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# User Experience/User Interface (UX/UI) design as the backbone of web-based climate service development

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**Abstract.** Design practices are often undervalued in climate service development. We combine a review of 55 operational web-based climate services with User Interface (UI) and User Experience (UX) design literature, using a systematic coding framework to assess how design practices are reported. The analysis identifies recurring gaps between recommended design methods and those documented in climate service development, including the near absence of formal usability testing (1 of 55 tools) and limited reporting on web accessibility (4 of 55). Projects mostly treat design as a secondary layer to refine conventional scientific visuals, overlooking core design workflow elements such as user research, iterative prototyping, and usability testing. We outline practical steps for integrating UI/UX design throughout the development process, helping teams plan design activities, work with designers, and manage expectations across development stages. Two case studies illustrate the workflow in practice. Climate and Water supports water managers assessing climate change impacts on water resources. POSUKHA provides drought forecasts for farmers. Together, they show that while design workflows can follow shared principles, visual and interaction solutions must remain tailored to specific user contexts. We show that UI/UX design is an end-to-end process to ensure usability, trust, and informed decision-making.

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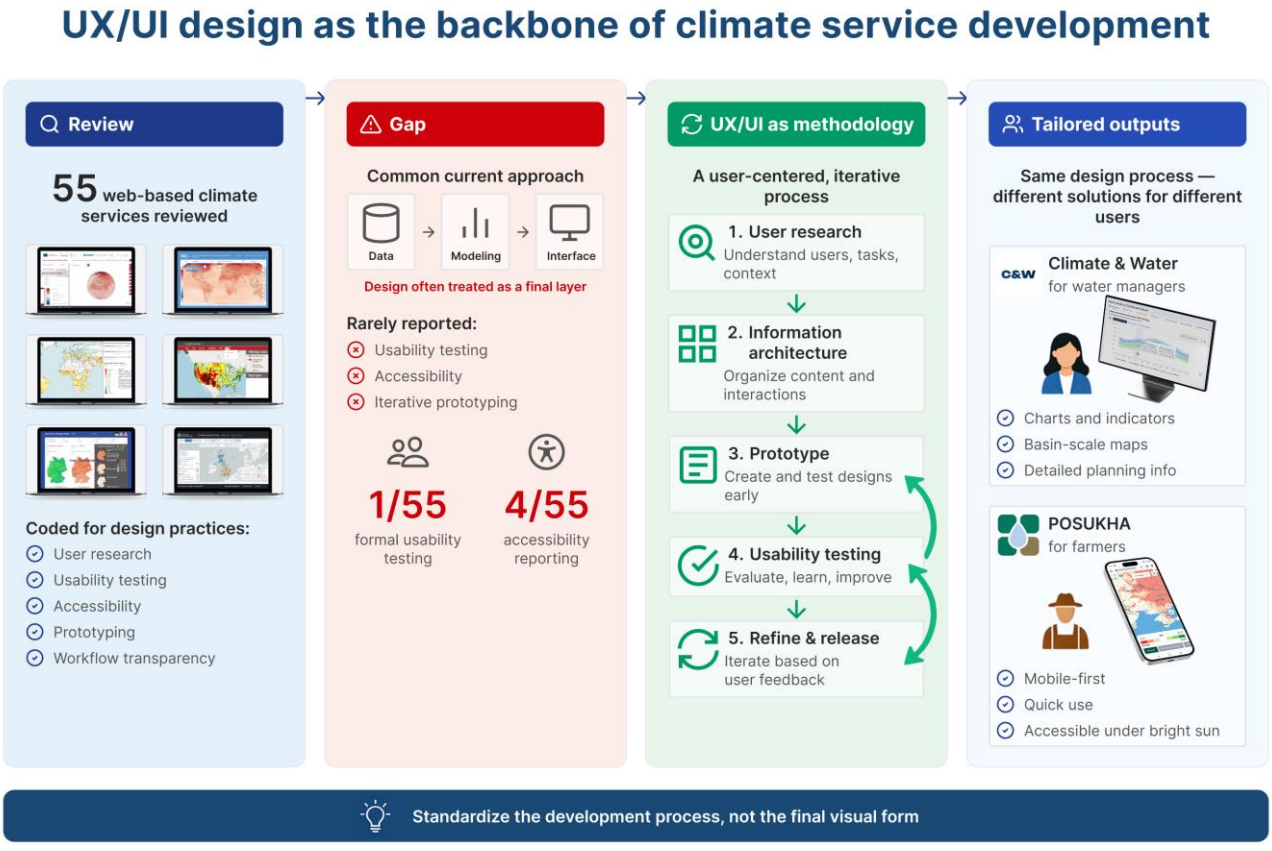


## 1 Introduction

Scientific discoveries are made for people. To make them easier to understand, we need visualizations that simplify complexity (McInerny et al., 2014). This is the task of design (Krug, 2006; Nielsen, 2000). Hierarchy, consistency, infographics, information architecture, simplification, typography, user experience, and color are some of the tools designers use (Cairo, 2016; Hegarty, 2011; Sedlmair et al., 2012; Wilke, 2019) – tools that help make ideas heard and understood.

User Interface (UI) and User Experience (UX) design influence how quickly and accurately users process information, trust it, perceive it, and act on it (Calvo et al., 2022; Hudlicka, 2003; Krug, 2006; Norman, 2013; Oakley and Daudert, 2016; Rosson and Carroll, 2002; Suhari et al., 2022; Weinschenk, 2011). Poor design can undermine even the most accurate data and damage credibility (Kurosu and Kashimura, 1995).

A few studies have examined how design practices can improve the visualization of environmental data (Grainger et al., 2016; Sedlmair et al., 2012; Terrado et al., 2022b). Sedlmair et al. (2012) introduced a nine-stage design study methodology and

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identified common pitfalls at each stage based on reflections from practice. Grainger et al. (2016) reviewed core visualization principles relevant to environmental science and introduced a framework for communicating data in non-expert contexts. Terrado et al. (2022b) examined typical weaknesses in climate service visualizations through the lens of user experience, graphic design, and psychology and offered practical recommendations to enhance their value for decision-making.

Research teams are encouraged to engage designers, psychologists, and communication experts more actively in the development of climate services (Bruno Soares and Buontempo, 2019), yet real-world examples remain rare (Houtkamp et al., 2025). Christel et al. (2018) and Calvo et al. (2022) demonstrated that an end-to-end design approach can bridge communication gaps across disciplines, transform complex probabilistic forecasts into actionable interfaces, and guide both the initial planning of web-based products and the iterative redesign of existing tools through user testing. Harold et al. (2016) showed how insights from cognitive and psychological sciences can improve the accessibility of IPCC figures. Fischer et al. (2022) worked with graphic designers to standardize visual outputs for downstream products, such as brochures and web factsheets. Grainger et al. (2020) tailored an infographic on water resources for three user groups – domain experts, farmers, and citizens – through an iterative, user-centered design process. Lauer (2020) highlighted that the absence of early-stage user research and the failure to involve UX designers ted to a web platform that failed to meet user needs; even a later professional redesign could not reverse the damage, and the tool ultimately remained unused. Other mistakes that occur due to ignoring design practices include focusing solely on technical aspects, neglecting user diversity, defining the target audience and its needs, creating overwhelming visuals, delivering information irrelevant to the audience, ignoring practices that already work well, and prioritizing technique-driven approaches over problem-driven design (Grainger et al., 2016; Sedlmair et al., 2012).

Despite several promising examples, the application of design practices in climate services remains inconsistent and unsystematic (Fleming et al., 2023; Terrado et al., 2022a). Multidisciplinary collaboration and user involvement are often treated as formalities rather than integral components of the development process (Bruno Soares and Buontempo, 2019; Houtkamp et al., 2025). Co-design, in particular, is often misunderstood as a brief, standalone activity, rather than a basis for ongoing interaction and iterative refinement (Fleming et al., 2023). In some cases, principal investigators may be familiar with concepts like co-creation or co-design, but lack a practical understanding of how the design process should be implemented and it is meant to achieve (Bruno Soares and Buontempo, 2019). As a result, many climate service projects follow conventional development models that are not sufficiently user-driven, which contributes to a persistent gap between project outputs and actual user needs (Hewitt and Stone, 2021). Moreover, web accessibility is still largely overlooked in climate service design.

Recent reviews focus on co-production, stakeholder engagement, governance, and impact evaluation in climate services, but give much less attention to how user research informs interface design, how usability is evaluated, or how accessibility is addressed in practice (Fleming et al., 2023; Hewitt and Stone, 2021; Houtkamp et al., 2025; Suhari et al., 2022; Visman et al., 2022). To address this gap, we reviewed web-based climate services, systematically coding how UI/UX design is reported in available documentation. In parallel, we reviewed foundational UI/UX design literature to synthesize design principles relevant to climate services.

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The overall aim of this study is to identify gaps in UX/UI design practices reported in web-based climate service development and provide practical guidance for integrating design throughout the development process. Although the paper focuses on web-based tools, these principles are also relevant to visual climate communication more broadly.

Within this broader aim, we focus on the transition from user research to interface design, where researchers may rely on conventional visualization formats. The tendency is evident in the repeated use of established visual formats, such as those developed for communicating climate projections in IPCC reports (McMahon et al., 2015), which are often reused across tools and platforms (IPCC, 2022; ECMWF, 2024). Rather than engaging directly with users, scientists often rely on conventional norms and prioritize consistency over usability (Dasgupta et al., 2015). Our focused research question is: Can visual solutions for key components of web-based climate services be meaningfully standardized, or must they be tailored to specific contexts and audiences? The review and UX/UI literature inform our discussion of standardisation and contextual tailoring, while two illustrative case studies provide concrete examples of how shared design principles are adapted to different audiences and decision contexts.

## 2 Methods

### 2.1 Literature selection related to individual web climate service development

Given the large and continuously growing number of web-based climate services, it was not feasible to review all existing platforms. To ensure an independent and transparent selection, we first screened web-based climate service platforms listed in seven major aggregator portals of climate tools (Fig. 1). From these aggregators, we identified 38 candidate platforms by applying the following inclusion criteria: (i) the service is operational and accessible at the time of review, (ii) the service provides an interactive web-based interface, and (iii) at least one peer-reviewed article, technical report, or official documentation describing the development of the service is available. Criterion (iii) was intended to exclude platforms for which the available sources described data, technical features, or user guidance, but not the development process of the service itself.

To complement the aggregator-based selection, we conducted additional searches in Scopus and Google Scholar using combinations of keywords such as “web service”, “web-based platform”, “interactive climate tool”, and “climate information portal”. Thus, we included 17 further platforms that were not listed in the aggregator portals but met the same inclusion criteria.

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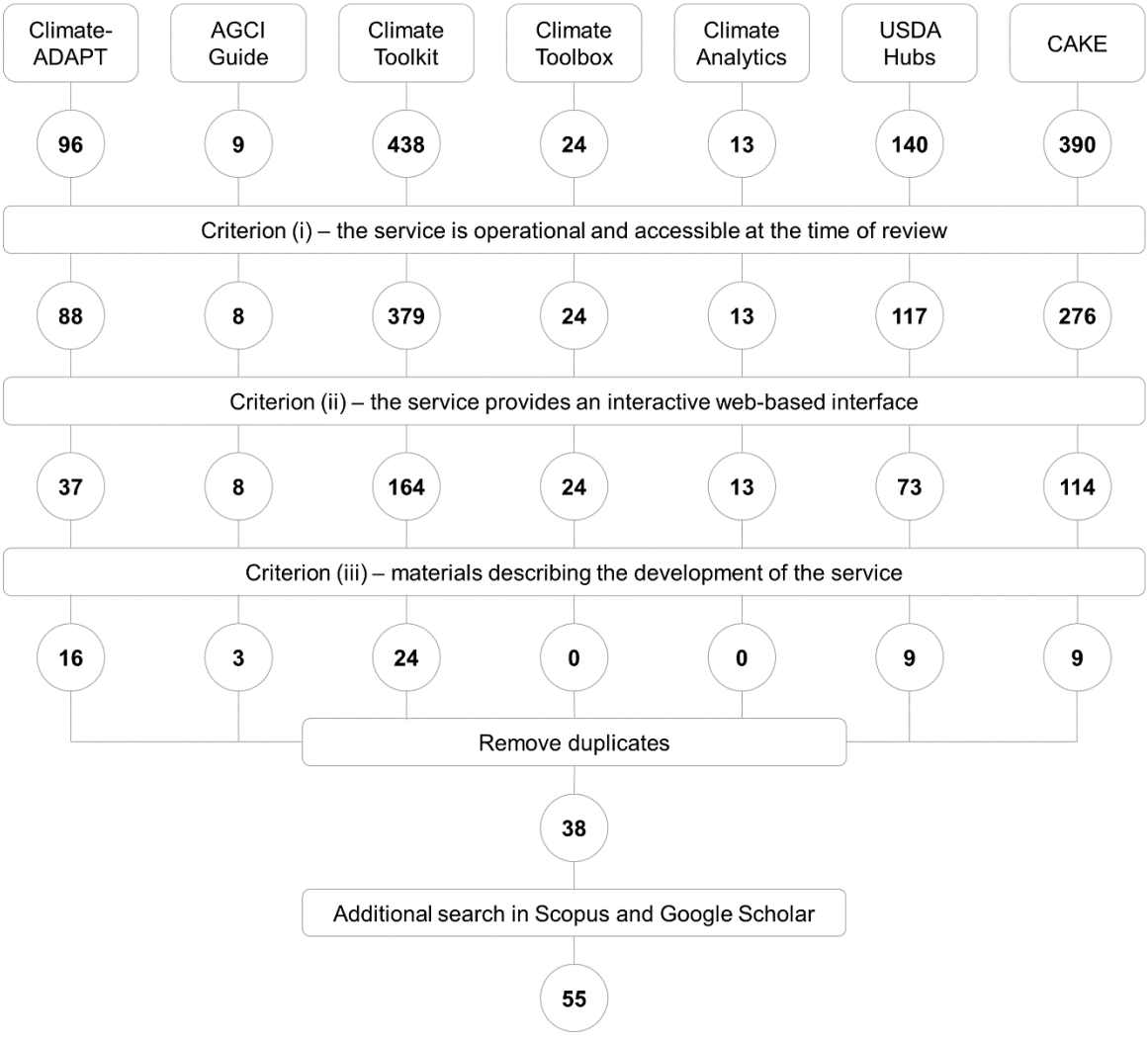


**Figure 1. Flow diagram of web-based climate service selection from seven climate service aggregators: Climate-ADAPT – https://climate-adapt.eea.europa.eu/en/countries-regions/countries; AGCI Climate Portal Guide – https://www.agci.org/projects/climate-portal-guide/portals-for-visualizing-targeted; NOAA Climate Toolkit – https://toolkit.climate.gov/tool; Climate Toolbox – https://climatetoolbox.org; Climate Analytics – https://climateanalytics.org/tools/all; USDA Climate Hubs – https://www.climatehubs.usda.gov/tools; CAKE (Climate Adaptation Knowledge Exchange) – https://www.cakex.org/resources/type/tool.**

The European Drought Observatory (EDO) Map Viewer was considered a boundary case during screening. The platform is operational and interactive, and several documents describe its scientific layers, system functions, and later technical upgrades (Magni et al., 2019). However, the sources we examined did not describe the original interface development process. The literature indicates that EDO evolved from the earlier Drought Monitoring of Africa system, but we did not identify a publication formally describing the creation of EDO itself (Barbosa et al., 2013).

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Appendix A documents the selection process and the source(s) used to describe platform development. For the 55 reviewed platforms, it also reports key descriptive characteristics, including geographic scope, country or region, target sector, primary information type, temporal focus, launch period, and primary audience. Thus, the final set of reviewed platforms reflects a broad and independent sample of operational web-based climate services across different regions, sectors, and application contexts.

### 2.2 Coding framework

Each article was systematically coded using a structured framework designed to capture how UI/UX design practices were reported. The coding scheme included indicators covering user research methods (interviews, surveys, workshops), usability testing, personas or scenarios, design workflow transparency, iterative prototyping, feedback loops, post-deployment evaluation, accessibility and inclusivity considerations.

For each indicator, articles were coded as Yes, Partial, or No, based strictly on explicit statements in the text. Absence of description was coded as "No", even if such practices may have occurred but were not documented. Coding rules are described in Appendix A. The coding framework was refined during an initial pilot phase on a small subset of papers. A binary Yes/No scheme proved too restrictive for cases where a design-related practice was mentioned but not described in sufficient methodological detail. Therefore, a third category, Partial, was introduced to reduce ambiguity and improve the consistency of classification in borderline cases. The content of each material was analyzed with the assistance of ChatGPT version 5.2, which was used only to support structured extraction of relevant information from the documents. Primary coding was conducted by V.O., and all coding decisions were subsequently checked by N.N. All final coding decisions were made by the authors after manual verification of the original source documents.

In addition, the role of UX/UI design within each tool was classified into five categories: (1) central methodological component, (2) supporting element, (3) purely visual or illustrative, (4) afterthought, or (5) not mentioned. This classification reflects whether design was treated as an integral part of the development process or as a secondary or cosmetic concern (Appendix A).

The review captures how design practices are reported, not necessarily how they were conducted in practice. Therefore, results reflect transparency and methodological visibility rather than an absolute assessment of design quality. Nevertheless, reporting practices are critical, as undocumented user research and usability testing cannot be evaluated, reproduced, or transferred to future projects.

### 2.3 UX/UI design literature relevant to web-based climate services

In addition to reviewing operational web-based climate services, we reviewed UX/UI design literature to clarify the role of the designer, identify essential stages of the design process, and synthesize key recommendations and recurring omissions that are particularly relevant to climate service development. The purpose of this review was not to provide a comprehensive overview

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of UX/UI research, but to contextualize the empirical findings from the web-tool analysis and to identify established design practices that are frequently underreported, weakly implemented, or misunderstood in the climate services domain.

Searches were conducted primarily using Google Scholar, complemented by reference snowballing from key publications. As an initial step, we screened articles published in the journals Climate Services and Environmental Modelling & Software to identify relevant studies and to familiarize ourselves with commonly used terminology in the context of climate service design and visualization. Based on this exploratory screening, we refined the search vocabulary and subsequently conducted targeted searches using combinations of terms such as “visuals”, “visualization”, “user-centered design”, “user experience design”, and “user interface design”, in conjunction with climate-, environmental-, and decision-support-related keywords.

Recurring concepts, methods, and recommendations were grouped into five analytical domains that structure the subsequent sections of this paper: (1) design workflows, (2) user research and participatory design methods, (3) user interface and interaction design for complex scientific information, (4) practical design recommendations for web-based climate services, and (5) web accessibility and inclusivity. To address the focused research question, we draw on the coding of reported user research and its influence on design decisions, the synthesis of UX/UI guidance, and illustrative accounts of how user insights informed interface choices in the two case studies.

## 3 Results: literature review

### 3.1 Patterns in reported UX/UI design practices

Section 3.1 examines how UX/UI design practices are reported across the reviewed climate services. Overall, the sample shows frequent reference to problem framing and target users, but much weaker reporting of usability evaluation, accessibility, and the translation of user input into concrete design decisions. Only 14% of the reviewed web-based climate services provided published materials of their development process (Fig. 1). The following subsections summarize the main patterns.

Across the reviewed sample, we did not identify a clear temporal trend in the reporting of design practices between tools launched before 2015, in 2015–2019, and in 2020–2025 (Appendix A). We also found no statistically significant differences by geographic scope, target sector, or primary audience. The main exception was the hazards and early warning sector, where design was more often acknowledged as a methodological component. Older tools also more often reported feedback loops.

#### 3.1.1 User research is common but weakly operationalized

Stakeholder consultation is common in climate service development, especially at the problem formulation and content definition (32 out of 55 reviewed web tools) (Table 1; Appendix A). However, interviews, surveys, and workshops are often mentioned only briefly, with little detail on how they were conducted, who participated, or how the findings informed interface design. User personas and usage scenarios are rarely created, despite their central role in guiding interface structure, interaction design, and information prioritization (5 out of 55).

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**Table 1. Frequency of reported user-centered design practices across reviewed web-based climate services.**

| **Design practices** | Yes | Partial | No |
|---|---|---|---|
| User research mentioned | 32 | 7 | 16 |
| Interviews | 9 | 0 | 46 |
| Surveys | 10 | 1 | 44 |
| Workshops / co-design | 20 | 10 | 25 |
| Usability testing | 1 | 17 | 37 |
| Personas scenarios | 5 | 1 | 49 |
| Design workflow transparency | 27 | 16 | 12 |
| Problem framing stage | 52 | 0 | 3 |
| Target user definition | 53 | 1 | 1 |
| Mockups iterative prototyping | 22 | 7 | 26 |
| Testing feedback loops | 22 | 15 | 18 |
| Post deployment evaluation | 23 | 5 | 27 |
| Accessibility & inclusivity reporting | 4 | 21 | 30 |
| Tool publicly available | 54 | 1 | 0 |
| Data accessibility described | 54 | 1 | 0 |
| UX/UI role[a] | 12 | 41 | 2 |

[a] "Yes" indicates that the UX/UI role is treated as a *central methodological component*. "Partial" combines the categories *supporting element (mentioned but not integrated), purely visual/illustrative,* and *afterthought*. "No" indicates that UX/UI design is *not mentioned*.

Only a few tools document how user research directly influenced design decisions, from workflows and navigation to visual and interaction choices (Blumenthal et al., 2018; Bojovic et al., 2021; Houtkamp et al., 2021; Goosen et al., 2014; O'Dwyer et al., 2018; Photiadou et al., 2021; Wilson et al., 2022). In most cases, engagement with users is used to select what information should be provided (e.g., variables, indicators, spatial scales), but not how that information should be structured, visualized, or interacted with (Appendix A).

This distinction matters for climate service effectiveness. When user engagement shapes content but not interface logic or visual prioritization, a service may remain scientifically relevant while being harder to interpret and use in decision contexts (Grainger et al., 2016; Houtkamp et al., 2025; Lauer, 2020). In such cases, the gap is not in the data itself, but in how the service translates data into usable decision support.

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### 3.1.2 Co-design is frequently misunderstood

Workshops are the most popular form of collaboration, but they are usually used to gather input or disseminate results rather than to co-develop interface structure, workflows, or usability criteria (30 out of 55, Table 1). Thus, activities described as “co-production” or “co-design,” often do not involve collaborative design in a strict sense.

Only a few studies use workshops as one of the methods of user research that clearly links workshop outcomes to later design changes (Barker et al., 2022; Blumenthal et al., 2018; Bojovic et al., 2021; Houtkamp et al., 2021; Goosen et al., 2014; O’Dwyer et al., 2018; Photiadou et al., 2021). In these cases, workshops have a clear structure, sequence, and traceable influence on interface layout.

This ambiguity is not only terminological. When consultation, dissemination, and co-design are presented interchangeably, it becomes difficult to evaluate whether users actually influenced workflows, navigation, or interface logic. As a result, the literature may overstate the degree of user-centeredness in climate service development while providing limited evidence that design decisions were genuinely shaped by users (Bruno Soares and Buontempo, 2019; Fleming et al., 2023). "Co-design" labels often hide provider-led agendas where the scientific "standard" is non-negotiable (Bruno Soares and Buontempo, 2019).

### 3.1.3 Usability testing is rarely reported

Formal usability testing is exceptionally rare among the reviewed tools (1 out of 55) (Houtkamp et al., 2021). In UX/UI design, usability testing involves task-based evaluation, think-aloud protocols, expert usability review, or measured usability indicators. However, even for long-running platforms, usability evaluation is usually implicit rather than formally documented.

Many papers report that interfaces were “improved” or “made more intuitive”, but do not describe how these claims were evaluated. In many cases, usability is assumed on the basis of long-term use or policy relevance, rather than being assessed through direct observation of user interaction. This indicates a gap between established usability methods in human-computer interaction research and their application, or at least their reporting in climate service development.

Without explicit usability evaluation, there is limited evidence that users can correctly navigate the interface, interpret outputs, or distinguish key signals from background complexity (Hegarty, 2011; McMahon et al., 2015; Swart et al., 2017). This weakens confidence that scientifically robust tools are also effective in practice for non-developer audiences.

### 3.1.4 UX/UI is commonly treated as a supporting layer

Design is commonly used to communicate conventional scientific visuals rather than to shape how users reason with information or act on it. As a result, interface design responds to technical and modelling requirements, such as functionality, performance, or output visualization, with limited attention to interpretation or use.

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This pattern is especially visible in early development stages. Most tools clearly define the problem they address (52 out of 55) and their intended users (53 out of 55) but, they rarely explain how these early insights translate into concrete design choices. Descriptions of how user needs inform layout, interaction logic, or visual structure are often absent.

Only a small number of tools treat UX and UI as a central methodological element (12 out of 55). In these cases, interaction design, cognitive effort, and clarity are explicitly linked to trust, interpretability, and decision support. For most tools, however, design remains implicit, subordinate to modelling and data-processing workflows, or limited to a visual delivery layer.

This imbalance has practical consequences. Considerable effort may be invested in data processing and modelling, while less attention is given to how users encounter, interpret, and apply the resulting information. The result can be tools that maintain scientific credibility but remain difficult to use effectively in practice (Calvo et al., 2022; Grainger et al., 2016; Lauer, 2020).

### 3.1.5 Accessibility and inclusivity are rarely formalized

Accessibility and inclusivity considerations are among the least systematically reported aspects of climate service design (4 out of 55). Some tools indirectly address cognitive accessibility through simplification, guided interpretation, or narrative structure, but explicit references to web accessibility standards (e.g. WCAG), colour-vision safety, assistive technologies, or inclusive design principles are rare (Barker et al., 2022; Chennault et al., 2020; Grocholski et al., 2022; Merten et al., 2014).

In most cases, accessibility is not addressed as an explicit design objective. Instead, it is assumed to follow from general design quality or narrowly defined as "data access" rather than inclusive usability.

Weakly formalized accessibility limits who can use the service efficiently, under what conditions, and with what level of confidence (Kim, 2023; Terrado et al., 2022b; Vaughan and Dessai, 2014). The lack of localization and attention to disabilities creates a "barrier to uptake" for the very communities climate services are meant to protect.

### 3.1.6 Design processes remain less transparent than data and models

A consistent pattern across the tools is asymmetric transparency. Climate services typically provide extensive documentation of data sources, models, uncertainty, and reproducibility, while offering minimal transparency regarding design workflows, user research methods, or interface evaluation.

Even in tools that demonstrate strong user engagement and long-term refinement, the design process often remains implicit. This makes it difficult to assess reproducibility, transferability, or methodological rigor and reinforces the view of UX/UI as secondary to “core” scientific work.

This asymmetry also limits cumulative learning. When modelling choices are documented but design choices are not, future teams can reproduce data workflows more easily than they can reproduce effective user-facing solutions. As a result, lessons about interface structure, interaction design, and evaluation remain difficult to compare, reuse, or build upon across projects (McInerny et al., 2014; Roth, 2019; Houtkamp et al., 2025).

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### 3.2 Approaches to climate service development

Climate service development is commonly framed around two approaches: demand-driven and top-down (also termed supply-led or capability-driven). The literature increasingly favors demand-driven approaches due to the limitations of top-down models (André et al., 2021; Hewitt and Stone, 2021). The latter assumes that scientists or developers independently decide what data and formats users need. In reality, user requirements, tasks, and usage contexts often differ from researchers' assumptions (Suhari et al., 2022). Scientifically accurate data alone does not guarantee understanding or action (Harold et al., 2016).

By contrast, the demand-driven approach focuses on users' actual needs, context, tasks, and constraints (André et al., 2021; Jacobs and Street, 2020; Terrado et al., 2022b). It helps avoid wasting resources, builds trust, and increases the likelihood that the service will be used in decision-making. McInerny et al. (2014) caution that visualizations created without user involvement can mislead or even undermine trust in the information. They therefore recommend involving users throughout the process, from selecting visualization formats to defining the messages that service should conveyed.

### 3.3 Design workflow

Web service development follows a workflow that includes problem framing, user research, information architecture, mockup creation, prototyping, iterative feedback, and release (Fig. 2). For a more in-depth discussion of problem framing, including domain understanding, task analysis, and data characterization, see Sedlmair et al. (2012).

A common mistake is skipping a clear information architecture, which involves organizing content around user tasks and mental models (e.g., language, prior knowledge, and workflow expectations) (Plaisant et al., 1998). Instead, research teams may rush into mockup design or assume that a simple flowchart handed to a web developer is sufficient.

While a flowchart can represent the information architecture, it should only be created after user research, analysis of comparable solutions, and clarification of technical and legal constraints. The architecture is then refined into a detailed mockup. Tools like Figma allow teams to create interactive mockups for user testing. The mockup should be handed over to developers only after testing and revision. The next step is to build a basic working prototype that allows users to perform core tasks. This prototype is refined and re-tested through an iterative process, as time and resources permit (Oakley and Daudert, 2016; Redish, 2012). Testing should never be postponed until the final version. However, even the final product may continue to be updated during post-project maintenance.

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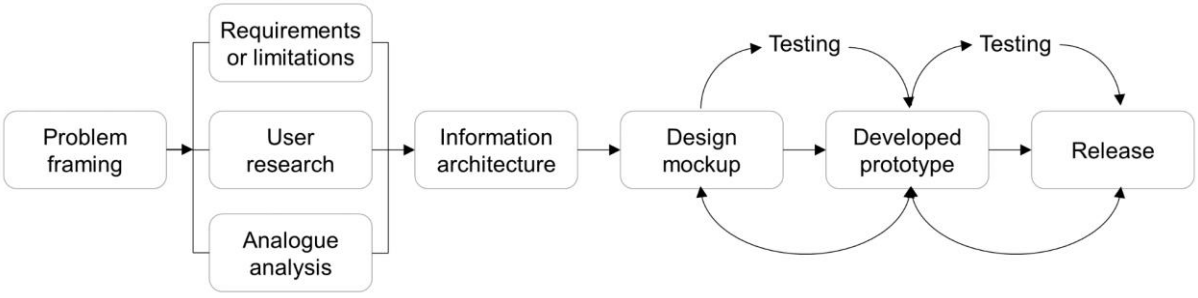


**Figure 2. The workflow of web-based climate service development.**

### 3.4 User experience research

Design begins with empathy, that is, understanding users' needs and expectations. Studying user experience is a necessary first step in developing climate services, as it lays the foundation for tools that are not only technologically effective but also relevant in users' daily work (Hewitt et al., 2021). As Sedlmair et al. (2012) note, the early stages of the design – "discover" and "learn" – require deep immersion in the usage context, audience needs, and constraints. Without direct interaction with users, teams risk of creating products that reflect developers' assumptions rather than actual audience needs (Swart et al., 2017). This is especially true for the visual layer of a web service: even high-quality data can become ineffective if it is presented in a way that doesn't align with the user's visual thinking and expectations (Terrado et al., 2022b). Therefore, user experience research must precede mockup creation, interface development, and visualization design.

#### 3.4.1 Identify your target audience

While your data may be used by specialists, colleagues, or researchers, they are often not the final decision makers, and this distinction matters. As McKay (2013) notes, attempts to design for "everyone" often result in solutions that work for no one. Teams should therefore clearly define target groups and consider their expectations, experience, and context.

To do this, start by defining typical user, including their age, background, education, and skills. One useful method is to create a persona: a fictional but data-based profile of a typical user from a specific audience segment (McKay, 2013; Redish, 2012). Personas are built from interviews, surveys, and observations and typically include a name, short description, key traits, and the common tasks under specific circumstances. They help teams avoid designing for an abstract or "elastic" user whose characteristics shift with each team member's assumptions. Well-defined personas help ground decisions about features, design, and priorities in real usage scenarios, making the final product more relevant and user-friendly.

#### 3.4.2 Conduct user interviews

User interviews are open conversations with the people who will use the product or service (Nunnally and Farkas, 2016). The goal is to understand their needs, experiences, and challenges, not to evaluate them. They are not interrogations or a rigid questionnaire. Sometimes one thoughtful answer reveals more than ten short responses. Interviews help uncover how users

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think, what they care about, and what challenges they face in the context of the service. They are especially useful for answering questions like:

- What problem does the service need to solve?
- For which users?
- How can the solution become useful and easy to use?

In short, interviews are a way to listen.

The number of respondents is usually inversely proportional to how well the team understand the user experience (Francis et al., 2010; Malterud et al., 2016; Sauro and Lewis, 2016). Typical sample sizes range from 5 to 100. If the service is designed for colleagues, fewer respondents and less adaptation of the visualization may be sufficient. But if the same data are presented to farmers, more user insight – and thus more respondents – is needed to tailor the visualization appropriately (Diemand-Yauman et al., 2011).

### 3.5 User interface

Effective visualization in climate services depends not only on the accuracy of the underlying data, but also on how information is prioritized, explained, and made actionable for specific users. The main recommendations synthesized from the reviewed literature are summarized in Fig. 3, which groups them into four domains: communication and storytelling (Bruine de Bruin et al., 2021; Cairo, 2016; Calvo et al., 2022; Center for Research on Environmental Decisions, 2009; Christel et al., 2018; Kraak et al., 2020; McInerny et al., 2014; Oakley and Daudert, 2016; Roth, 2021; Sedlmair et al., 2012; Suhari et al., 2022), structure and consistency (C3S and WMO, 2025; Courtney and McNeal, 2023; Segel and Heer, 2010; Yablonski, 2025), content clarity (Calvo et al., 2022; Dasgupta et al., 2015; Grainger et al., 2016; Hewitson et al., 2017; McKay, 2013; Muehlenhaus, 2013; Oakley and Daudert, 2016; Terrado et al., 2022b; Weinschenk, 2011), and user interaction (Calvo et al., 2022; Norman, 1988; Terrado et al., 2022b). The principles summarized in Fig. 3 are explained in more detail in Appendix B, which contains the extended discussion and examples behind this synthesis. Together, these principles help reduce cognitive overload, improve interpretability, and support more informed use of climate information.

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**Figure 3. Main principles of effective web interface synthesized from the reviewed literature.**

### 3.6 Recommendations for web-based climate services

#### 3.6.1 Visual hierarchy – emphasize what matters, mute what does not

Design should distinguish layers of information and their relative importance. In interactive dashboards or geographic interfaces, visual elements should be prioritized according to the expected tasks of the target audience. For example, a minimalist light-grey basemap effectively highlights the thematic layer (Muehlenhaus, 2013), while selected elements can be brought to the foreground to support user orientation. A growing number of map toolkits offer multiple base maps and allow specific layers (e.g., cities, rivers, roads, etc.) to be edited and repositioned, including above the main thematic content (Fig. 4A) (Osypov et al., 2024; Svala, 2025). At the same time, adding markers for airports, schools, and similar features may be excessive and visually overwhelming. When conducting user research or testing, ask which elements users rely on to complete specific tasks (Oakley and Daudert, 2016).

Prioritization applies to charts and graphs as well (Sect. 3.6.3).

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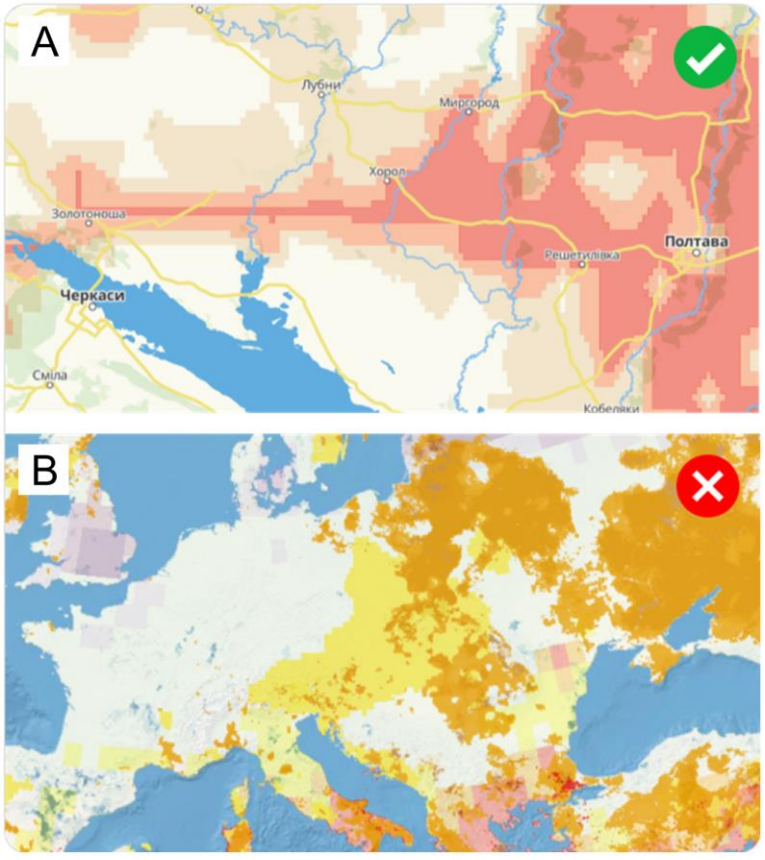


**Figure 4. Drought maps across Ukraine and Europe. A – To assess droughts, farmers navigate using administrative boundaries, rivers, and roads. B – A map without such reference elements is inconvenient for farmers (Sources according to the order of the images:** POSUKHA (n.d.)**;** European Drought Observatory (n.d.)**).**

### 3.6.2 Legend design principles

A legend should be immediately understandable and unambiguous. Its placement, color choices, and number of categories must be tailored to the specific data and visualization goal (IBM, n.d.) (Fig. 5). Avoid using a legend if the data can be clearly understood without it (Fig. 5B).

There is no universal rule for legend placement on maps or charts. Instead, consider how quickly users can learn to use the legend in the chosen position. For instance, if legends in figures are consistently placed to the right in most figures, but one is positioned at the bottom, this inconsistency increases cognitive load. Minimize the distance between the legend and the chart or map to reduce the effort needed to match colors or symbols to data values.

The legend should be perceptually uniform, meaning that equal steps in the data correspond to equal perceived differences in color across the scale. This prevents visual distortion and preserves the integrity of the data representation (Crameri et al., 2020). A common mistake is the use of rainbow color scales, which are inherently perceptually non-ordered and/or non-uniform, regardless of variation (Crameri et al., 2020).

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335 To avoid such pitfalls, the Scientific Colour Maps library was developed and can be integrated into Python, R, QGIS, and other platforms (Crameri, 2018). Other tools like ColorBrewer offer a web-based interface for selecting appropriate colormaps (Brewer et al., 2013). Crameri et al. (2020) and Crameri and Hason (2024) also review freely available colormap toolkits and guidelines on when and how to use different types.

Ideally, the number of categories in a legend should not exceed seven. If possible, reduce it to five, as larger numbers of colors 340 are harder to distinguish and memorize, especially under time pressure or for users with cognitive limitations (Fig. 5C) (Kraak and Ormeling, 2021). Excessive divisions or continuous gradients can confuse users and impair data interpretation (Fig. 5D).

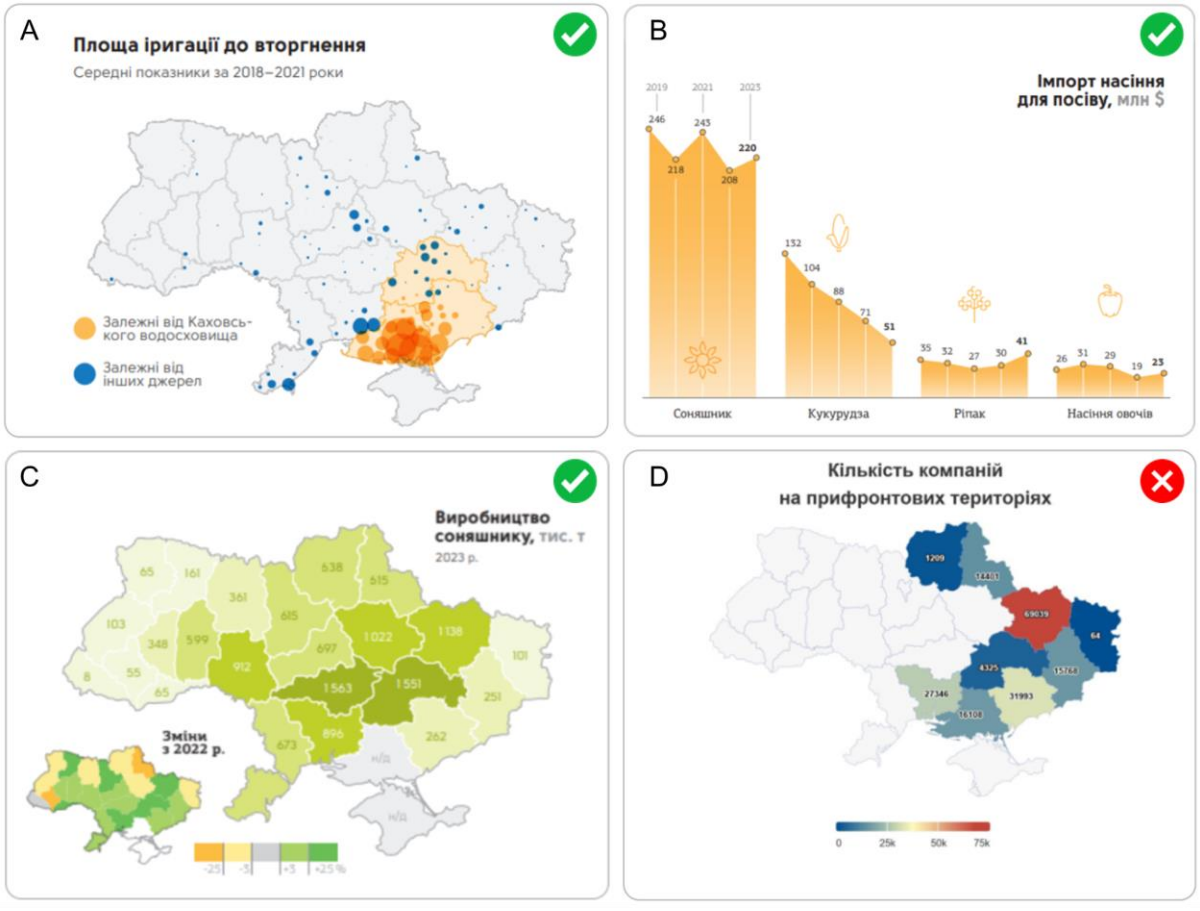


**Figure 5. Examples of flexible legend design depending on data and visualization goals. A – Irrigation area before the destruction of the Kakhovka Dam: only zones dependent and independent of the reservoir are shown, with no additional detail.**

345 B – Visualization presented without legends. C – Five intervals are sufficient to convey change. D – Uneven spacing in legend bands can lead to inconsistent data resolution across ranges, which may result in misinterpretation (Sources: images A, B and C – Top Lead et al. (2025); image D – “Reconstruction of Zaporizhia” (n.d.)).

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### 3.6.3 Chart design principles

An effective chart requires more than data accuracy; it must also communicate clearly and prompt the desired action (Few, 2004; Harold et al., 2016; McInerny et al., 2014). When viewers spend too long interpreting a figure, they may miss its message entirely and even lose sight of the broader context of the work (Daron et al., 2021; Kause et al., 2020; Midway, 2020). Thus, chart design should begin with questions such as: What tasks should the graphic enable? What should it reveal? (Cairo, 2016). Several resources can support choosing graphic forms (Ribecca, n.d.), organizing the display (e.g., by value, alphabetically, or by other criteria) (Cairo, 2016), and formatting chart elements (Wilke, 2019).

Climate scientists often take the lead in developing climate services, but their approach to visualization can unintentionally reduce its effectiveness. Dasgupta et al. (2015), working with visualization designers, identified several recurring issues that limit the clarity and communicative power of scientific visuals created by climate scientists:

- Plot overly detailed data (e.g., daily/monthly) even when the goal is to show annual trends.
- Prioritize data completeness over visual clarity or interpretability.
- Include all available data due to the effort invested in its extraction.
- Design visualizations for self-use, not for external audiences or decision-makers.
- Use overly complex color maps, often misaligned with the intended message (e.g., rainbow scales instead of effective divergent schemes for highlighting extremes).

To address these issues, Dasgupta et al. (2015) proposed the following practical guidelines:

- Keep the audience in mind by designing for external users rather than only for personal analysis.
- Direct attention to salient elements by using visual cues such as contrast, positioning, or annotation to guide the viewer's focus to the most important features.
- Make the message clear and self-contained by ensuring that the visualization communicates its meaning through highlights, captions, and contextual text.
- Use color meaningfully so that it reflects data semantics. For example, a gray trend line may blend into the background instead of standing out.
- Be cautious with software defaults, as many ineffective charts result from settings that do not align with best practices for communication.

### 3.6.4 Visual communication of uncertainty

Users need clarity about what is known, what is uncertain, and how data was processed or selected (McInerny et al., 2014; Suhari et al., 2022). Communicating this through visualisations can be challenging, but it is vital for informed decision-making.

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There are no universal conventions for visualizing uncertainty (Daron et al., 2021; McInerny et al., 2014), partly because uncertainty must be presented in ways that fit the specific task and avoid unnecessary complexity (Kause et al., 2020). Even when tasks are similar, people tend to prefer familiar formats for receiving information about uncertainty. Different organizations become accustomed to specific formats, which makes a one-size-fits-all solution difficult (Taylor et al., 2015).

Thus, teams should identify charts that are already familiar to their audience. Several studies have examined how climate-conscious organizations outside the climate science community perceive climate information. Lorenz et al. (2015) showed that people tend to rely on visual formats they believe they understand best rather than those they actually interpret most accurately. Greis et al. (2015) identified that simple line charts with confidence intervals and bar charts remain the most intuitive formats. By contrast, more complex visualisations, such as box plots or percentile-based maps often cause confusion (Kause et al., 2020). For example, nearly two-thirds of respondents found box plots unclear, and 79% struggled to interpret 10-90th percentile rainfall maps, partly because they did not understand what percentiles mean (Kause et al., 2020). One proposed compromise was to explain in the figure caption, using familiar wording, what the percentiles represent. Organizations also tend to focus on the most likely outcome or on worst-case scenarios when evaluating risks (Taylor et al., 2015). Ultimately, direct engagement with the audience remains essential for selecting the most effective representation.

### 3.7 Web accessibility

Web accessibility goes beyond accommodating users with visual, auditory, or other disabilities; it ensures that all users can accurately perceive and understand information. While making maps and charts fully accessible can be challenging, their design should still aim for clarity and inclusivity (Mason et al., 2024). Detailed guidance is provided in the Web Content Accessibility Guidelines (WCAG) 2.1 (World Wide Web Consortium, 2025). This section focuses on aspects most relevant to web-based climate services.

#### 3.7.1 Fonts

Use a contrast ratio of at least 4.5:1 for regular text and 3:1 for large text (18 px or larger) against the background (World Wide Web Consortium, 2025). There are various free tools and plugins available for checking contrast (e.g., https://www.tpgi.com/color-contrast-checker/).

Pay attention to the units used in the editing software. For instance, Microsoft Word measures font size in points (pt), while design tools like Figma use pixels (px) by default. For reference, 12 pt ≈ 16 px, 14 pt ≈ 18.66 px, and 18 pt ≈ 24 px.

Avoid placing text over complex or non-uniform images. The contrast between the text and different parts of the background will vary, making the text harder to read and increasing cognitive load.

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### 3.7.2 Color scales

As noted above, recommended color libraries should be perceptually uniform, perceptually ordered, readable in black-and-white print, and accessible to users with color vision deficiencies (Crameri, 2018; Crameri and Hason, 2024).

### 3.7.3 Text, captions, and hyperlinks

Make text content clear and understandable, as it must be programmatically accessible for screen readers to translate or read aloud (Kim, 2023). Define technical jargon and uncommon terms, and avoid metaphors or ambiguous phrases (World Wide Web Consortium, 2025).

When developing web content, include alternative text for all informative visualizations that are not purely decorative. The descriptions are invisible to users but essential for assistive technologies. Alt-text typically does not exceed 150-200 words and should clearly explain the content of the visual.

Hyperlink text should clearly indicate where the link leads and what the user can expect to find (Fig. 6A) (World Wide Web Consortium, 2025). Links should be highlighted by color and/or underlining. Vague hyperlinks like "Click here for more information" are poor practice.

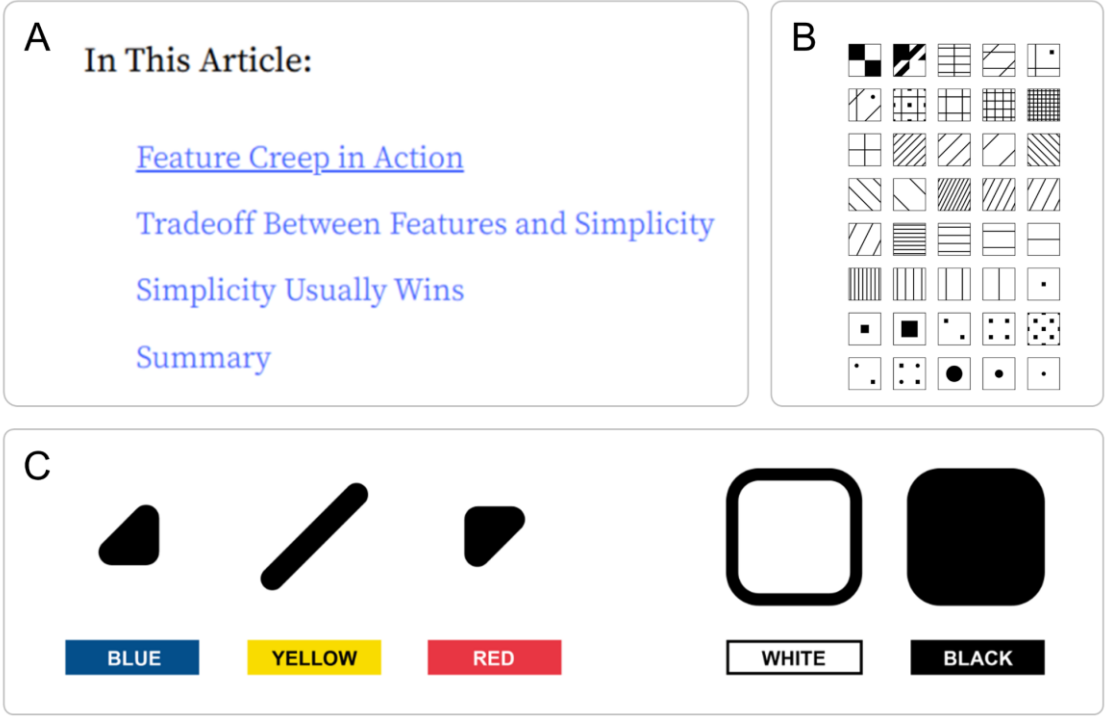


**Figure 6. Web accessibility. A – Examples of web link visualization. B – Example of hatching and its combinations. C – Five graphic symbols represent the Primary Colors (Blue, Yellow, Red) plus White and Black (Sources according to the order of the images:** Loranger (2015)**;** Munoz (2023)**;** ColorADD (n.d.)**).**

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#### 3.7.4 Using alternatives to color for data representation

Do not rely on color alone to convey key information. Combine color with text, icons with labels, or color with patterns to enhance clarity. For example, in Fig. 5B, the label "Corn" is supported by a schematic icon. This approach is also effective for maps, charts, and diagrams, where patterns can be applied to polygons and different line styles can be used distinguish data categories (Fig. 6B, C) (ColorADD, n.d.).

These practices are particularly helpful for people with visual impairments and for general readability in dim light. Use distinct pattern structures for categorical data and similar patterns with varying densities for quantitative data. If necessary, vary the pattern orientation to prevent adjacent elements from blending together.

## 4 Results: case studies

The following case studies are presented as illustrative applications of the review findings and synthesized design principles. Their role is to complement the review by showing how similar user-centered design processes can lead to different interface solutions depending on audience needs, tasks, and contexts of use.

Sections 4.1 and 4.2 highlight design practices that are typically overlooked in climate service development, such as user research (Appendixes C, D, E, F, G, and H), usability testing (Appendixes I and J), and web accessibility. In addition, Appendixes K and L illustrate the continuous role of the designer, highlighting key insights from each stage of development. The design process is also briefly summarized on Behance (Nikitenko, 2025a, 2025b, 2025c).

### 4.1 Climate & Water – web tool for water managers

#### 4.1.1 User research

We applied the synthesized methodology (Fig. 2) to develop a web tool that presents future water resources for Ukrainian river basins (https://climatewater.uhmi.org.ua/). National legislation provided the overarching framework, requiring that climate change impacts be integrated into 6-year River Basin Management Plans. Based on this, we identified target audience – water managers at River Basin Management Authorities (RBMAs) – and defined key tasks the platform should support.

We conducted a survey among RBMA staff and created a user persona, a step still rarely documented in climate service development (Fig. 7A). The survey showed that (Appendixes C, D, and E):

- users were most familiar with bar charts, line graphs, and maps (Fig. 8), while boxplots were the least understood;
- selecting a catchment by official delineation was a priority;
- runoff volume was identified as the most critical parameter for planning, and thus should be set as the default view;
- six additional parameters – discharge, air temperature, precipitation, evaporation, groundwater recharge, and soil water – covered the majority of their data needs;

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- along with future relative changes in parameters, users also expected to see their absolute values.

The persona helped transform separate survey findings into a coherent user model that reflected the working context, priorities, and mental logic of RBMA staff. This was critical for avoiding an abstract "water sector stakeholder" perspective and for linking design choices – such as default parameters, navigation logic, and visualization formats – to the actual planning needs of water managers.

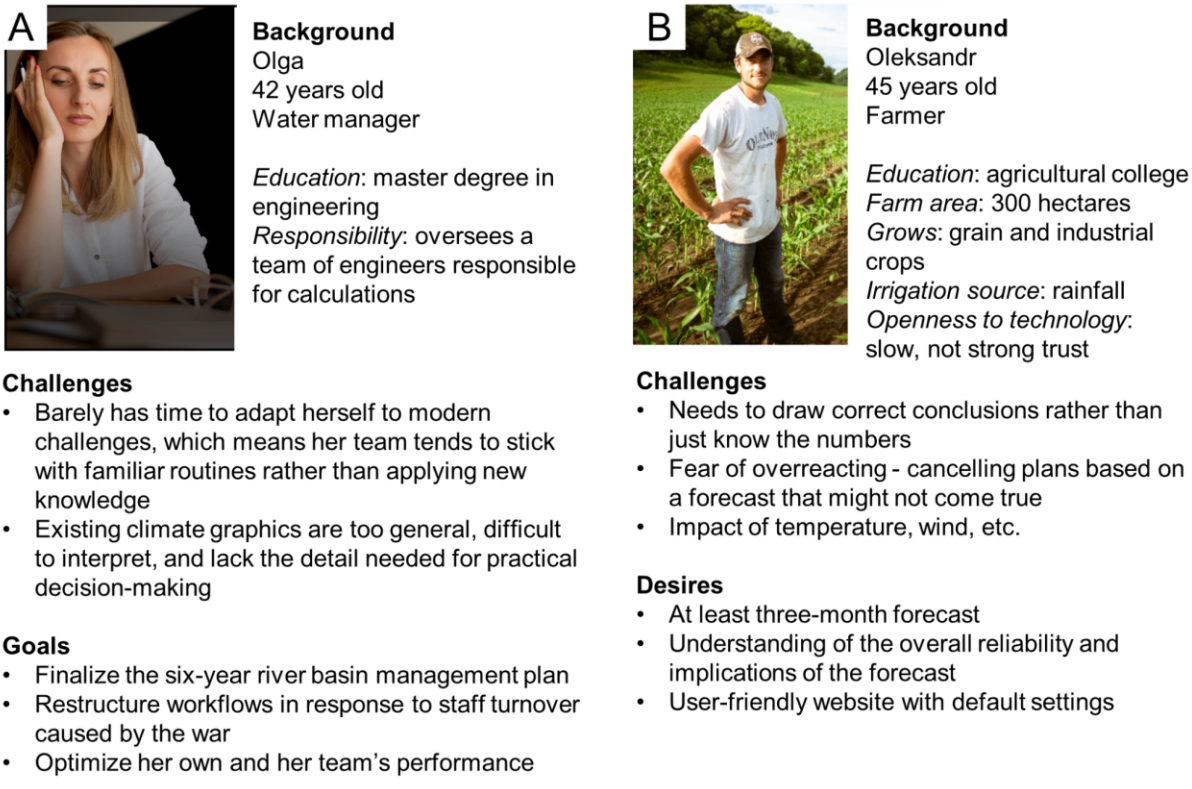


**Figure 7. User personas of web platforms. A – Persona of a Climate & Water user. B – Persona of a POSUKHA user.**

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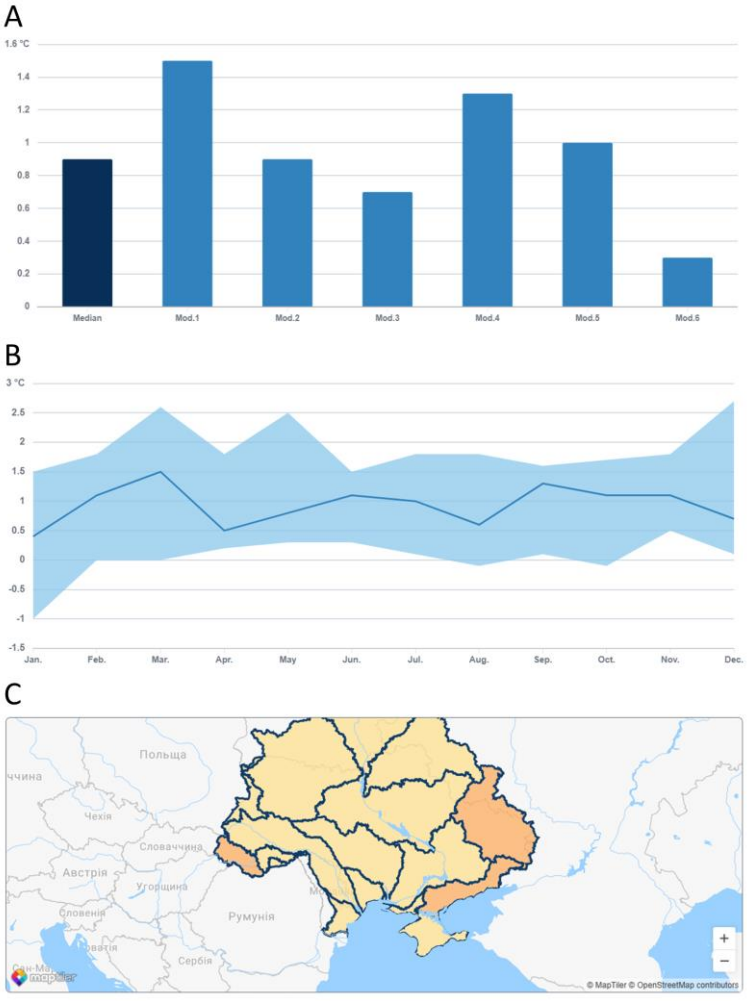


**Figure 8. Presentation of climate projections at the Climate & Water web platform. Users were most familiar with bar charts (A), line graphs (B), and maps (C).**

### 4.1.2 User interface

Design literature encourages the use of visual references (Fig. 3). When designing the layout of Climate & Water, one of the main references was the financial website Trading Economics (Trading Economics, 2025a), which presents large volumes of trend data in a clear and accessible format. The homepage of Climate & Water adopts a similar structure, however, instead of financial indicators, it displays recent changes in runoff, temperature, and precipitation. On the data analysis page, GDP growth chart (Trading Economics, 2025b) inspired the placement of a filter bar directly above the chart, as well as the use of a two-level dropdown menu for navigating more than 150 official watershed units.

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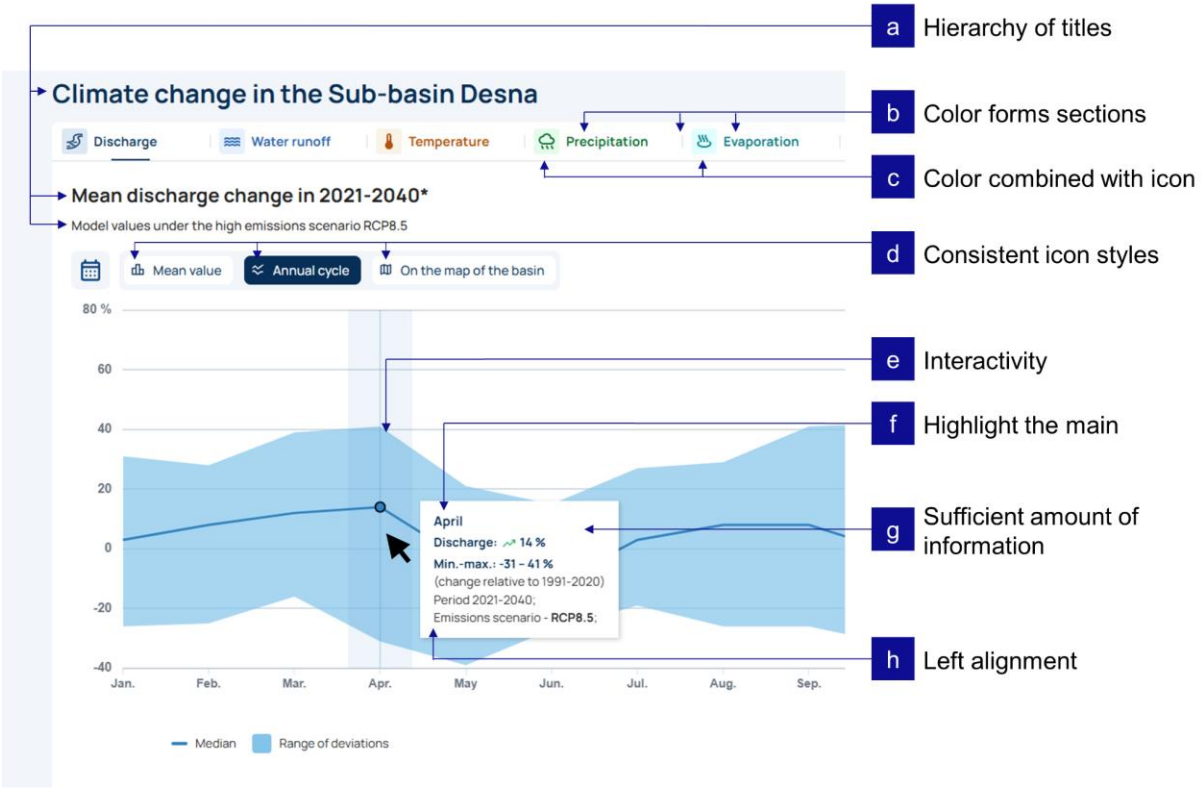


**Figure 9. Data analysis layout at the Climate & Water web platform.**

More broadly, the interface applies several principles synthesized from the reviewed literature, including structure, focus on key information, simplification, and interactivity (Fig. 3; Appendix B). Information perception is facilitated by breaking the chart's description into short, hierarchical headings (Fig. 9a), where indentation, font size and weight help users distinguish information levels.

Interactivity is repeatedly used to help prioritize key information (Figs. 9 and 10). When hovering the cursor over a specific month, the corresponding data zone is highlighted, and a tooltip appears (Fig. 9e-h). Similarly, the selected climate model and median are highlighted more vividly, while the remaining models appear in a lighter color (Fig. 10a). Color markers in blue and green within the tooltip provide additional visual cues, helping users quickly locate the relevant data (Fig. 10c). The supporting information pages also follow a consistent layout that reduces cognitive load: numbered lists aid navigation (Fig. 11a), subpoints 2.X are indented further than point 2, and narrow text blocks improve readability by making line tracking easier (Fig. 11f).

Unlike many reviewed climate services, where usability is assumed rather than explicitly tested (Sect. 3.1.3), several interface decisions in Climate & Water were directly refined through user testing. Interface testing showed that 90% of respondents, when asked “What data do you see for April?”, instinctively moved the cursor to April and relied solely on the tooltip

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information – even though the same data is available in the chart title and axis labels. The user behavior highlights the importance of interactivity to guide attention and reduce cognitive load: it is far more convenient to check a tooltip than to visually scan the entire screen for relevant values.

A similar result emerged in navigation design. In the first design iteration, the "Menu" button was represented by three horizontal lines, a common "hamburger" icon in interface design. However, user testing showed that this symbol was not clearly understood by the intended audience. The usability testing was conducted through 12 moderated sessions with a group consisting of 3 men and 9 women, with an estimated age range of 30–40 years based on visual assessment (Appendix I). As a result, it was replaced with the word "Menu" (Fig. 11b).

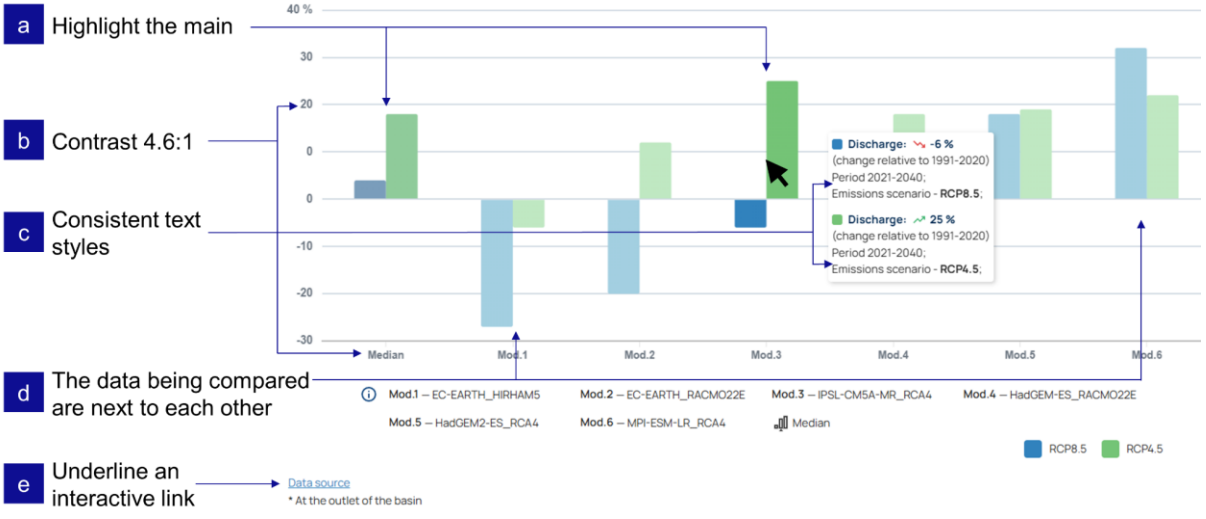


**Figure 10. Bar chart at the Climate & Water platform, comparison mode.**

User research revealed that some users were unfamiliar with certain terms – or, more critically, understood them incorrectly, which is quite common issue across climate services (Suhari et al., 2022; Terrado et al., 2022a). As a solution, we included all specialized terminology in a glossary and data source section, using adapted, user-friendly language (Fig. 10e).

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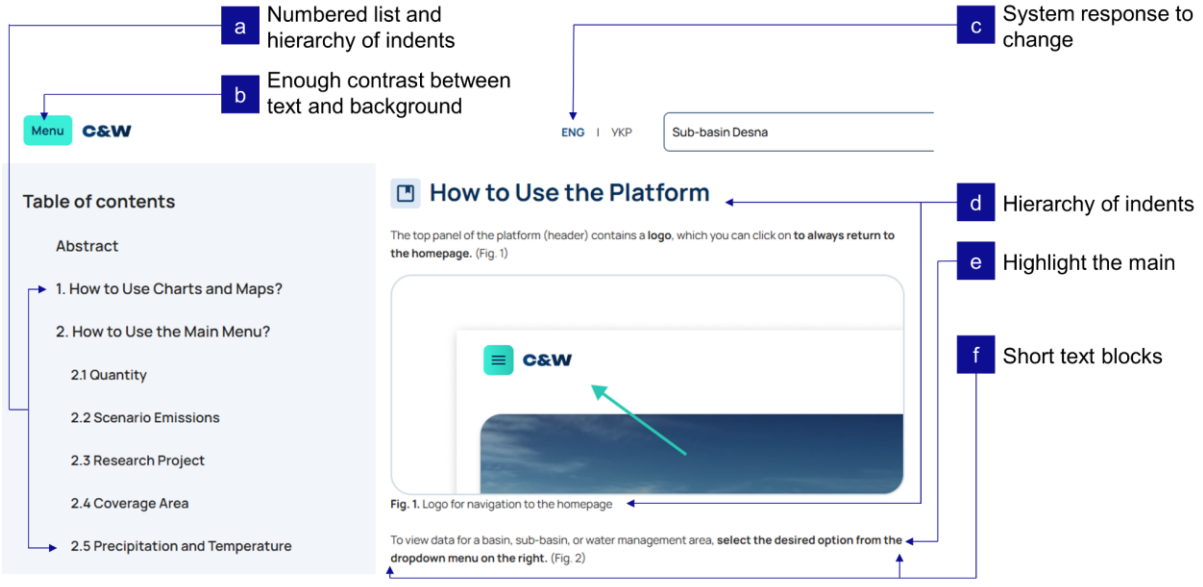


**Figure 11. Pages with supporting information at the Climate & Water web platform.**

The base map also reflects one of the key principles identified in the literature review: visual hierarchy should emphasize what matters and mute what does not. The map remains minimalist, but to improve orientation, city and river layers are brought to the foreground (Fig. 12). As users zoom in, smaller towns and rivers become visible.

**Figure 12. Thematic and base maps at the Climate & Water web platform. Cities and river layers are brought to the foreground to improve orientation.**

### 4.1.3 Web accessibility

Following the web accessibility recommendations outlined in Sect. 3.7, textual elements are supported by icons (Fig. 9c, d), all designed with a consistent visual style – uniform line thickness, unfilled shapes, and sharp corners.

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Although blue and green are not the most contrasting colors from a web accessibility standpoint, they offer sufficient distinction to differentiate emission scenarios (RCP4.5 and RCP8.5) (Fig. 10a). When combined with clear labels and consistent use throughout the interface, this solution adequately supports users with color vision deficiencies.

We used light gray for axis labels to avoid distracting from the main data (Fig. 10b). Although gray is often associated with inactive elements and can risk being too faint, the chosen shades meet the 4.5:1 contrast ratio (Sect. 3.7.1).

#### 4.1.4 Visualization of uncertainty

To visualize uncertainty, we chose to present the median and each individual climate model (Fig. 8A). Initially, we considered simplifying the scenarios by grouping them into three representative cases – for example, the median, 10th, and 90th percentiles (Appendix K). However, for water managers who typically work with specific flow exceedance probabilities (e.g., 50th, 75th, 95th), introducing percentiles added unnecessary confusion. Therefore, directly displaying each model proved to be the most straightforward way to communicate uncertainty. On the annual cycle chart and map, uncertainty is further conveyed through interactive tooltips.

This case study directly addresses several gaps identified in the review. In contrast to the broader literature, where user research, personas, usability testing, and accessibility considerations are often weakly reported, Climate & Water documents how these practices informed specific design decisions, from parameter prioritization and terminology adaptation to tooltip behavior, navigation, and map composition. In this sense, the case validates the review finding that such practices are feasible in climate service development, while also showing that they materially influence how climate information is structured and interpreted.

### 4.2 POSUKHA – drought forecast for farmers in Ukraine

#### 4.2.1 User research

We assessed users' sources of information about droughts and climate change, their experience with other farming-related digital services, the working conditions they face, their understanding (and common misconceptions) of droughts, and the types of information they need to make decisions (Appendix F). Based on these findings, we created a user persona (Fig. 7B).

One section of the survey focused on interaction with data visualizations: which types of maps are familiar, what information is most important on these maps, and how often and under what conditions farmers seek drought-related information.

#### 4.2.2 User interface

POSUKHA was primarily designed for mobile phones, reflecting the preference of most farmers (https://posukha.uhmi.org.ua; Appendixes G and H). In line with the interface principles synthesized from the literature (Fig. 3; Appendix B), the landing page was designed around one main user task, simplified content presentation, and reduced cognitive load. The landing page opens with a tagline – "the first drought forecasting web service in Ukraine" – and a clear "Explore Droughts" button. To

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ensure fast and intuitive interaction, users are immediately presented with a drought forecast map and its legend, without needing to apply filters beforehand. For meteorological droughts, we preselected the widely used SPI (Standard Precipitation Index) and displayed it using a seven-category legend (Fig. 13f). Thus, the interface prioritizes the main user action – checking the drought forecast – while additional explanatory content is available by scrolling down the landing page or visiting the "Information" section in the menu (Fig. 14d).

The map interface was also directly shaped by user research, illustrating one of the main gaps identified in the review: climate services often define user needs but do not clearly show how those needs inform interface decisions. Farmers' fields often lack formal addresses, therefore, search functionality alone is insufficient. User research showed that most respondents navigate using administrative unit labels and borders (30%) as well as roads (29%) (Appendix G). Therefore, we brought cities to the foreground and improved visibility of borders and main roads (Fig. 13b, e).

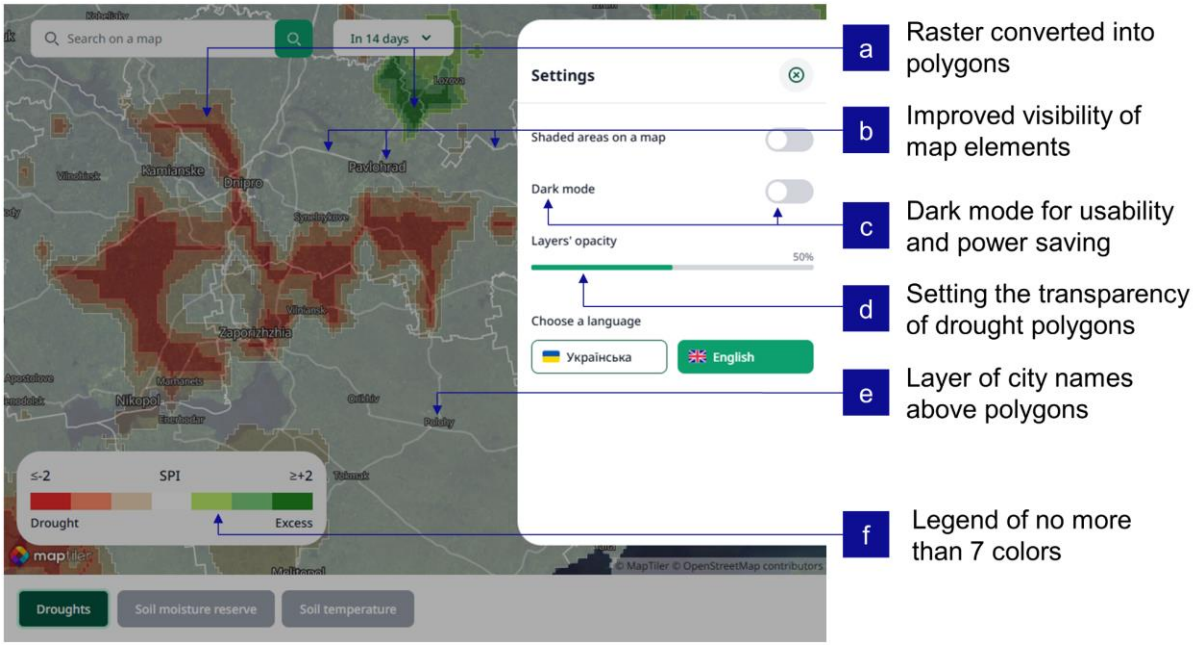


**Figure 13. Map settings at the POSUKHA web platform.**

User preferences also informed the default map style: most users prefer the "Satellite" map view (45% of respondents), followed by the "Streets" view (39%), while other styles are less popular (Appendix G). Therefore, we set the default to the Satellite map (Fig. 13) and added the option to switch to the Streets view (Fig. 14b). To align with user habits, we also adopted the layout and gesture controls commonly used in Google Maps (Fig. 14a).

### 4.2.3 Web accessibility

Distinguishing map polygons can be difficult for people with visual impairments, as well as for any user viewing the screen in bright sunlight, particularly relevant for farmers in the field. To make SPI values accessible beyond color alone, we:

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- Enabled users to adjust the transparency of drought polygons (Fig. 13d);
- Added a dark theme for use outdoors or in low-light settings, which also helps conserve battery (Fig. 13c);
- Included a "map pattern" option for identifying drought levels through hatching with varying intensity (Fig. 14e);
- Used different hatching angles to prevent adjacent categories from blending visually.

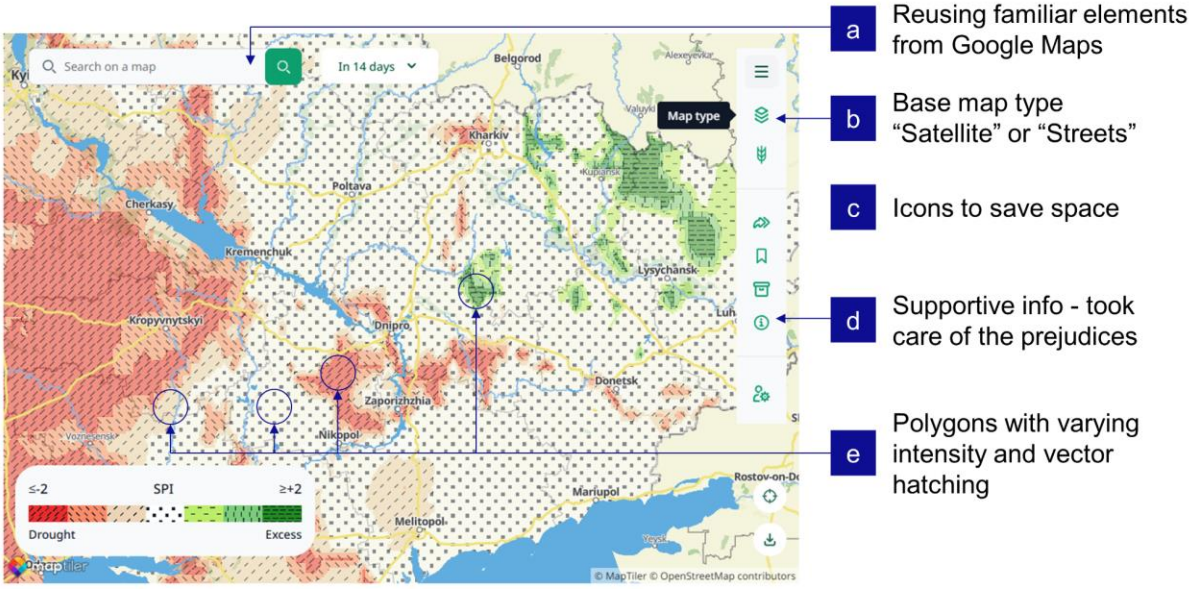


**Figure 14. Web accessibility features at the POSUKHA web platform.**

POSUKHA further extends the review findings by demonstrating that the same general design workflow can lead to very different interface solutions when applied to a different user group and decision context. Whereas the review showed that climate services often underreport how user needs shape interface design, this case makes that link explicit: mobile-first layout, default map settings, road and boundary visibility, and accessibility options were all derived from the working conditions and information habits of farmers. Together with Climate & Water, this supports the conclusion that while user-centered design principles can be standardized as a development process, the resulting visual and interaction solutions must remain context-specific.

## 5 Discussion

### 5.1 User-centered design as a methodological core

The study showcases that user scenarios drive design decisions. Scenarios refer to users' tasks and the context in which they operate (McKay, 2013). For instance, farmers work in the field, rely on mobile phones, make quick assessments, and often navigate without formal field addresses. In contrast, water managers follow structured planning cycles, depend on formal

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575 documentation, and consider multiple technical parameters. These differences lead to distinct interface needs and expectations, underscoring the importance of communication, empathy, and a deep understanding of users' workflows.

In contract, we found that most projects clearly define their problem and intended users, however, rarely explain how these insights shape the interface structure, interaction logic, or visualizations. This pattern suggests a divide between climate science workflows, where transparency and reproducibility around data and models are well established, and design workflows, which
580 tend to remain implicit, empirical, or hard to formalize. As a result, many design decisions that strongly influence how users interpret information, trust results, and act on them remain largely invisible in the literature, even for long-running and widely used platforms.

The review shaped the development of our two case studies. Because it highlighted the importance of a demand-driven approach and showed that UX/UI is still too rarely treated as a central methodological element, we devoted the first two weeks
585 of the project to hiring a designer. This early decision shaped the rest of the workflow. The designer ensured that user-centered methods were implemented from the start, including individual interviews to identify needs, one-to-one usability testing with screen recording, and the application of interface design principles as well as web accessibility standards. Thus, one of the clearest lessons drawn from the review was that better climate services do not emerge only from better data or models, but from assigning responsibility for design as a methodological process.

590 We demonstrated that user research must be the first step in developing a climate service. While the project scope often already defines the target sector and types of information needed, and while existing literature may offer visualization recommendations, these resources are not sufficient on their own to start gathering and presenting sector-specific data. For example, Daron et al. (2021) and Kause et al. (2020) proposed survey-based visualization solutions for communicating precipitation change to non-experts – such as line graphs with confidence intervals and three-panel maps showing the median,
595 10th, and 90th percentiles of projection ensembles. However, the authors emphasized that such solutions could not be universally applied. The latter was confirmed in our case: interviews with water managers revealed that their mental model is based on the concept of discharge reliability. In this paradigm, a 50% exceedance probability indicates a typical flow, while 90% and 10% correspond to low-flow and high-flow years, respectively. In this context, introducing 10th and 90th percentiles of projection ensembles would have caused confusion rather than clarity. Thus, rather than relying on the vague label "non-
600 expert", the research team should define the specific user group, conduct user research, and create a persona.

### 5.2 Why climate services cannot rely on a standard visual solution

Our findings suggest that there is no one-size-fits-all solution for visual design in web-based climate services. Visualizations must respond directly to the needs of the target audience. Even when similar data are presented, design choices, such as the base map, cannot simply be copied from one context to another. For example, farmers require fast and simple insights, which
605 calls for minimal information, even though the platform could technically include numerous indicators and parameters. By contrast, water managers need a broader range of data for planning and reporting, including access to full datasets and tables.

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Thus, user needs cannot be standardized, as they are shaped by many factors which evolve over time, including environmental context and user habits. A design that worked ten years ago may no longer be effective today (Muehlenhaus, 2013).

A comparison between POSUKHA and the EDO (European Drought Observatory, n.d.) further illustrates why a general-purpose observatory cannot simply be "zoomed in" to replace a dedicated sectoral climate service (Fig. 15). While the EDO literature documents indicators, scientific layers, system functions, and technical upgrades in considerable detail, it does not provide evidence of the user-centered design process behind the current Map Viewer (Magni et al., 2019). POSUKHA, by contrast, was shaped directly by user research among Ukrainian farmers, which influenced not only content selection but also map defaults, navigation logic, interaction patterns, and accessibility features. Because farmers requested a forecast with at least a two-week horizon (Appendix G), development effort focused on implementing a forecast component rather than increasing the number of retrospective drought indices, which become available only with a one-week delay. This suggests that territorial coverage and scientific completeness are not sufficient to create a standard solution for all audiences: effective climate services must also reflect users' habits, constraints, and decision contexts. As emphasized in Sect. 3.1.6, documenting the design process is essential for understanding why similar information is presented differently across platforms and for moving more transparently toward better design solutions.

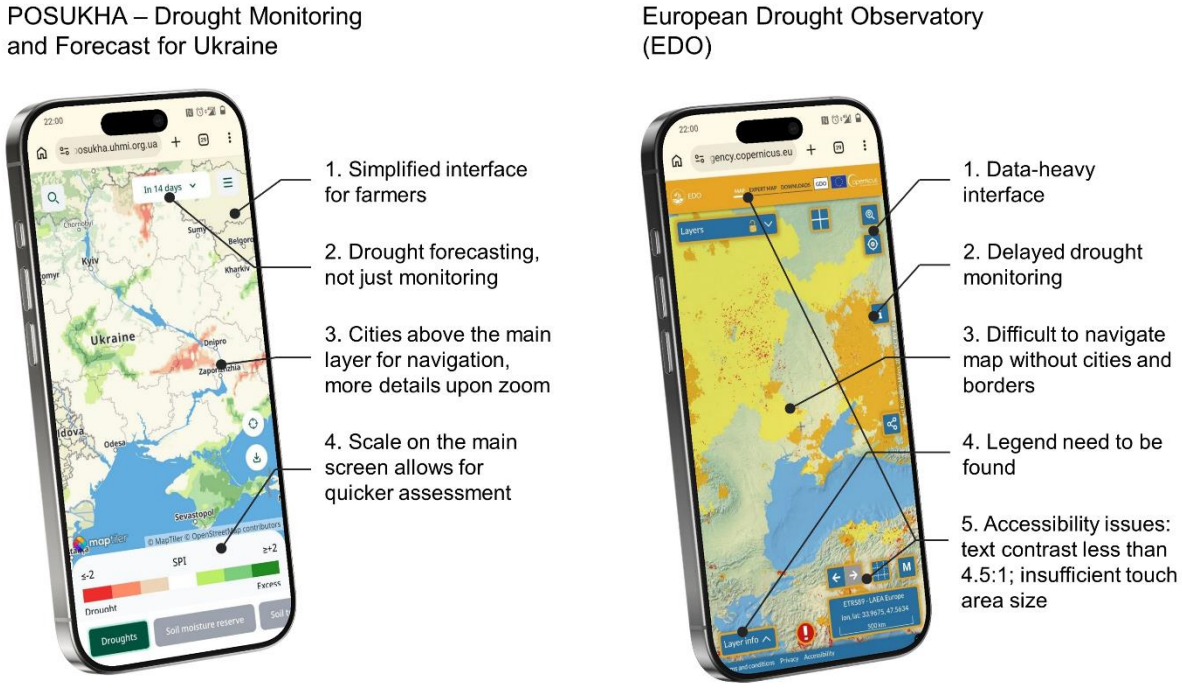


**Figure 15. Comparison of EDO and POSUKHA showing why a general-purpose observatory cannot replace a dedicated sectoral climate service (sources:** European Drought Observatory, n.d.; POSUKHA, n.d.**).**

However, it is important to distinguish between standardizing specific design choices and standardizing the development process itself. We advocate for a design study to be a standard component in climate service development, comprising user

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research, iterative prototyping, and testing. This recommendation aligns with recent literature that calls for more structured, user-centered approaches. Wall et al. (2017) propose indicators to assess the usability of climate science, while Williams et al. (2020) outline methods for evaluating user capacities during service design. André et al. (2021) emphasize assessing the quality of knowledge, particularly how visual information is conveyed. Suhari et al. (2022) and Visman et al. (2022) note that despite frequent references to co-production, guidance on how to involve users meaningfully and iteratively remains limited. Terrado et al. (2022b) and Fleming et al. (2023) further call for concrete frameworks to embed design thinking and visual communication practices. Our study responds to this gap by offering actionable, design-focused recommendations that enhance both the usability and impact of climate services.

### 5.3 Organisational implications for research projects

Available evidence suggests that the main barrier to integrating design into research projects lies less in direct cost than in how responsibilities are structured (Cassanelli et al., 2017). Houtkamp et al. (2021, 2025) likewise argue that UX/UI design requires specialised expertise and explicit integration into the project from the start. In our experience, this is particularly visible in web development, where specialists with formal training in informatics or design can often implement solutions faster and more effectively than Earth science researchers for whom web development is an additional skill rather than a core competence. However, research teams do not always have the organisational flexibility, or even a clear recognition of this need, to involve such specialists. Finally, user research and testing do not usually lead to a single optimal solution, but rather to several possible directions, which then have to be balanced against software development effort, cost, and implementation complexity.

### 5.4 Limitations

The study focuses on design practices within climate service development and does not fully address the broader co-production processes that include governance, institutional dynamics, and long-term engagement (Fleming et al., 2023; McClure et al., 2024). While we emphasize the role of UX/UI designers, the effectiveness of climate services often depends on sustained interdisciplinary collaboration that extends beyond design tasks (Visman et al., 2022). Our guidance supports but does not substitute the broader participatory frameworks that underpin successful co-production efforts.

Design solutions are often constrained by technical and legal feasibility. In the case of POSUKHA, the project had to rely on freely available meteorological data and did not include a long-term user support service. From a farmer's perspective, a field-specific dashboard or app would likely have been more convenient than a map-based interface. However, the spatial accuracy of freely available meteorological data did not justify such a level of localisation, nor did it fit the scope of a non-commercial development. The map-based web service therefore represented a pragmatic compromise between user needs and what could be implemented reliably within the project conditions.

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Overall, our findings highlight that UX/UI design goes beyond aesthetics, as it shapes how climate information is understood and trusted. When users can clearly interpret data, they are more likely to engage with it, rely on it, and act on it. We emphasize that design must be integrated from the earliest stages of research to ensure that climate services truly serve their users.

## 6 Conclusions

We examined how design practices are reported and applied in climate service development, based on a structured review of 55 operational web-based climate services. The findings show that core design elements, such as user research, usability testing, and web accessibility, are rarely documented in a systematic or transparent manner, even though many projects clearly define their target users and articulate specific problems.

We provided structured guidance for integrating design as a continuous component of climate service development, particularly in web-based tools. Addressing the focused research question, the case studies illustrate how user research informs choices about visual formats, information priorities, navigation, and accessibility. Our findings suggest that while certain design principles – such as progressive disclosure, information hierarchy, and accessibility – can serve as general best practices, the implementation of visual solutions must be adapted to specific user groups, their mental models, and the context of decision-making.

Users of climate services differ in knowledge, skills, need for detail, and time available for processing information. Each operates within specific tasks where climate data must be applied. As the amount of available information continues to grow, it becomes increasingly difficult to identify and interpret what is relevant. User research helps teams assess whether conventional visual formats suit these tasks and identify where adaptation is needed. Design principles can then guide solutions intended to reduce cognitive load, enhance clarity, and support user trust.

Furthermore, we distinguished between standardizing the development process and the visual outputs themselves, arguing for the former as a necessary practice in climate service development. By embedding user research early and iteratively throughout the project, research teams can avoid common pitfalls such as ambiguous visualizations, overwhelming complexity, or misalignment with user expectations. Ultimately, the needs and tasks of the target audience must drive every stage of the climate service design process.

## Data availability

The supplementary materials supporting this study, including the files named Appendixes A–L, are openly available at Zenodo (Nikitenko and Osypov, 2026): https://doi.org/10.5281/zenodo.20126857

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## Author contribution

Nataliia Nikitenko – Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review and editing; Valeriy Osypov – Conceptualization, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review and editing.

## Competing interests

The authors declare that they have no conflict of interest.

## Ethical statement

Participants in the surveys, individual interviews, and usability-testing sessions were informed about the purpose of the research and the voluntary nature of their participation. Consent was obtained before participation and for the use of the results. For individual interviews and usability-testing sessions, consent was provided orally. Where sessions were recorded, separate oral consent to recording was obtained at the beginning of the session. The reported results were anonymized, and participants' names and surnames are not disclosed in the manuscript or the supplementary materials.

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