security impacts on Nepal (Khatri, 2025). The floods of September 2024, amplified by climate change (e.g., Liang, 2024), affected 20 plants and reduced electricity production by at least 1.1GW (IHA, 2025). The Nepal Electricity Authority (NEA) does not routinely consider changes to climate in their environmental management plans when proposing new infrastructure (e.g., NEA, 2022b), despite extreme weather having an increasingly negative impact on hydropower operations across South and Central Asia (Agrawala et al., 2003; IHA, 2025).

Within this complex and evolving decision context of hydropower development in Nepal, we explore the application of climate information distillation to support decisions to enhance resilience to climate change.

1.2 Climate information distillation

To support government policy, sectoral decision makers and local communities to adapt to climate variability and change, climate services are being developed and delivered in a wide range of contexts (Hewitt et al., 2012). Increasingly, there is recognition that climate services are most effective when they involve dialogue and collaboration (Hewitt and Stone, 2021), with advances in understanding how co-production processes can best support engagement (Vincent et al., 2018, McClure et al., 2024). While co-produced climate services can be effective (e.g., Golding et al., 2017; Terrado et al., 2023), it is not sufficient to simply bring stakeholders together as the process of developing climate services can involve trade-offs and potentially lead to unintended maladaptive outcomes (Biella et al., 2024). It can also be a challenge to collaborate given diverse knowledges, skills, agendas and values, especially in contexts with complex power relations, competing institutional mandates and time-limited opportunities for engagement (Jacob et al., 2025).

Beyond the challenges of co-producing climate services among diverse stakeholders, when using climate information within climate services to inform decision making, data and metrics from multiple sources must be assessed and synthesised, each source with varying spatial and temporal relevance, quality, and associated uncertainties. During this process of analysis, there is an inevitable component of subjectivity and expert judgement in choices made, such as deciding which data to include and exclude, or which metrics are appropriate to assess model performance and quantifications of uncertainty. To determine the most essential information, different technical and value-based perspectives must be taken into account. The climate information distillation process (Jack et al., 2021) recognises this, where "distillation" is described by the Intergovernmental Panel on Climate Change (IPCC, Doblas-Reyes et al., 2021) as "the construction of (potentially user-targeted) information that is defensible and evidence-based (Giorgi, 2020), and the translation of this information into a specific context, targeting a specific purpose and set of values". Jack et al. (2021) express that and distillation aims to make decisions and assumptions transparent and open for deliberation throughout the process of creating information.

In practice there is a tension between promoting discussions around such assumptions and the domain expertise needed to develop information and products, especially in situations when stakeholders are funding- and time-constrained and have varying technical knowledge to collectively understand and interrogate choices. As observed by Vincent et al. (2018) while co-production has many advantages, it can vary from using the approach to develop an entire climate service or applied only to elements within a climate service. In complex real-world climate-sensitive decision contexts, can co-production principles (e.g., McClure et al., 2024) be maintained while allowing pragmatism and empowering technical experts to make informed choices about constructing information without deliberating all assumptions with stakeholders?

To advance methods for distilling climate information and support climate adaptation decisions, here we present the application of a Climate Information Distillation Framework (CIDF); a structured approach to guide the analysis, synthesis and communication of climate information to guide climate-related decisions (Figure 1; adapted from Daron et al., 2022). The framework aims to facilitate open conversations throughout the development of climate information to ensure transparency and contextual risk framing, while enabling the use of expert judgement where appropriate. The scope of climate information is narrowed throughout the process, starting with identifying the broad needs of stakeholders and understanding the decision landscape (step 1) and collaboratively narrowing these down to jointly agree analysis aims and appropriate metrics, timescales, and scenarios for the analyses (step 2). Steps 3 and 4 rely more on expert judgement from scientists as 'fit for purpose' climate datasets are

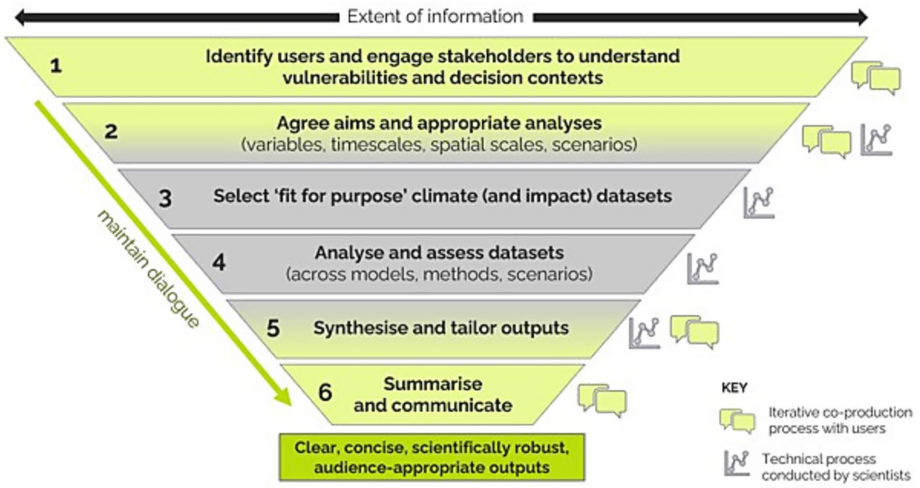

FIGURE 1
Climate information distillation framework (adapted from Figure 2; Daron et al., 2022). License CC BY 4.0.

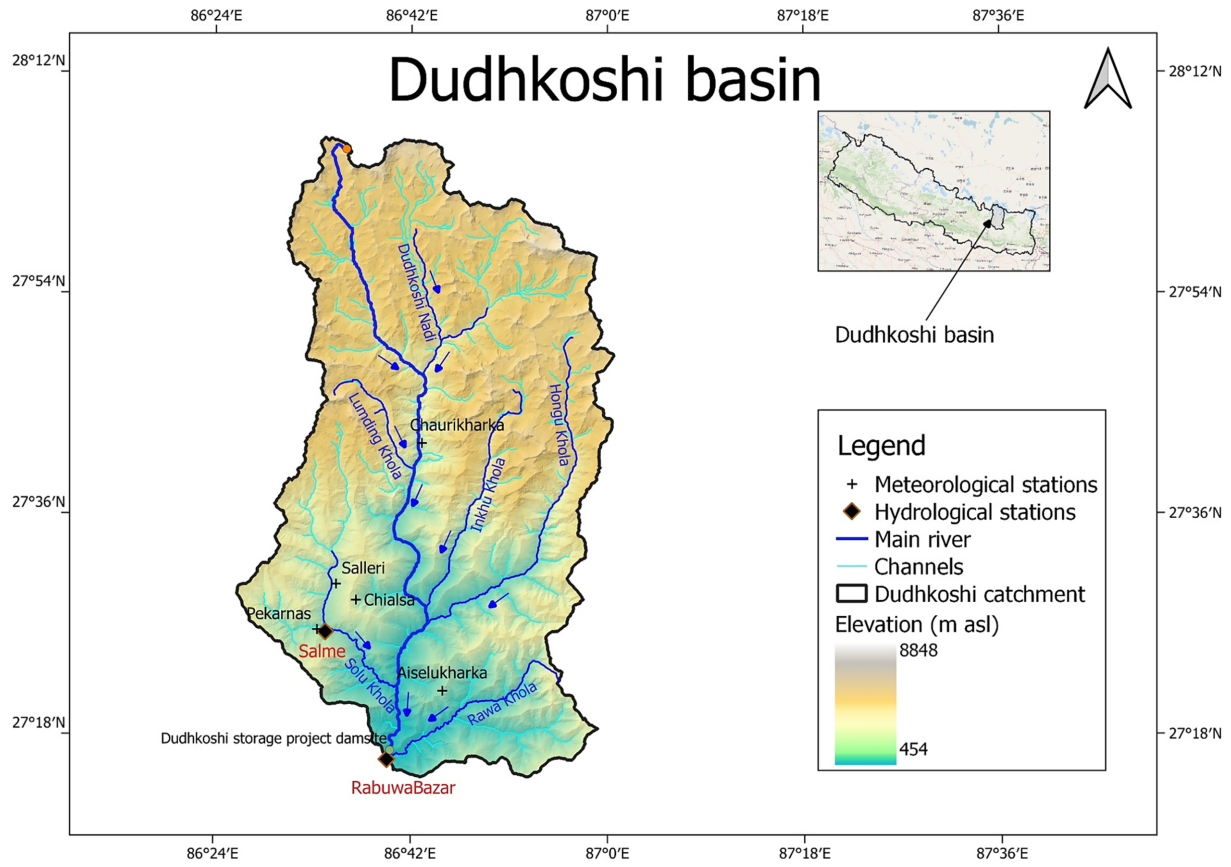

FIGURE 2
Map of Dudh Koshi basin showing location of observation stations. License CC BY 4.0.

selected and analysis conducted, although these decisions are based on the information gathered in steps 1 and 2, and key decisions are clearly communicated with stakeholders. The final steps (5 and 6) reintroduce co-production techniques as technical information is synthesised into useful and usable outputs, supported by appropriate methods of communication with stakeholders. This framework was initially proposed as a theoretical approach to distil climate information. In this study, we demonstrate its use as a practically focused and scalable technique, aiming to support climate service development across a range of applications, sectors and contexts. The paper elaborates how the CIDF was used to structure and guide activities to create scientifically robust and audience-appropriate outputs for hydropower stakeholders in Nepal, with a section dedicated to each step in the CIDF. In section 6 we reflect on the benefits and challenges

of using this framework, and section 7 concludes on the value of the approach for the study in Nepal and subsequent studies that may benefit from this framework.

The study presented is taken from work undertaken in the Asia Regional Resilience to a Changing Climate (ARRCC) programme, funded by the UK's Foreign, Commonwealth and Development Office (FCDO) from 2018 to 2022. The ARRCC programme aimed to co-develop innovative weather and climate services in South Asia, spanning weather warnings and forecasts, to seasonal and longer-term climate change information (Daron et al., 2022). Within the ARRCC programme, the Climate Analysis for Risk Information and Services in South Asia (CARISSA) project focused on improving the uptake and use of climate change information in the region, and particularly in focal countries: Afghanistan, Bangladesh, Nepal, and Pakistan. As described in section 2, engagement in Nepal demonstrated the need for enhanced climate information in the hydropower sector to support resilience in a changing climate.

2 Step 1: Engaging stakeholders to understand the decision context

For a given climate risk, the volume and extent of scientific information that may be relevant to managing that risk can be very large. This is represented by the "extent of information" at the top of the CIDF (Figure 1). To begin to constrain the scope and amount of information that might be relevant to a specific decision context, it is essential to identify what information users and broader stakeholders involved in decisions need to address the risk.

2.1 The engagement process

During the scoping and planning phase for CARISSA, a regional consultation workshop was held in Nepal bringing together programme partners and a range of South Asian stakeholders interested in the application of climate change information (Met Office, ICIMOD, 2019a). Participants included representatives of national government ministries (e.g., water, agriculture), National Meteorological and Hydrological Services (NMHSs), research and academic organisations, regional and international bodies (e.g., SAARC, World Food Programme), and funding agencies. This was our departure point and these initial discussions guided everything that followed within the wider CARISSA project. During the workshop, it was highlighted that there was a need for robust evidence on how climate change may impact at-risk sectors, particularly the water and hydropower sectors in Nepal and Pakistan where knowledge and actionable information was lacking. This formed the basis for subsequent in-person and online engagement activities bringing the Nepal hydropower community together with project scientists to co-produce relevant and reliable climate information to serve priority needs.

The project team organised a series of engagement activities to better understand the decision contexts and narrow down climate information needs from the hydropower community. A set of in-person meetings were organised with a wide range of people in the Nepal hydropower sector, including representatives from government ministries, hydropower companies, and local and international non-governmental organisations took place in August 2019. These engagements helped in understanding specific use cases for climate information as well as build trust between the project team and different stakeholders. A further focussed session was conducted with hydropower stakeholders in September 2019 during the regional workshop on climate services for the water and hydropower sector (Met Office, ICIMOD, 2019b). It was during this workshop that the concept of climate information distillation was first introduced to project stakeholders, with initial feedback supporting the development and testing of the approach.

After these initial engagements, the project team maintained a dialogue through several online meetings with key national stakeholders (e.g., Electricity Regulatory Commission, Nepal Electricity Authority and the Water and Energy Commission Secretariat) to better understand the priorities and challenges faced in the development of hydropower in Nepal and provide regular updates on decisions that were being made about the climate information. This dialogue was sustained while progressing through the steps in the CIDF method.

2.2 Understanding the risks

Engagement revealed that extreme hydrological events (drought, extreme rainfall, and flash flooding) in the current climate and future were of utmost concern to the stakeholders consulted. During drought events, less power can be generated as there is not enough water to force the turbines. During high rainfall events, high river flow leads to significant levels of sediment being carried in the rivers, damaging turbines and other infrastructure, and at even higher levels of flow, whole power plants can be damaged. To limit damage to the turbines, water is diverted away from the turbines during high flow events, decreasing power generation. Stakeholders also explained that it is often cascading hazards (e.g., heavy rainfall leading to flood-induced landslides and impacts to built infrastructure) that are most damaging to the hydropower sector (e.g., Li et al., 2022). These priority concerns were decided based on conversations during engagement activities (section 2.1) where stakeholders had a strong focus on power generation and hydropower infrastructure. Different variables and climate risks may have been prioritised if there were a different set of stakeholders involved in the process, so inevitably the choices reflect the priorities of those most engaged.

'Run of the river' hydropower facilities are dominant in Nepal. These usually have a very small reservoir or pondage above the turbine and therefore are reliant on river flow. Developers and operators struggle with the lack of historical and forecast data of river flow, both in the planning and operational stages. During engagements, they expressed that improved forecasts of high river flow across different lead-times would be useful in knowing when to dredge sediment or close facilities to prevent damage from high sediment load.

From a climate perspective, there was a clear lack of knowledge around how rainfall (and its associated cascading hazards) might change in the future. There was also a need for user training to better understand the uncertainties and limitations of climate model information for use in decision-making. Participants from the workshops agreed to develop a pilot study to create future climate information using the latest available science for a river basin in Nepal, focusing on changes in extreme rainfall events. The Dudh Koshi basin in eastern Nepal was selected as project scientists had prior knowledge and experience working in the basin.

2.3 Understanding the decision context

As well as identifying key risks and concerns, the engagement also elucidated important elements of the decision context. In Nepal, the public-private partnership finance model for hydropower is based on "build–own–operate–transfer" (BOOT) mechanisms (e.g., Hallmans and Stenberg, 1999), where hydropower developers own plants for the first 30 years of operation, after which they are passed to the government. Dialogue revealed that there is a common perception among developers that climate change will only affect the distant future, with limited knowledge that climate extremes are already increasing and having significant impacts now. Stakeholders also referred to the practice of accepting that extreme events will happen periodically and cause inevitable damage to hydropower infrastructure. To manage these risks, operators rely on insurance payouts to fund repairs, often using these opportunities to repair to a higher standard than the initial build. This is preferable to using initial investments to build to higher specifications since this increases costs and reduces the project's Internal Rate of Return (IRR), making it less attractive to investors compared to other available hydropower projects. The financing model, and practices of stakeholders, creates challenges for climate risk management with little incentive to take account of climate change information during the construction of new hydropower plants. And since decision time horizons rarely extend decades into the future, the onus is on government and regulators to consider the long-term resilience of the sector and potential impacts on communities.

The engagements revealed that the landscape of decision making is complex, with conflicting incentives and limited accountability. It was deemed critically important to maintain a dialogue with key national stakeholders and use methods that support the co-production of climate information to achieve greater buy-in and relevance, in line with climate service co-production principles (Vincent et al., 2018; McClure et al., 2024). The continuous dialogue proved even more critical as the COVID-19 pandemic began in 2020, limiting in-person engagement opportunities and diverting interests of stakeholders away from long-term climate change risks.

3 Steps 2 and 3: Analysis aims and data selection

Step 2 of the CIDF is to agree the aims of the analysis and to select appropriate analysis methods, including methodological choices (e.g., variables, timescales etc.). Step 3 is to evaluate and select 'fit for purpose' climate and impact datasets that can be used to meet the analysis aims. Throughout this process, even though the nature of the work was technical and led by the project scientists, following the principles of effective distillation (Jack et al., 2021), assumptions and decisions were made transparent and communicated to stakeholders who were highly engaged through regular dialogue.

3.1 Analysis aims

There were three clear aims that came from the user engagement consultation: (1) increase access to information on current river flow, including information on extreme rainfall events that impact high flow; (2) understand how rare high-impact extreme rainfall might be affected by climate change in the 21st century; and (3) understand how this changing hazard will impact the hydropower sector and what this means for adaptation policy and strategies. The latter requires input beyond climate science to understand how the hazard interplays with hydropower infrastructure to create a risk.

3.2 Selecting climate metrics and data

To inform analyses appropriate to address these aims (Step 2), a literature review was conducted focusing on case studies of historical extreme precipitation events in Nepal and South Asia (Richardson, 2020a). It identified that extreme precipitation events are typically associated with exceptionally heavy localised rainfall over short time periods, which are not captured by large-scale spatial averages and seasonal means. Useful analyses of extreme rainfall in the past and future should therefore focus on the characterisation of rainfall in fine-scale temporal and spatial resolution datasets, where available. The review also identified key climate processes and large-scale atmospheric circulation patterns that drive extreme rainfall events in Nepal and the surrounding region. This information could inform process-based evaluation of available climate models, evaluating model ability to capture important dynamical features of the atmosphere. This step of the process, although informed by aim statements that were co-produced, relied more on expert judgement from the project scientists who understand the climate system and how large-scale atmospheric dynamics influence the occurrence of extreme rainfall.

To further refine what constitutes relevant information, and support decisions on appropriate analysis (Step 2), discussions with stakeholders highlighted a range of extreme rainfall metrics relevant to their widely varying requirements, relating to the safety, security and economics of the hydropower sector. It was collectively agreed that the Rx1day 'wettest day' and Rx5day 'wettest 5-days' metrics (WMO, 2009) during the Nepal summer monsoon season (June–September) would be the most informative of high river flow events, as these metrics are correlated with floods that are known to damage hydropower infrastructure (Bhatt, 2017; Basnyat et al., 2020; Pandey et al., 2021). Stakeholders also revealed that despite a requirement to understand plausible river flow extremes during the design process of new hydropower infrastructure, there was a lack of long-term data records with which to make reasonable estimates of rainfall extremes.

With knowledge of the relevant analysis aims and information of most interest, the study progressed to Step 3 to explore relevant datasets. A review of different historical datasets highlighted a significant challenge in selecting the most suitable datasets; observational-based estimates of precipitation over Nepal lack consensus and show a considerable spread in magnitude (Steptoe, 2022). Without a single best data source, it was decided by the project scientists that the data analysis should incorporate a framework for assessing the credibility of precipitation extremes across Nepal, accounting for the substantial variation in precipitation data. This resulted in a blended consensus estimate of historical precipitation extremes (outlined further in Steptoe and Economou, 2023). Once a more robust historical baseline for precipitation extremes had been established, analysis of future changes could be contextualised.

To estimate the impact of future climate change on extreme rainfall, a focused study by project climate scientists was conducted to identify suitable models and simulations that provide reliable information on future rainfall changes in Nepal (Richardson, 2020b). Project climate scientists built on existing understanding of extreme precipitation during the monsoon season and how well contemporary climate

models are able to represent monsoon dynamics in South Asia (e.g., Knutti et al., 2010; McSweeney et al., 2015). A "process-based evaluation" of available climate models was determined to be a more relevant and robust approach to model dataset selection than simply evaluating the precipitation and its correlation with observation data, given the biases (Steptoe, 2022). The evaluation (Richardson, 2020b) focused on how well available models, including Global Climate Model (GCM) simulations and downscaled Regional Climate Model (RCM) projections, simulate the key processes that drive extreme precipitation in the region. The study first assessed GCM simulations from the fifth Coupled Model Intercomparison Project (CMIP5), since these were used for the boundary conditions of 17 dynamically downscaled RCM projections from the Co-Ordinated Regional Downscaling EXperiment (CORDEX, Giorgi and Gutowski, 2015). These RCM projections and further available downscaled simulations from other studies were also assessed. Focusing on aspects such as monsoon circulation, drivers of intra-seasonal variability (e.g., Boreal Summer Intra-Seasonal Oscillation, BSISO), and other large-scale climate drivers, the study identified a limited subset of suitable models that reliably captured the overall climate patterns important for rainfall processes in Nepal and drive extreme precipitation in the region. This subset then informed the synthesis and further analysis in Step 4.

To make assumptions transparent, dialogue with stakeholders was used to explain that currently available datasets and models were unlikely to provide reliable local-scale evidence. This was due to a lack of models simulating the climate at high spatial resolutions (i.e., kilometre scales) and the presence of complex topography introducing errors into models and observational datasets. The assumption was that national-scale information was possible to achieve, through combining process-based evaluation and use of a wide range of simulations available from global and regional climate model simulations, though recognising the trade-off that national-scale information would have reduced utility for many hydropower stakeholders.

3.3 Hydrological data

An additional step was needed to translate the outputs from the climate model analysis, focusing on rainfall, into more relevant variables for the hydropower sector determined through stakeholder consultation, particularly river flow as this directly links to energy generation and flood risk. The "fit-for-purpose" climate datasets of interest for extreme rainfall and flood events were temporally (sub-daily) and spatially (higher resolution) disaggregated rainfall datasets. The Multi-Source Weighted Ensemble Precipitation (MSWEP) v2.8 global precipitation dataset across Nepal, one of the three suggested by Steptoe (2022), was used to sample the precipitation variability, in combination with available daily, observed precipitation data of 5 stations in the Dudh Koshi basin. Rainfall data from these 5 stations (Chaurikhark, Salleri, Aiselukhark, Pekarnas Chialsa) from 1980 to 2020 were collected from the Department of Hydrology and Meteorology (DHM) and analysed (Figure 2). Discharge data from 1964 to 2020 from Rabuwabazar gauge station was also collected from the DHM.

There are several studies investigating the direct use of GCMs in hydrological modelling [e.g., Vieira and Stadnyk (2023) examining multi-year drought] and multi-model ensembles are found to provide more reliable outputs for basin runoff (Chokkavarapu and Mandla, 2019). However, due to the existence of biases and low resolution of the GCM and RCM datasets, bias correction and downscaling methods are applied to make the use of data as inputs for hydrological modelling (Christensen et al., 2008; Chen et al., 2012). The impacts of climate projections on hydrological processes are highly uncertain (e.g., greenhouse gas emission scenarios, climate models and their outputs, downscaling techniques, bias correction techniques, hydrological modelling), unavoidable and complex (Minville et al., 2008; Refsgaard et al., 2010). The uncertainties associated with GCM and RCM projections propagate in future hydrological and hazard analyses, and so required a sub-sampling strategy informed by the evaluation of climate models for representing precipitation processes in the region (section 3.2).

While the integration of climate data with hydrological datasets is essential to ensure that information can be informative for decisions, it is not without its challenges. A key challenge is that climate analysis and hydrological modelling are conducted at different scales. As described in section 3.1, the climate analysis assessed changes in rainfall across the whole of Nepal, whereas the hydrological modelling was conducted for a specific site within a drainage basin of the Dudh Koshi river—as a pilot study location. Uncertainties are introduced when relating information from one scale to another and assumptions had to be made, including assuming that local-scale changes to extremes will be consistent with the broader national-scale changes; an assumption which is contentious.

Practical challenges were also present. The work was conducted within a time-bound project, yet the hydrological impact analysis had to be conducted after the climate analysis, with a dependency on the climate data outputs. A technical translation step was needed to change the format of the climate data into a relevant format for use in hydrological modelling. Finally, climate model projections are ensemble-based to sample uncertainties, meaning multiple simulations with different initial conditions, parameters, driving models, and emissions scenarios. It is not practical to utilise all simulations, while at the same time sampling uncertainties in the hydrological impacts, so careful sub-sampling strategies are required.

4 Step 4: Data analysis for decisions

4.1 Distilling future climate projections

Following insights from initial engagements and ongoing dialogue, project scientists decided that there was a need for both qualitative scenarios of future changes in extreme precipitation to inform more general users (e.g., policymakers) as well as quantitative data for technical users (e.g., those interested in standards for hydropower infrastructure such as engineers and planners). To generate this variety of information, first a set of scenarios representing the range of future projected changes in Rx1day and Rx5day over Nepal was required. The scientific criteria used for selecting representative model simulations as scenarios included:

- Considering model simulations across different Representative Concentration Pathways (RCPs) and future time periods. This was done to capture uncertainty from human decisions about the rate at which greenhouse gas emissions are reduced.
- Assessing the range of projections from GCM and RCM simulations and, due to the need for higher resolution, selecting RCM simulations spanning the range of projected outcomes. This was done to capture uncertainty linked to how physical processes were represented by the climate models.

- Spanning all three RCMs in the CORDEX WAS-44 set of available model simulations, and a unique selection of GCM-RCM couplings to span the range of available options. This was done to capture the full range of plausible climate futures from the models.
- Prioritising RCM simulations driven by GCMs that best represent large-scale climate processes relevant to extreme precipitation in the region. This was done to narrow down the uncertainty in climate projections by using expert judgement to evaluate which models represented regional climate features most realistically.

Projected changes were calculated for an area-average over Nepal for Rx1day (maximum daily rainfall) and Rx5day (maximum 5-day accumulated precipitation) for the 2050s and 2080s. These metrics were selected as they were of interest to stakeholders. The analysis was not done for sub-national scales as the ability of climate models to accurately simulate differences in extremes at sub-national scales in Nepal data was deemed insufficient by project scientists. Based on the scientific criteria outlined, model simulations were selected, and since future greenhouse gas scenarios are not assigned likelihoods, information across RCP scenarios was compiled together (see Steptoe and Richardson, 2022). The final set of scenarios (Figure 3 for Rx1day) represented lower ("best case"), middle, high, and upper ("worst-case") scenarios, presented as pathways from the present day to the 2080s, equating to little change, moderate increases, large increases, and very large increases in precipitation extremes, respectively.

4.2 Results of hydrological analysis

The hydrological study focused on analysis of extreme flood events in the Dudh Koshi basin as a pilot location. The approach started with analysing observed extreme precipitation (using station and scaled gridded rainfall data) and assessing the temporal (sub-daily) and spatial patterns that corresponded to extreme historical flood events. The rationale for the methodology is that the future climate will change compared to the past, but historical extreme precipitation, and corresponding high flows are useful to assess limitations associated with the climate model projections.

For future precipitation, the future climate datasets were selected using process-based evaluations of the available CORDEX CMIP5 models (Richardson, 2020b; section 3.2). Two CORDEX CMIP5 projections (RegCM4-CSIRO-Mk3-6.0 and RegCM4-CanESM2) were used for RCP 4.5 and RCP 8.5 scenarios, representing the lowest and largest plausible changes in JJAS Rx1day precipitation from the available 17 RCMs (Richardson, 2020b). The projected daily precipitation was then bias corrected and downscaled using historical observed and gridded satellite data. Precipitation simulations from RCMs can be biased relative to observed datasets due to limited process understanding or low spatial resolution and need to be bias corrected and downscaled before being used for climate impact studies (Cannon et al., 2015; Gudmundsson et al., 2012; MoFE, 2019). Catchment scale gridded satellite rainfall datasets were used for the analysis to overcome the limitations of sparsely distributed stations within the basin.

Hydropower and other infrastructures in the past have been traditionally designed using extreme precipitation assuming that the statistics will not significantly change over a long term (commonly known as the stationarity assumption, DOED, 2018). However, because of climate change, the statistics of extreme precipitation patterns are seen to have significantly changed, requiring a non-stationary statistical approach (American Society of Civil Engineers and Ayyub, 2018). Historical Rx1day datasets were computed using a non-stationary rainfall frequency analysis, described in Coles (2001) and Wi et al. (2016). The Rx1day precipitation for different return periods for both the historical and future conditions was further downscaled to 3-hourly temporal and 0.1° x 0.1°spatial resolution and used in the event-based hydrological model to derive the historical and future floods of different return periods. Spatial and temporal variations of extreme rainfall within the catchment are important for countries like Nepal with high topographical variations because it affects local flood hydrographs (Shrestha et al., 2023; Wilson et al., 1979; Zoccatelli et al., 2011). Spatial and temporal disaggregation of the future extreme values were based on MSWEP 3 hourly and 0.1° x 0.1° spatial resolution data (Beck et al., 2019) of a selected historical extreme event of 5 September 2007 observed in the Dudh Koshi basin.

The investigation of Rx1day as a critical factor revealed a wide range of plausible changes in the intensity and frequency of future floods. For example, projections for the 2050s suggest that a 100-year flood event could range from a slight decrease to as much as a 65% increase compared to the historical period (1980–2005), corresponding to the little

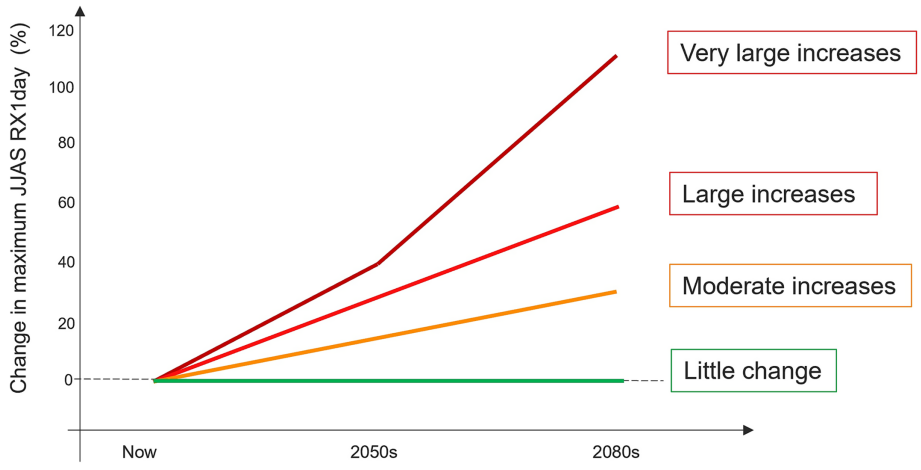

FIGURE 3
Four plausible scenarios of future changes in daily maximum precipitation (Rx1day) during the monsoon season in Nepal, spanning the range of model projections.

change and very large increases in the future Rx1day rainfall (Figure 3). Moreover, floods historically considered to be 100-year events are projected to occur as frequently as every 25 or 30 years in the future (2050s) in the case of projected very large increases in the future Rx1day rainfall. The projected increase in frequency and intensity of rainfall events has important implications for the cost and safety of hydropower projects.

The analysis highlights the high uncertainty in future flood projections, underscoring the need for careful selection and distillation of climate information as demonstrated in this study. Relying solely on historical climate data for design will be insufficient to support resilient design approaches for hydropower projects.

5 Steps 5 and 6: Synthesis, tailoring and communication

The final two stages of the CIDF are about taking the data from the study and presenting it in a way that is useful and usable by the stakeholder group. In Figure 1, this is represented as a further narrowing down of the potential information as it is likely that stakeholders will not need all the data created during the analysis steps. Throughout the analysis process, the project team re-engaged with key stakeholders through a series of online meetings. The meetings provided an opportunity to revisit decision contexts and determine how science and delivery requirements might have changed, as well as sharing the progress on the analysis. Climate information is inherently challenging to communicate and integrate into decisions because of the uncertainties about what the future may look like (Lemos et al., 2012). While the analysis in this study narrowed down the range of plausible futures, there was still a wide range of future change in rainfall extremes (>100% range) and river flow (>65% range) for the Dudh Koshi basin, based on assumptions and methods used.

The project team decided that the best way to deliver this information would be at an in-person workshop, bringing together project partners and stakeholders (Met Office, ICIMOD, 2022) as this would provide an opportunity to co-produce tailored information and work through the uncertainties in a collaborative setting (Vincent et al., 2018). Interactive exercises were run to bridge the uncertainty about extreme rainfall in a changing climate with decision making contexts. These included "serious games" focusing on investments under uncertainty, and the co-production of information through climate risk narratives (CRNs), described in the next sections.

5.1 Learning through serious games

Games that require actions and lead to consequences have been found to be an effective method for helping people engage with complex topics and decisions, including adaptation decisions and the need to consider different plausible future climate pathways (Flood et al., 2018). A game called "Decisions for the Decade" (Red Cross Red Crescent Climate Centre, 2026) was used to support dialogue around long-term investment decisions under climate uncertainties. This particular game was selected as members of the project team had had success using it in other settings where stakeholders, users, and climate information providers have come together to understand the decision space.

Stakeholders were asked to imagine a hypothetical scenario where they were owners of a hydropower plant and had to decide how much to invest in 'profit' or 'protection'. To understand their risks, they were provided with an example dataset to calculate the risk of extreme rainfall. The aim was to make the most profit without the hydropower plant being destroyed. Over a series of rounds, by chance (rolling of a dice) participants could experience an uneventful season, where the number of extreme rainfall events was less than predicted, and a very eventful season, where the number of extreme rainfall events exceeded the baseline. As has been found in previous studies (e.g., de Suarez et al., 2012), by inhabiting the space of a decision maker living in a plausible future climate, some people expressed surprise at the emotional response they felt when their power plant was damaged during a particularly eventful season, and said it would affect their level of risk appetite/aversion and inform how they made decisions in the future. By taking workshop participants through this exercise to consider alternative plausible climate futures for Nepal, people were more comfortable having conversations about what the uncertainty in future projections means to them and how it could be addressed in their particular contexts.

5.2 Climate risk narratives

The workshop utilised Climate Risk Narratives (CRNs; Jack et al., 2020) to help support climate resilience planning decisions, and to embed information on extreme rainfall into future scenarios relevant to hydropower. Grounded in scientific analysis, this approach considers multiple narratives of different plausible futures, spanning uncertainties in future climate and societal responses. The approach is effective to ensure all stakeholder voices are heard and valued in the construction of information, as well as to highlight the uncertainty that exists when thinking about the future. In this study, CRNs were constructed to consider different climate and socio-economic futures, as well as reflect on the present state of the hydropower sector and vulnerability to climate variability. The aim was to prompt thinking and spark discussions around what adaptation decisions are needed to avoid undesirable futures.

Prior to the in-person workshop, a set of three draft narratives were prepared by the project team, informed by stakeholder contexts through ongoing dialogue and initial engagement activities (step 1 of the CIDF) and the construction of relevant climate information (steps 2–4) situating the wider risks facing Nepal's hydropower sector. The first narrative focused on present-day climate risks to the hydropower sector in Nepal, and the other two focused on two alternative futures for the year 2050 capturing plausible scenarios with (a) optimistic and (b) pessimistic assumptions about the future. 2050 was selected as it is within the planning window for new hydropower plants (30 years) but far enough into the future to see significant impacts of decisions about climate, adaptation, and societal change. The analysis of extreme rainfall provided quantitative information to use in the narratives, and it was decided that a moderate and very large increase (Figure 3) in extreme rainfall would constitute the two alternative futures, spanning much of the uncertainty space, though not the very low change scenario. These assumptions were made explicit to stakeholders, consistent with the CIDF approach. The narratives also included technical details about the climate and hydropower sector in Nepal, with the present-day narrative situated in factual information that was used to anchor discussions about plausible futures. The future scenarios included imaginative and speculative details of what everyday life might be like in Nepal in 2050 (e.g., financial and social conditions, cultural events) to promote engagement from participants and foster a sense of creativity about the future, but also to encourage people to think beyond the confines of their experience and domain expertise to consider holistic scenarios that impact people's lives.

The draft CRNs were prepared as 1-page of written text per narrative. In the workshop, each narrative was read aloud before splitting people into small facilitated interdisciplinary groups to discuss the content and suggest edits to the information based on their knowledge, perspectives and areas of expertise, with all voices and perspectives having equal weight. Groups were asked to come up with imaginative names for the narratives, to further summarise the potential alternative futures. It was in these conversations where value was realised, through active listening across scientist and stakeholder perspectives, and mutual agreement on the information to be included in the narratives that was anchored in real-world experiences and diverse knowledge. The process of engaging with different narratives also acted, in part, to disseminate and embed the new extreme rainfall information and knowledge created during the study. A finalised set of co-produced CRNs were shared with all stakeholders who participated in the workshop, synthesising and incorporating the suggested edits of all groups (see Supplementary material).

5.3 Communicating project outputs beyond engaged stakeholders

The final step of the CIDF approach (step 6) is to summarise and communicate information, with the aim of communicating clear, concise, and scientifically robust audience-appropriate outputs. The primary audience for this work were Nepalese stakeholders from the hydropower sector, including those working in government, engineering, and research. Secondary audiences were other stakeholders and academics working in hydropower, particularly in South Asia, although some of the lessons can likely be applied globally, and other academics working in climate services who might be interested in seeing how a theoretical co-production method can be applied to a real-life challenge. More broadly, we wanted to engage people working in science communication, and the general public.

A range of communication methods were used, reflecting the different ways in which information is received and used by different audiences (see Table 1). Most of the outputs were passive communication approaches, however, the in-person workshop provided a forum to discuss and agree next steps among the project team and primary stakeholders to further embed climate information, including the extreme rainfall information created in this study, into hydropower planning decisions. Following the two-day workshop, a series of next steps were collectively identified:

1) Developing a training programme for policymakers and project developers to help build understanding of current and future climate change and how data can be used to inform decisions at all levels. More specific training courses could be added for sub-areas of the sector, such as training on data access and analysis.
2) Improving the visibility, availability and accessibility of both observational data and climate model projections for the region. This could include developing tools which would help non-specialist users to access and interpret the data, as well as work with policymakers to incorporate climate information into official government guidelines.
3) Mandating the inclusion of climate risk assessments when planning new hydropower developments, supported by new guidelines for users.

The ambition of these next steps went beyond the scope of the study, though the engagement continued among stakeholders, supported by subsequent initiatives and projects.

TABLE 1 A summary of how different communication methods were used to reach different audiences.

Group	Audience	Outputs	Justification
Primary audience	Nepalese hydropower stakeholders and academics	• 1-page summary • 3-page summary • Technical report • In person workshop	• general overview • detailed overview • technical details for those who need them (e.g., engineers or academics to reproduce methods) • Forum to discuss findings and agree next steps
Secondary audiences	Hydropower stakeholders and academics from across South Asia	• 1-page summary • 3-page summary • Technical report • Social media posts	• general overview • detailed overview • technical details for those who need them (e.g., to reproduce methods in new region) • raise awareness of work to a broad audience
	Academics working in climate services	• 1-page summary • Workshop report • This paper • Blog and podcast • Social media posts	• general overview • details of how workshop engagement was run • analysis of how theoretical method worked when applied to a real-world problem • general overview for audience with no background in hydropower • raise awareness of work to a broad audience
Tertiary audiences	Science communication professionals	• 1-page summary • Blog and podcast • Social media posts	• demonstrate how complex science can be condensed into informative overview • using two different methods to tell a story about this work and its impact to reach new audiences • raise awareness of work to a broad audience
	General public	• Blog and podcast • Social media posts	• accessible overview of how scientists, policymakers, and practitioners can work together internationally to solve real world challenges • raise awareness of work to a broad audience

6 Discussion and limitations

Analysing, synthesising, and communicating climate information for a given decision context is a non-trivial scientific and technical challenge, and ensuring any information provided is fit-for-purpose requires appropriate framing and engagement with users of the information (Cash et al., 2003; Vaughan and Dessai, 2014). In Nepal's evolving hydropower sector, decision contexts are complex and ever-changing, driven by changing societal contexts, geopolitical influences, government and business forces, and risks and opportunities facing the sector (Shrestha, 2025); climate variability and climate change are only of partial relevance. However, given the trends in relevant climatic impact-drivers (Ruane et al., 2022), such as extreme rainfall, and the projected changes over the coming century, it is timely and prudent for stakeholders acting in different roles across Nepal's hydropower sector to engage with climate information in a robust manner. The CIDF approach described in this paper aims to support the process of engaging with complicated and uncertain climate information, as well as impacts data that is produced using climate data as inputs.

The study has revealed many strengths of adopting and following the CIDF approach. In particular, the recognition that, as highlighted by Vincent et al. (2018), long-term co-production can be pragmatic and flexible. Yet we go further to argue that not all stakeholders need to or should be engaged in every step of the information construction process, and that some steps can be achieved by domain experts (e.g., scientists, policy makers or those representing at-risk communities) trusted to make informed judgements to analyse or synthesise information without needing to explain highly technical concepts to non-scientific audiences. In doing so climate information construction for decision support can be made more flexible and scalable. The CIDF helps climate information providers manage the construction and synthesis of information while recognising the need to maintain a dialogue with stakeholders. Overall, the approach was successful in achieving buy-in from Nepal hydropower stakeholders, and feedback received following the July 2022 workshop found that 14 of 15 respondents found the workshop and engagement activities to be relevant to their work (Agree or Strongly Agree) and two thirds of attendees felt more comfortable using future climate projections to inform their decision making.

There are however limitations for the CIDF approach and its application. The first challenge is a fundamental issue in the development of "needs-driven" climate services and how to understand and articulate needs, since the needs of different stakeholders within a context can vary depending on roles, values and experiences, but also the process of selecting "users" is itself a challenge given competing agendas, interests and power dynamics (Baulenas et al., 2023). In the case study presented, the problem statement was initially defined by those working to support climate adaptation efforts in the region, noting the growing importance of the hydropower sector in Nepal and potential negative impacts if climate change is not accounted for. Defining a more precise problem definition requires engaging the most relevant people and decision-makers, to further articulate climate information needs across government, industry and civil society. However, this method is imprecise and is heavily influenced by those who have the time and enthusiasm to engage, plus necessary scientific literacy to understand how climate information may be used to guide policy and decision processes. As a result of consultation and exploration with stakeholders who volunteered their time, the focus was agreed to be on extreme rainfall changes but alternative views and perspectives (e.g., those of communities living downstream of hydropower facilities) may have resulted in a different articulation of priority needs. The CIDF approach does not provide a solution to prioritise different needs based on understanding of decision contexts and vulnerabilities.

Climate information is only one small part of the decision and information landscape. The CIDF focuses on the hazard and associated physical impacts but does not extend fully to understanding the economic and social impacts associated with these hazards. The framework can also miss the wider context and information landscape that stakeholders are operating in. These challenges could be addressed by working in larger, multidisciplinary teams to bring in a broader range of expertise. This will ensure information that is provided is context-relevant and helps stakeholders understand their risks and opportunities, though comes with a trade-off given the potential for more expense and time associated with convening such teams.

In the analysis step, there can be limitations in accessing high-quality observational and model data, both in terms of access to IT infrastructure and high levels of technical expertise (e.g., Steptoe and Economou, 2023). Working across different spatial scales adds additional challenges. For example, in this study, we understood there was a need to understand and interpret extreme rainfall information at a basin-scale for hydrological analysis, however, the quality of the climate information is poor at small spatial resolutions, increasing errors and uncertainties in the information.

Although the CIDF is a step-by-step approach, we found that the steps were more blurred in practice. For example, we might have learned something in step 2 which would inform the communication resources we developed in step 6. We do not propose that the framework is redrawn to reflect this, but we have tried to show the flow of information through the colour scheme of the diagram and adding an arrow which highlights the importance of maintaining dialogue with key stakeholders throughout the process. We would encourage climate services practitioners to have a multidisciplinary team throughout the process (i.e., containing engagement specialists, and analysis specialists) as well as the specific skills required for each step.

Finally, there were practical restrictions that made it challenging to fully implement the CIDF approach. The first challenge was the reliance on remote engagement for much of the study due to the COVID-19 pandemic and restrictions that arose. Although this was a unique situation, increased online engagement is becoming more prevalent due to funding and institutional carbon restrictions limiting the amount of international travel. In-person engagement is key to building relationships and trust, as well as practically offering opportunities to share knowledge and co-produce information. While dialogue could be maintained online, this was limited by those who had the time and infrastructure in place to engage over video call, and limited opportunities for deeper engagement, or opportunistic engagement. In addition, staff turnover within the project team and with stakeholders, meant that knowledge and understanding was often lost, with a difficulty to re-engage new people and understand personal as well as institutional needs. Resource limitations also hampered efforts to collaborate across a multi-disciplinary team from the UK and Nepal.

7 Conclusion

Through testing and iterating the CIDF in the case study application, we find that the approach achieves the benefits of a co-produced

climate service while offering a practical framing to navigate a complex scientific and decision-making context. In Nepal, the outcomes have been impactful in motivating the need for more stringent guidelines and regulations in hydropower development, to ensure that investments are climate resilient and communities are protected from the changing risks associated with an increasing frequency of extreme rainfall events. The process has also enhanced understanding among climate information providers on the needs of the hydropower sector.

In the IPCC sixth assessment report, it is concluded that "there is high confidence that distilling climate information for a specific purpose benefits from a co-production process" (Doblas-Reyes et al., 2021). Yet there are few studies explicitly implementing a distillation approach and limited guidance for climate service providers in how and when to apply different co-production techniques in climate information distillation. There is a need to further enhance and test theoretical frameworks in real-world contexts, to ensure they can be used at scale and equip climate service providers with the tools to more rapidly synthesise uncertain climate information and provide valuable contributions to climate change adaptation decisions.

This work highlights the importance of conducting and sharing case study examples applied to real-world contexts. While the framework comprises a sequence of steps, the process is not linear but iterative, with a need for engaging key stakeholders throughout the process. Most importantly is the need for flexibility in using the CIDF as a framing but adjusting activities based on the reality of application contexts, such as travel restrictions impacting opportunities for in-person engagement, changing project teams and people involved, and many more unforeseeable factors that inevitably arise in a volatile world. Although co-production and joint decisions have value, some steps in the CIDF can rely on expert judgement informed by stakeholder input, such as the selection of appropriate climate models based on appropriate methods of evaluation. Understanding which decisions need to be made collaboratively, and which can be made through expert judgement, can make the climate services co-production feel more achievable in multidisciplinary teams.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

RO: Investigation, Methodology, Writing – review & editing, Conceptualization, Writing – original draft. JD: Conceptualization, Funding acquisition, Writing – original draft, Supervision, Writing – review & editing. HS: Methodology, Investigation, Writing – original draft, Conceptualization, Formal analysis, Data curation. KR: Formal analysis, Writing – original draft, Data curation, Investigation, Conceptualization, Methodology. MS: Supervision, Writing – original draft, Conceptualization. DB: Formal analysis, Methodology, Investigation, Writing – original draft, Conceptualization. CF: Writing – original draft, Conceptualization, Investigation. SP: Methodology, Formal analysis, Investigation, Writing – original draft. GL: Formal analysis, Investigation, Writing – original draft. DS: Formal analysis, Investigation, Writing – original draft.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2026.1789662/full#supplementary-material

SUPPLEMENTARY DATA SHEET 1

Climate Risk Narratives: An overview of Climate Risk Narratives and explanation of how these were used in this study, including the final co-produced Climate Risk Narratives (present day, positive future, negative future). Reprinted with permission from the Met Office, licensed under © Crown Copyright, https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/business/international/arrcc_hydropower_crns.pdf.

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