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## Scenario thinking to address deep uncertainty

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**DOI**
10.1016/j.jhydrol.2025.133547

**Publication date**
2025

**Document Version**
Final published version

**Published in**
Journal of Hydrology

**Citation (APA)**
Wu, W., Eamen, L., Dandy, G., Maier, H. R., Razavi, S., Kwakkel, J., Huang, J., & Kuczera, G. (2025). Beyond the traditional paradigm of water resources management: Scenario thinking to address deep uncertainty. *Journal of Hydrology*, *661*, Article 133547. https://doi.org/10.1016/j.jhydrol.2025.133547

Journal of Hydrology 661 (2025) 133547

Contents lists available at ScienceDirect

Journal of Hydrology

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

# Beyond the traditional paradigm of water resources management: scenario thinking to address deep uncertainty☆

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ARTICLE INFO

*Keywords:*
Water resources management
Decision-making
Deep uncertainty
Scenario thinking

ABSTRACT

Sustainable management of water resources is crucial for humanity. However, traditional methods for achieving this are becoming obsolete. This is because they are underpinned by the assumption that we have a good understanding of how water availability and demand will change in the future. However, based on our current experience with climate change, this is not the case. In fact, rather than having a good understanding of what the future might look like, it is, in fact, deeply uncertain. Consequently, a new paradigm for water resources management is needed; one that accounts for deep uncertainty by embracing scenario thinking. We categorize and summarize different causes of deep uncertainty in water resources management and provide examples of how an emerging paradigm rooted in scenario thinking can deal with these. We hope to stimulate discussion to enable this new paradigm to be developed further and embedded in standard practice.

## 1. Introduction

Sustainable management of water resources is an existential issue for humanity. It has become an increasingly challenging task due to the occurrence of rapid changes, our lack of understanding of these changes, and the complexity of human-water systems (Razavi et al., 2025). For example, shifts in precipitation patterns due to climate change have affected water availability across space and over time, creating more extreme events such as severe droughts and floods that overwhelm existing water infrastructure. This challenge is further amplified due to our limited and varied knowledge of these changes and their impacts in the future, thereby preventing the development of a consensus on effective management solutions. This state of incompleteness and contestedness in understanding regarding (a) the relationships between actions and their consequences; (b) the probabilities of different future outcomes and (c) the relative importance of the different outcomes due to the presence of future unknowns or conflicting opinions – is referred to as deep uncertainty (Marchau et al., 2019; Walker et al., 2013). Recognized as a grand challenge in water resources management (WRM) (Wu et al., 2023), deep uncertainty renders traditional WRM approaches obsolete and necessitates a new paradigm for designing solutions to water management issues.

The traditional paradigm for water resources planning and management is typically based on the systems approach (Biswas, 1976), which usually involves the use of one or more system models that take exogenous input and decision variables to predict the values of outputs. These outputs are then assessed by stakeholders to identify the best set of solutions. The systems approach can be simulation-based, where various combinations of decision variable values are tested to identify the best solution(s); or optimization-based, where an optimization model is used to identify efficient or 'optimal' solution(s) (Loucks and van Beek, 2005; Maass et al., 1962). Regardless of which method is used, uncertainties can occur in system inputs, model(s) or model parameters, and the outputs. In the traditional paradigm, these uncertainties are usually described and analyzed using probability density functions based on historical data or 'degrees of belief', relying on a 'best guess' estimate of

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☆ This article is part of a special issue entitled: 'AUS grand challenges' published in Journal of Hydrology.

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https://doi.org/10.1016/j.jhydrol.2025.133547

the future (see Fig. 1a), rather than acknowledging the deeply uncertain nature of the future and embracing the whole range of possible futures that may occur. Therefore, a new paradigm is needed for WRM under deep uncertainty to allow for consideration of long-term changes in exogenous inputs, incomplete or contested knowledge of the underlying processes (e.g., the models themselves), and human involvement affecting choices made throughout the entire solution process (i.e., including both the analysis and final decision-making processes).

A variety of methods has been developed to account for deep uncertainty in WRM, which are generally underpinned by the use of scenarios (Elsawah et al., 2020; Kwakkel and Haasnoot, 2019; Walker et al., 2003). Scenarios represent various possible future 'states of the world' reflecting alternative realizations of the deep uncertainties (Mahmoud et al., 2011). Consequently, the resulting analysis shifts from a single projection of the future with associated disturbances (i.e., uncertainty considered in the traditional paradigm) to dealing with multiple plausible futures (see Fig. 1b). The potential future effects of different WRM decisions, such as how much water to release from a reservoir system, are evaluated by running system model(s) under these scenarios. Performance metrics such as water security levels or flood risk under specific scenarios (e.g., average or extreme) or across all scenarios (e.g., for investigating consistency in performance or robustness) can be explored depending on the purpose of the investigation. Methods have also been developed to address deep uncertainty in WRM using different values of key variables of the underlying processes or human preferences and values used in making choices. Although these methods are not often called scenarios, they account for the uncertainty introduced by human involvement. We refer to this using the term'scenario thinking' on a high level to facilitate discussion.

Despite the increasing popularity of the approaches rooted in scenario thinking to inform WRM decisions under deep uncertainty (Bradfield et al., 2005; Fortes et al., 2015; Haasnoot and Middelkoop, 2012; van Notten et al., 2005), the adoption of these approaches has been slow, and they are still not the mainstream methods used when dealing with WRM problems under deep uncertainty. To help facilitate a shift from the traditional paradigm of WRM to embracing scenario thinking in mainstream scientific and engineering studies, there is a need to clearly articulate what the different sources of deep uncertainty are and to present examples of how these can be addressed using the new paradigm.

In this study, we first identify different sources of deep uncertainty and their impacts on WRM. Then we discuss how the new paradigm of WRM under deep uncertainty is fundamentally rooted in scenario thinking, with examples from literature. By disseminating the concept of deep uncertainty arising from different sources and the use of approaches rooted in scenario thinking to represent it in WRM in a concise and systematic way, we hope to stimulate a healthy discussion among water resources researchers and modelers and facilitate the shift from the traditional paradigm of WRM that assumes a 'best guess' future to the new paradigm based on scenario thinking. This should enable a better understanding of the potential impact of proposed interventions, actions, or management decisions over time, leading to better-informed solutions for both human society and the environment.

## 2. Deep uncertainty and its sources in water resources management

The concept of deep uncertainty has been increasingly recognized in recent years as a key challenge in environmental decision-making and policy formation for water resources system management. From a systems perspective, there are three key sources of deep uncertainty, namely: (a) non-stationarity in exogenous inputs, (b) incomplete or contested knowledge of underlying processes and (c) differing human preferences and values affecting choices made through the solution process. Here, we illustrate these sources through the Optimal Water Mix for Adelaide project (referred to as the Optimal Mix project) (Wu et al., 2017; Wu et al., 2016), complemented by other examples where needed. The overall aim of the Optimal Mix project was to identify the optimal portfolio (i.e., mix) of different water sources (e.g., surface water from reservoirs and rivers, desalinated seawater, recycled wastewater, and harvested stormwater) for Greater Adelaide in Australia under climate change. This aimed to facilitate the identification of priorities for infrastructure investment. Models were used to evaluate the performance of different mixes of various water sources in terms of economic cost, energy consumption, and ecological impact. A multi-objective Genetic Algorithm was used to identify Pareto-optimal solutions. Since it was a public project, the input from not only the decision makers and analysts but also the public were considered, thereby encompassing all three sources of deep uncertainty (Maheepala et al., 2014).

The first source of deep uncertainty arises from the exogenous inputs to the system, with unknowns about future system states being the best known example. In the Optimal Mix project (Wu et al., 2017; Wu et al., 2016), the impacts of climate change on water availability and demand, controlled by variables such as precipitation, temperature, and evapotranspiration, were considered. This is the most widely considered source of deep uncertainty and has been included in many water resources studies (Pachos et al., 2022; Van't Klooster and Veenman, 2021). Other examples of the first source of deep uncertainty in WRM include socioeconomic developments (e.g., population growth), land use

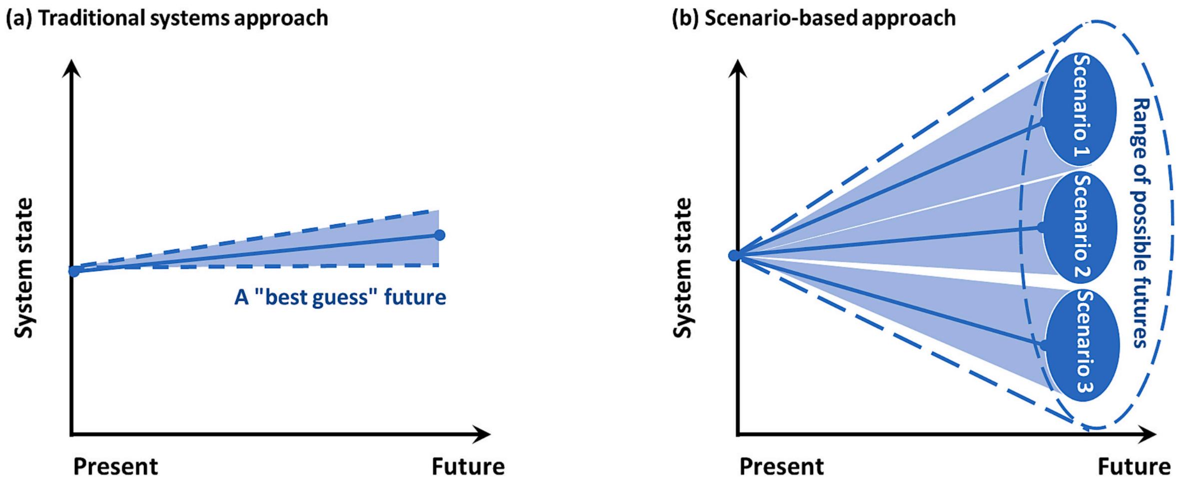

**Fig. 1.** Approaches for water resources management: Plot (a) Traditional systems approach focusing on a 'best guess' future; and Plot (b) Scenario-based approach focusing on multiple plausible futures.

change (e.g., urbanization), technological advances, political reforms, and other cross-sectoral changes (Dandy et al., 2023; Mitchell et al., 2025; Wu et al., 2023; Wu et al., 2020). Population growth and land use change affect water demand, among others, which has been considered in many WRM studies considering deep uncertainty (Vertommen et al., 2021; Wu et al., 2017). Technological advances mainly affect system efficiency and thus both water availability and demand. Political reforms can lead to fundamental changes to the processes and regulations based on which governments manage water resources (e.g., the distribution of water) and consumption (e.g., demand management strategies), which can potentially lead to disruptive changes in both water availability and demand (Mamatova et al., 2016). In addition, biodiversity conservation initiatives can influence water use priorities (Jewitt, 2002), carbon and nitrogen credit markets can potentially alter land and water management practices (Chandra, 2024; Lal et al., 2008), and the recognition of indigenous rights can also shape regional water allocations via water-sharing agreements, adding further complexity to WRM (Jackson, 2005; Moore, 1989; Razavi et al., 2025).

The second source of deep uncertainty arises from a lack of or contested knowledge about system demarcation and functioning. This source is primarily epistemic in nature (Walker et al., 2003) and is related to the 'wickedness' (Kwakkel et al., 2016b; Wu et al., 2023) or ambiguity (Dewulf et al., 2005) of WRM problems. Management of water resources systems typically involves a range of stakeholders with different understandings of what the system is, how the system functions, and what the problems are. Moreover, scientific knowledge of and other relevant information about water resources systems is often incomplete. Consequently, there exist multiple plausible interpretations of what the relevant system is that must be considered. Referring again to the Optimal Mix project, the different water sources considered in the project are surface water from reservoirs and rivers, desalinated seawater, reclaimed wastewater, and harvested stormwater. However, there are other potential sources that could have been considered, e.g., groundwater and rooftop rainwater, but were not included for various reasons – political or technical. The consideration of different potential sources will undoubtedly change the final solution(s) obtained.

The third source of deep uncertainty arises from varying, sometimes conflicting, stakeholder interests, norms, opinions or standards, typically in evaluating possible decision outcomes and their relative importance (but it can be at any stage of the solution process). This source of deep uncertainty is primarily 'normative', rooted in rules, expectations, or values that are widely accepted within a particular community (Taebi et al., 2020). These various parties may have different worldviews and thus different understandings of which solution is good and which is bad, and consequently pursue their own objectives. In practice, different worldviews can affect people's decisions at every stage of the solution process (e.g., including problem formulation, solution technique selection, and final solution selection). However, their impact is mostly investigated in the context of final decision-making where potential solutions are ranked and a final solution is selected. In such situations, there is no objective basis for ranking decision alternatives because any aggregation over the complete set of objectives across all involved parties encounters the 'Arrow incompleteness' issue (Arrow, 1950; Franssen, 2005; Kasprzyk et al., 2016), which refers to the condition where there is no aggregation procedure that can meet the basic requirements for making a fair and logical decision.

Take the Optimal Mix project as an example, all stakeholders directly involved in or impacted by the project had strong opinions about the priorities regarding which water sources should be used (Wu et al., 2016). For example, there were some concerns by the public over the use of harvested stormwater and reclaimed wastewater for potable uses, although these options may be efficient solutions for the decision makers. Another example is the ongoing debate over the Great Renaissance Dam in the Nile basin where the various riparian states fundamentally disagreed on whether it should have been built in the first place, how it would be filled, and how it should be operated (Ayferam, 2003; Basheer et al., 2023; Etichia et al., 2024; Ranjan, 2024; Yalew et al., 2021). For Ethiopia, it is a major means for delivering renewable electricity as part of a bid to foster economic growth. However, this threatens the objectives of the downstream countries, e.g., irrigation, freshwater supply, and energy generation.

## 3. Impact of deep uncertainty on water resources management

The impact of the three different sources of deep uncertainty on a typical multiobjective water resources optimization problem is illustrated in Fig. 2. As shown in Fig. 2a, unknowns about the future system states, such as those that can be characterized using various trajectories or values of the exogenous inputs to the system (i.e., the first source of deep uncertainty), can affect the performance of the system into the future in terms of the different values of system constraints and management objectives derived. In the context of a multiobjective optimization problem such as the Optimal Mix project, this will lead to different Pareto optimal solutions depicting tradeoffs between three competing objectives: minimizing the operational cost, minimizing the energy consumption, and minimizing the ecological impacts (see Fig. 2b).

The second source of deep uncertainty arising from different understandings of system demarcation and functioning can affect the entire solution process including problem formulation, solution technique selection, and final decision-making, as shown in Fig. 2c. For example, the different understandings of system boundaries and/or functions of different groups of stakeholders can lead to different definitions of system boundaries and/or different objective functions being selected, which can lead to completely different objective spaces and thus potential solutions (as demonstrated by the blue and green Pareto fronts in Fig. 2d versus the brown Pareto front in Fig. 2e). Even when a similar problem formulation is achieved, the different knowledge about the system can lead to the selection of different models, solution techniques, and/or parameter values, which can lead to very different solutions (as illustrated by the blue versus green Pareto fronts in Fig. 2d). In the Optimal Mix project, the public's strong objection to the use of harvested stormwater and reclaimed wastewater for potable uses led to the decision that these two sources can only be used for non-potable purposes, changing both the decision and objective space of the problem and, thus, the final solutions. In addition, the stakeholders' very different views over which water sources should be prioritized for potable or non-potable uses led to the development of two different priority sets (i.e., the order of preferences), from which followed two sets of different optimal solutions (Wu et al., 2016). Finally, this second source of deep uncertainty can also affect the final decision-making process, as different understandings of the systems may lead to different interpretations of the impact of potential solutions and thus different final solution(s) being selected (as shown by the solid dots in Fig. 2d and Fig. 2e).

The third source of deep uncertainty differs significantly from the second source, as it arises from the varying interests and worldviews of stakeholders rather than the lack or contestation of knowledge. For example, in the Optimal Mix project, the modelling and optimization platform (eWater Source) was pre-selected by the decision maker (Wu et al., 2021). Such a decision can significantly influence the shape and position of the Pareto front. By comparing the Pareto fronts under different assumptions (e.g., model structures, parameters, or boundary conditions), a more realistic picture of the trade-offs can be presented for more objective decision-making.

However, both the second and third source of deep uncertainty involve human judgment. Driven by different agendas or preferences, different stakeholders can make very different choices throughout the modeling and decision-making process. This can lead to not only different solutions being selected at the final decision-making stage, but also different problem formulations (including system boundaries),

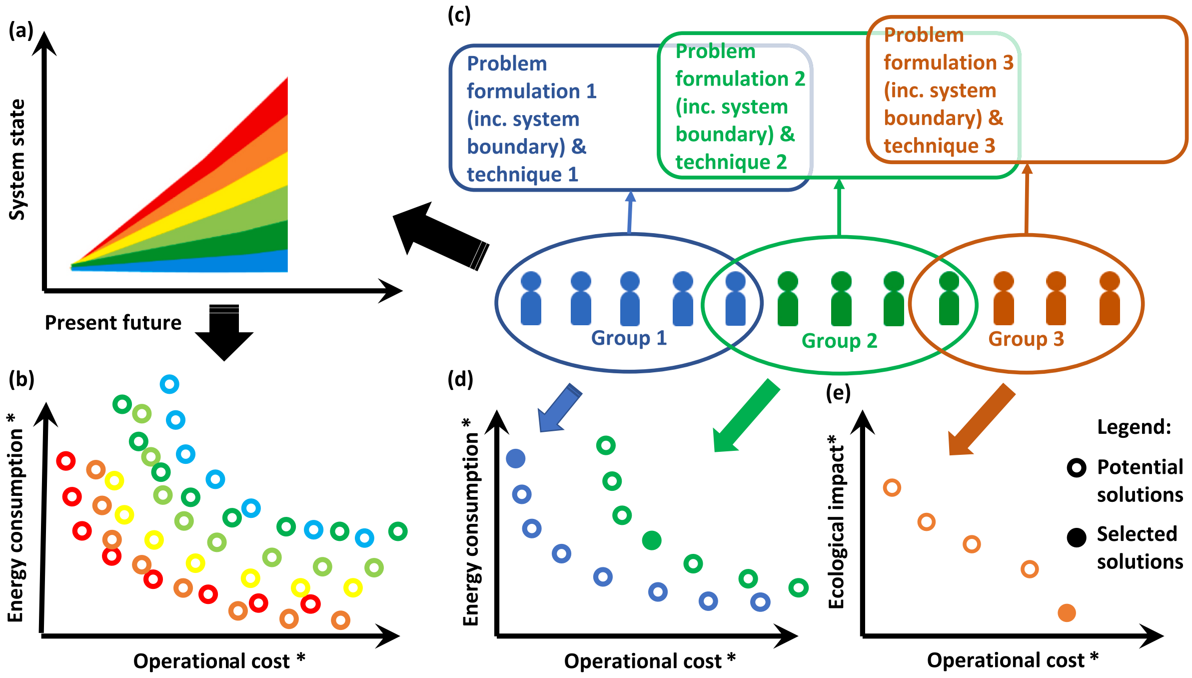

**Fig. 2.** Illustration of deep uncertainty from different sources and its potential impact on scenario-based modeling for water resources management: Plot (a) deep uncertainty from unknowns about future system states due to uncertainty in exogenous system inputs (source 1), e.g., under climate change; Plot (b) impacts on Pareto optimal solutions depicting tradeoffs due to source 1; Plot (c) deep uncertainty from human involvement, due to their contested or incomplete knowledge of the system (source 2) or different worldviews (source 3); Plot (d) impacts on Pareto optimal solutions depicting tradeoffs due to different models or solution techniques from source 2 or source 3; and Plot (e) impacts on Pareto optimal solutions depicting tradeoffs due to different problem formulations from source 2 or source 3 (*Assuming a water resources system optimization problem with two objective functions to be minimized).

models or solution techniques used, etc., leading to very different final outcomes (as demonstrated in Fig. 2d and Fig. 2e).

Although the three sources of deep uncertainty have distinct roots, they are also interconnected, leading to intertwined impacts on various aspects of WRM. Both the knowledge and perspectives of stakeholders (i.e., sources 2 and 3, respectively) can evolve over time, and become more uncertain as time moves into the distant future. For example, people's preference to avoid reclaimed wastewater for potable purposes may change over time after being educated about the benefits and risks involved. A good example is Singapore, which historically relied on water imports; but the complex political context in the region has prompted it to seek an independent water supply, especially after its separation from Malaysia to become a sovereign state in 1965 (Lee and Tan, 2016). Apart from building additional reservoirs, reclaimed wastewater was identified as a plentiful and sustainable water source. Despite initial health concerns and associated public resistance, Singapore has become a world leader in wastewater recycling for both potable and non-potable uses through government intervention and public education (Tortajada, 2020). This example illustrates that the knowledge and perspectives of stakeholders can contribute to the expanding envelope of uncertainty into the future, as shown in Fig. 2a. This can result in varying optimal solutions for the same problems.

Moreover, individuals' comprehension of system demarcation and functionality can be significantly influenced by their perspectives, and vice versa. This reciprocal relationship can lead to a nuanced interplay between knowledge and worldview. On the one hand, the same body of information can elicit divergent interpretations among stakeholders with differing worldviews. On the other hand, as stakeholders' understanding of the world evolves over time, their perspectives may also undergo transformation. This evolution can take two paths: their knowledge may become more refined and accurate, or conversely, if their knowledge becomes increasingly narrow or biased, their perspectives may become more limited or even radicalized. This shifting perspective can influence stakeholders' decisions throughout the solution process, leading to a spectrum of outcomes.

## 4. Scenario thinking applied to different sources of deep uncertainty in water resources management

The concept of deep uncertainty is underpinned by assumptions of the existence of multiple plausible futures acting in parallel worlds, which is best represented using scenarios (Godet, 2000a; Maier et al., 2016; Wu et al., 2023). Scenarios are descriptions of possible future alternatives or states of the world (SoW) and the different combinations of the course of events that may lead to them from the present time (Godet, 2000b). The use of scenarios for the planning of the future dates back to post World War II when the RAND Corporation used scenarios to support the US military (Amer et al., 2013; H. Kahn and Wiener, 1967). It was quickly adopted in most fields considering the planning of the future, including water resources management (WRM) (Dong et al., 2013; Pallottino et al., 2005; Vervoort et al., 2014). Scenarios are often characterized using critical variables that are deemed exogenous inputs to the system under consideration (i.e., the first source), e.g., various possible inflows into a reservoir system or factors contributing to the formulation of the problem, e.g., system boundary (Wu et al., 2023). However, scenario thinking can also be applied to characterize the differences in stakeholders' understanding of the system due to contested or incomplete knowledge (Lambert et al., 2012) or different world views (Lienert et al., 2015). This leads to different choices made in the solutions process, affecting problem formulation, technique selection, and final decision making. In this section, the manner in which scenarios or scenario thinking can be applied to address the three sources of deep uncertainty in WRM is discussed.

### 4.1. *Accounting for deep uncertainty due to changes in exogenous inputs*

Long-term changes in exogenous system inputs of water resources systems, such as precipitation, inflow, and demand (Herman et al., 2014;

Kasprzyk et al., 2012), have long been considered in WRM, as they play a critical role in shaping the water cycle and ultimately affect the balance between water availability and demand. These variables are often considered under the umbrella of long-term drivers such as climate change (Herman et al., 2014; Wu et al., 2017), population growth (Beh et al., 2015; Wu et al., 2017), and technological development (Wu et al., 2020).

A commonly used approach in WRM for dealing with this type of deep uncertainty is through a set of qualitatively or quantitatively distinct trajectories or values for exogenous inputs, or scenarios (Maier et al., 2016). Depending on the purpose of the study, scenarios can be developed using two different approaches to represent deep uncertainty by describing: (a) the possible conditions at a certain point in time when system performance needs to be evaluated, referred to as 'snapshot scenarios' (see Fig. 3a) (Giuliani and Castelletti, 2016; Marchi et al., 2016; Miro et al., 2021; Mortazavi-Naeini et al., 2015; Wu et al., 2017) or (b) the continuous changes of system state with time (i.e., trajectories) that will eventually lead to the end point of the evaluation period in the future, referred to as 'pathway scenarios' (see Fig. 3b) (Huang et al., 2024; Kim and Chung, 2014; Kwakkel et al., 2016a; Trindade et al., 2019; Yao et al., 2023). Therefore, they are also referred to as discrete and continuous scenarios, respectively (Dong and Giesen, 2011).

In the first approach scenarios are often used to describe possible conditions for a specific (discrete) future time, e.g., the year 2025 or 2050 conditions in the Optimal Mix project (Wu et al., 2017), the year 2030 and 2070 conditions in a study on water resources management in Southern California (Miro et al., 2021), the year 2030 and 2050 conditions in the design of a stormwater harvesting scheme in South Australia (Marchi et al., 2016), the year 2070 conditions in the planning of a complex urban bulk water supply system in Australia (Mortazavi-Naeini et al., 2015), and years 2096–2100 conditions in the long-term planning and management of the Lake Como system in Italy (Giuliani and Castelletti, 2016). These are based on different projections of exogenous inputs, typically water availability as a result of rainfall, temperature, and evapotranspiration, and demand as a result of population growth or policy changes (e.g., demand management) (Huang et al., 2025; Marchi et al., 2016; Miro et al., 2021; Mortazavi-Naeini et al., 2015; Wu et al., 2017; Wu et al., 2016). Sometimes different Representative Concentration Pathways (RCPs) as reported in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) and climate models (Giuliani and Castelletti, 2016) are also considered. Since these scenarios are used to represent deep uncertainty at a certain time in the future instead of the continuous pathway from the present to the future, time series data are not necessarily required. However, stochastic methods such as stationary time series data (Beh et al., 2015; Marchi et al., 2016; Raso et al., 2019; Wu, 2016) or Monte Carlo simulation (Mortazavi-Naeini et al., 2015) are often used to represent stochastic uncertainty due to natural variability at those specific future times.

In the second approach, however, continuous time series data are required to describe the changes in exogenous inputs with time through the evaluation period from the present to a specific future time. One common application of this approach is to use scenarios to describe time-dependent changes in climate affected variables such as temperature and precipitation (Basheer et al., 2023; Bhave et al., 2018; Huang et al., 2024; Marton and Knoppova, 2019; Spence and Brown, 2018). Sometimes they are based directly on the different IPCC RCPs to investigate the impact of different emissions levels (Kim and Chung, 2014) or different climate models (Smith et al., 2022). This pathway approach to applying scenarios has also been used to characterize changes in demand, e.g., due to population growth, and has often been used in water resources infrastructure planning studies (Beh et al., 2017; Borgomeo et al., 2018; Fletcher et al., 2017; Huang et al., 2024; Manocha and Babovic, 2018; Pachos et al., 2022; Roach et al., 2018; Yao et al., 2023). Another typical use of this approach is to develop Dynamic Adaptive Policy Pathways (Haasnoot et al., 2013) for WRM, where policy pathways are developed to identify a series of actions that can change due to continuous learning and feedback as new information becomes available (Chadwick et al., 2021; Haasnoot et al., 2024; Kwakkel et al., 2016a; Trindade et al., 2019; Werners et al., 2021). Consequently, the pathway approach offers a more natural framework for adaptive decision making compared to the snapshot approach.

### 4.2. Accounting for deep uncertainty due to lack of or contested knowledge and different worldviews

Deep uncertainty arising from incomplete or contested knowledge (i.e., the second source), or different worldviews (i.e., the third source) often manifests in similar ways in WRM, but imposes significant complexity, as they both involve human judgment as discussed above. Therefore, to solve WRM problems under deep uncertainty arising from these two sources of deep uncertainty, traditional approaches such as those relying on probability distributions become obsolete, and scenarios representing stakeholders' involvement are often developed based on *identifiable impacts*, rather than the underlying source of deep uncertainty that is not always apparent.

Despite the fact that deep uncertainty due to incomplete/contested knowledge or different worldviews can impact any stage of the solution process of WRM problems, the most common stage to account for deep uncertainty arising from these two sources is the final decision-making stage. At this point, a final solution needs to be selected from a set of solutions provided. There is a large body of literature on WRM decision-making accounting for stakeholders' preferences, with various methods developed, such as Multi-Criteria Decision Analysis (MCDA) (Belton and Stewart, 2002) and Analytic Hierarchy Process (AHP) (Saaty, 1988). As

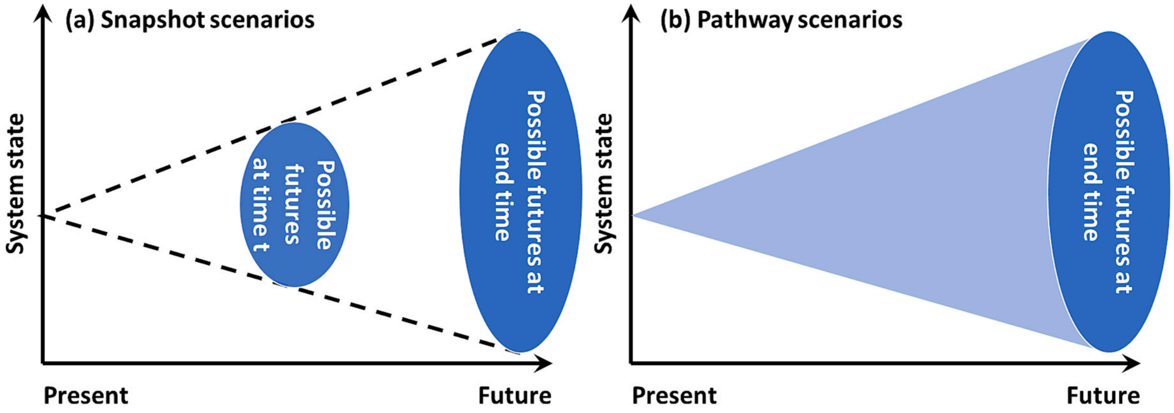

**Fig. 3.** Illustration of scenarios representing deep uncertainty arising from exogenous inputs of a system.

part of MCDA, stakeholders' preferences are incorporated into the decision-making process through the selection and weighting of decision criteria, as well as the evaluation of alternative solutions against these criteria (Hyde et al., 2005). AHP is a more structured approach, where complex decisions are decomposed into a hierarchy of criteria and alternatives (Gallego-Ayala and Juízo, 2014). Stakeholders' preferences are elicited through pairwise comparisons, where stakeholders assess the relative importance of criteria and the performance of alternatives. Irrespective of the method used, scenario thinking plays a critical role. Stakeholders' preferences can be seen as scenarios under which alternative solutions are evaluated. This helps stakeholders understand how their preferences and those of others affect the evaluation outcomes. Such understanding is essential for consensus-building and mitigating future risks arising from deep uncertainty due to incomplete/contested knowledge or differing worldviews.

However, incorporating deep uncertainty arising from incomplete or contested knowledge or differing worldviews at stages other than the final decision-making stage in WRM is more complex. To achieve this, a set of plausible narratives or stories tailored to different stakeholder groups needs to be constructed (an example is provided in Fig. 4), often via stakeholder engagement activities, such as stakeholder workshops and focus groups (Lempert and Groves, 2010). These narratives are then utilized to generate actionable strategies or quantitative data that can be incorporated into the solution process. Take the Optimal Mix project as an example, where a strong narrative for the selection of the simulation–optimization modeling platform was the government's motivation to move to a uniform modeling platform for all government projects, leading to the selection of a specific modeling platform. The narrative to exclude harvested stormwater and reclaimed wastewater for potable uses was based on perceived public health and safety concerns. This led to a decision by the project team (in consultation with the decision makers) to restrict these two water sources for non-potable uses only, thereby limiting the scope of the overall optimization problem. In both cases, alternative options and associated potential futures were not explored.

In contrast, the differing preferences of the decision makers and the public for the order in which different water sources are to be used were captured using different scenarios derived from different narratives obtained from stakeholder engagement activities. On the one hand, a business-as-usual narrative leads to one specific set of priorities to use water from different sources based on economic costs (i.e., one scenario). On the other hand, environmental concerns collected from focus groups led to a different set of priorities based on energy consumption and ecological concerns. Both scenarios were considered in the project and their impacts were investigated. This approach of considering multiple and sometimes conflicting stakeholder preferences in the solution process, especially during problem formulation, has recently been further developed into a formal approach called rival framings (Quinn et al., 2017), which uses several formulations of the problem side by side and explore their implications. This approach has been used in many recent WRM studies (Bertoni et al., 2019; Liu et al., 2022; Moallemi et al., 2020; Wheeler et al., 2018). Multiple problem formulations have also been used as part of formal optimization problems (Di Matteo et al., 2017).

It is evident that the impact of deep uncertainty on WRM due to incomplete or contested knowledge, or different worldviews can occur at any stage of the solution process and there are often no one-size-fits-all solutions to account for deep uncertainty resulted from human involvement. Consequently, the development of tailored solutions that make use of story narratives is key. This requires methods that go beyond the traditional systems approaches that rely heavily on numerical techniques and adopt scenario-thinking-based approaches (Wu et al., 2023).

## 5. Conclusions

The sustainable management of water resources is an existential issue for humanity. Deep uncertainty, stemming from non-stationarity in exogenous system inputs, stakeholders' incomplete/contested knowledge of the underlying processes, or differing stakeholder preferences and values, poses significant challenges to traditional WRM approaches. It has been recognized as a grand challenge of WRM, necessitating a paradigm shift towards embracing approaches rooted in scenario thinking, where scenarios are defined as various possible future 'states of the world' resulting from deep uncertainty. To facilitate the transition towards scenario thinking, this paper categorizes the various sources of deep uncertainty, elucidates their impact, and articulates how they can be accounted for through scenario thinking during the entire solution process for WRM problems via the use of real-world examples. It is evident that embracing scenario thinking offers a promising avenue to navigate the complexities of uncertain futures by exploring multiple plausible futures and their implications. It also offers a pathway towards

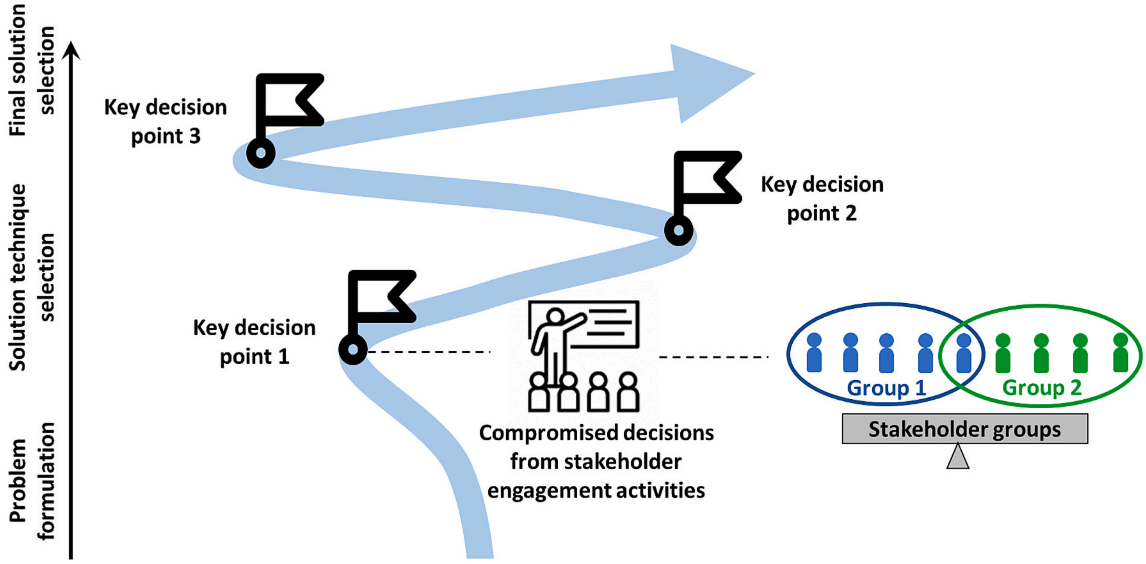

**Fig. 4.** Illustration of scenarios representing deep uncertainty arising from lack of or contested knowledge and different worldviews. The example shows how stakeholders' narratives may influence decisions throughout the solution process, i.e., compromised decisions made from stakeholder engagement activities (*assume two stakeholder groups with contested knowledge or different worldviews are involved at key decision point 1).

a better understanding of the complex interactions within water resources systems and the interactions with human society. This can lead to more informed and sustainable decision-making for the benefit of human society and the water resources system it depends on. By disseminating these concepts systematically, we aim to foster discussion and encourage the adoption of more sustainable and resilient water management solutions.

It should be noted that while this paper has focused on methods that are used to deal with deep uncertainty in water resources management, alternative approaches from other fields offer valuable insights for future research. For example, resilience thinking, which is widely used in urban planning, treats social and environmental systems as interconnected (Lempert, 2012; Sellberg et al., 2018). This can lead to approaches that promote not only adaptation but also transformation (i.e., restructuring systems when incremental changes are insufficient), such as pathway diversity that advocates for multiple available pathways into the future and the ability of management strategies to switch between them (Sellberg et al., 2024). Beyond modelling techniques, mixed-method approaches (e.g., multi-scale approach, three horizon approach) offer valuable tools for linking global uncertainties to national and local decision-making and exploring changes over time, thereby enabling a forward-looking, multi-level perspective on more complex decision-making contexts under deep uncertainty (Gunashekar et al., 2021; Mohapatra et al., 2025; Rutting et al., 2022). Future research could explore how to apply these complementary approaches to water resources management, thereby providing a more holistic strategy to address deep uncertainty.

## CRediT authorship contribution statement

**Wenyan Wu:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Leila Eamen:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Graeme Dandy:** Writing – review & editing, Methodology, Conceptualization. **Holger R. Maier:** Writing – review & editing, Methodology, Conceptualization. **Saman Razavi:** Writing – review & editing, Methodology, Conceptualization. **Jan Kwakkel:** Writing – review & editing, Conceptualization. **Jiajia Huang:** Writing – review & editing, Visualization, Data curation. **George Kuczera:** Writing – review & editing, Conceptualization.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Wenyan Wu reports financial support was provided by Australian Research Council. Wenyan Wu reports a relationship with Australian Research Council that includes: funding grants. Leila Eamen reports a relationship with Global Water Futures that includes: funding grants. Leila Eamen reports a relationship with Canada First Research Excellence Fund that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

Wenyan Wu acknowledges support from the Australian Research Council via the Discovery Early Career Researcher Award (DE210100117). Leila Eamen acknowledges support from Global Water Futures (GWF), the Canada First Research Excellence Fund (CFREF) project. Jiajia Huang acknowledges support from The University of Melbourne via the Melbourne Research Scholarship.

## Data availability

No data was used for the research described in the article.

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