Convergent and transdisciplinary integration: On the future of integrated modeling of human-water systems

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Abstract

The notion of convergent and transdisciplinary integration, which is about braiding together different knowledge systems, is becoming the mantra of numerous initiatives aimed at tackling pressing water challenges. Yet, the transition from rhetoric to actual implementation is impeded by incongruence in semantics, methodologies, and discourse among disciplinary scientists and societal actors. This paper confronts these disciplinary barriers by advocating a synthesis of existing and missing links across the frontiers distinguishing hydrology from engineering, the social sciences and economics, Indigenous and place-based knowledge, and studies of other interconnected natural systems such as the atmosphere, cryosphere, and ecosphere.

Specifically, we embrace ‘integrated modeling’, in both quantitative and qualitative senses, as a vital exploratory instrument to advance such integration, providing a means to navigate complexity and manage the uncertainty associated with understanding,
diagnosing, predicting, and governing human-water systems. While there are, arguably, no bounds to the pursuit of inclusivity in representing the spectrum of natural and human processes around water resources, we advocate that integrated modeling can provide a focused approach to delineating the scope of integration, through the lens of three fundamental questions: a) What is the modeling ‘purpose’? b) What constitutes a sound ‘boundary judgment’? and c) What are the ‘critical uncertainties’ and how do they propagate through interconnected subsystems? More broadly, we call for investigating what constitutes warranted ‘systems complexity’, as opposed to unjustified ‘computational complexity’ when representing complex natural and human-natural systems, with particular attention to interdependencies and feedbacks, nonlinear dynamics and thresholds, hysteresis, time lags, and legacy effects.

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Abstract

The notion of convergent and transdisciplinary integration, which is about braiding together different knowledge systems, is becoming the mantra of numerous initiatives aimed at tackling pressing water challenges. Yet, the transition from rhetoric to actual implementation is impeded by incongruence in semantics, methodologies, and discourse among disciplinary scientists and societal actors. This paper confronts these disciplinary barriers by advocating a synthesis of existing and missing links across the frontiers distinguishing hydrology from engineering, the social sciences and economics, Indigenous and place-based knowledge, and studies of other interconnected natural systems such as the atmosphere, cryosphere, and ecosphere.

Specifically, we embrace ‘integrated modeling’, in both quantitative and qualitative senses, as a vital exploratory instrument to advance such integration, providing a means to navigate complexity and manage the uncertainty associated with understanding, diagnosing, predicting, and governing human-water systems. While there are, arguably, no bounds to the pursuit of inclusivity in representing the spectrum of natural and human processes around water resources, we advocate that integrated modeling can provide a focused approach to delineating the scope of integration, through the lens of three fundamental questions: a) What is the modeling ‘purpose’? b) What constitutes a sound ‘boundary judgment’? and c) What are the ‘critical uncertainties’ and how do they propagate through interconnected subsystems? More broadly, we call for investigating what constitutes warranted ‘systems complexity’, as opposed to unjustified ‘computational complexity’ when representing complex natural and human-natural systems, with particular attention to interdependencies and feedbacks, nonlinear dynamics and thresholds, hysteresis, time lags, and legacy effects.

Highlights

- For transformative research and insight generation, the modeling paradigm must shift from predictive to diagnostic and exploratory.
- To overcome disciplinary barriers, we must focus on ‘systems complexity’ rather than ‘computational complexity’.
- To achieve success in integrated modeling of human-water systems, we must invoke sensitivity analysis and multi-fidelity modeling.

Keywords

Integrated modeling, modeling purpose, uncertainty, knowledge systems, disciplinary barriers

1. Why convergent and transdisciplinary integration?

1.1. Context

Integrated modeling is a process by which models of different but related systems, originating from different knowledge and sectoral domains, are connected to enable the exchange of knowledge and the representation of feedback mechanisms across a larger, more inclusive system. Integrated modeling has been subject to extensive research in the past two decades for integrated assessment within different scientific communities, to address complex problems in human-natural systems [Belete et al., 2017; Hamilton et al., 2015; Anthony J Jakeman and Letcher, 2003; Van Beek et al., 2020; Van Vuuren et al., 2012; Voinov and Shugart, 2013] However, the interdisciplinary links in integrated models of social-
ecological systems have arguably been biased towards biophysical processes, particularly those from meteorology, hydrology, the cryosphere and ecology, with slow progress on converging towards overarching ‘environmental system theories’ [Ayllón et al., 2018]. Extending such a theory to directly include the human and policy dimensions is advancing [Gain et al., 2020; Kelly et al., 2013] but needs much more attention compared to the modeling of biophysical processes alone [Zare et al., 2017]. This extension is hindered by several grand challenges, including the complexity of decision-making processes at individual or institutional levels, and epistemological barriers to bridge state-of-the-art social and natural theories [Elsawah et al., 2019; Mao et al., 2017].

More broadly, the significance of transdisciplinary scholarship [M G Lawrence et al., 2022], associated with ‘convergence research’ [National Research Council et al., 2014], post-normal science [Funtowicz and Ravetz, 1990], or systems integration [J Liu et al., 2015], has been widely recognized across all areas of science and engineering. In a recent workshop of the American National Academies of Science, Engineering and Medicine, ‘convergence’ was defined as ‘an integration of knowledge and ways of thinking to tackle complex challenges and achieve new and innovative solutions that could not otherwise be obtained’ [National Academies of Sciences et al., 2019]. The convergence of the life sciences, physical sciences, engineering, and social sciences has been referred to as a ‘revolution’ in some areas of research [Sharp et al., 2011]. As a result, research funding agencies are increasingly paying attention to convergence – for example, ‘Growing Convergence Research’ has been one of the “10 Big Ideas” of the National Science Foundation in the United States since 2017. Integrated modeling is often deemed a well-established framework to tackle the challenges associated with convergence and transdisciplinary scholarship.

Nevertheless, integrated modeling is a challenging endeavor. The goal of integration is not merely to dissolve knowledge systems into a modeling process but rather to uphold and preserve the integrity of these knowledge systems [Tengö et al., 2014]. Integrated modeling of human-water systems must acknowledge the multidimensional nature of water—not solely as a physical resource, but also as a cultural, social, and spiritual entity vital to the well-being, livelihoods, and identity of communities worldwide [E P Anderson et al., 2019; Sofi et al., 2020]. Additionally, as individual models typically arise from different disciplines (often with different semantics, perceptions, scales, and terminologies), integrated modelling can push the parties involved in these endeavors to the limits of their disciplinary and other comfort zones.

Integrated modeling should move away from the conventional, rather ‘prescriptive’, approach to modeling with established assumptions, rules, and anticipated behaviors, to a more ‘explorative’ approach. This involves actively seeking out new patterns, relationships, and dynamics within the subject of study, without preconceived notions or assumptions, aiming to uncover unexpected information, connections, or possibilities that may not have been previously considered. In this context, modelers from different disciplines continuously adapt their models and their interactions with reference to the greater whole to represent observed or speculated system behaviors that cannot be explained by individual models in isolation. In other words, integrated modeling can be seen as an inversion of ‘reductionism’, and perhaps even of Occam’s Razor, which has historically been the guiding principle of scientific discovery and decision support.

By moving away from ‘reductionism’ towards ‘convergent and transdisciplinary integration’, we aim to shift our focus from using models to assert ‘answers’, to using models as a means to explore questions, diagnose systems, and possibly to discover new questions, which might have historically been overlooked
but are crucial to ask. This shift is at the heart of the philosophy of exploratory modeling, which relinquishes the ideal of a model as a predictive tool that turns the best available knowledge into the best estimate of the future state of a system. Rather, under this philosophy, a model is perceived as a tool for interpretative thought and hypothesis testing, crafted to pinpoint and encapsulate a range of potential uncertainties and assumptions, thus exploring their implications and consequences [M P Anderson et al., 2015; Moallemi et al., 2020]. It also takes a societal problem perspective and recognizes the need to embrace multiple perspectives, not just within but outside the scientific community, engaging with other societal actors throughout the modeling process. Therefore, integrated modeling here is viewed in its broadest terms, encompassing not only coupling various models (e.g., social and hydrological models) but also cultural differences in advancing science and practice (e.g., Indigenous versus western ways of water valuation).

1.2. Our goal with this paper

This paper draws from the varied backgrounds of the authorship team, who have different experiences in transdisciplinary research, bringing together the knowledge of multi-disciplinary scientists and multi-sectoral stakeholders to identify persistent challenges in, and provide a perspective on the future of, integrated modeling of human-water systems. Our goal is to accelerate efforts in the research community to reach beyond standard framings of water-related problems and extend our frontiers to include contemporary cross-boundary disciplines and diverse worldviews. This is needed if we are to anticipate future pressures and proactively steward the water resources on which we depend. To do so, we discuss the interfaces between hydrology and its related environmental disciplines of the atmospheric, cryospheric, hydrogeologic, and ecosystems sciences, as well as its traditional applications to water management through water engineering and its broader societal interfaces including socio-economic systems and Indigenous knowledge. We argue that historical advances in integrated modeling have been primarily focused on technical, software and implementation aspects, but more remains to be done on the semantic, epistemic, and conceptual challenges of the ‘integration problem’. Several general and inter-related issues have persisted that require urgent attention if integrated modeling is to achieve its potential in serving science and society.

We hope this paper helps readers when pondering the following decisions in the process of integrated modeling of human-water systems at the river basin scale:

(1) What system components and processes need to be modeled for the problem in question?
(2) What level of fidelity (i.e., realism in terms of the level of detail or complexity) should be built into each individual model in terms of process representation and space-time scales?
(3) How should the different models be interfaced with one another (e.g., in a sequential, modular, or two-way coupling manner) to build the integrated model?
(4) How should uncertainty be handled in each model and in the integrated model as a whole?

and crucially
(5) How should the modeling process be conducted to engage societal actors to maximize the capture of relevant knowledge and the value of integration?
Regarding the last question, primary consideration needs to be given to good modeling practices that frame the modeling objectives using appropriate interest groups and experts, and that are cognizant with and transparent about the choices made at each step in the modeling chain. We emphasize the need for relevance-driven, multi-fidelity model integration, linking models with varying levels of fidelity to take advantage of the strengths of each individual model, while minimizing their weaknesses, to embrace and communicate uncertainty across sectors and disciplines.

We acknowledge that there are diverse perspectives in the literature regarding the concept of model complexity, particularly in relation to uncertainty. Oreskes [2003] presents a ‘complexity paradox’, which states that as the complexity of a model increases by incorporating more processes, the certainty in model predictions may actually decrease, even though our trust in the model may increase. Saltelli et al. [2020] argue that complexity can hinder relevance in mathematical modeling, cautioning that modelers may be seduced by the idea of adding unjustified complexity with the hope to more accurately represent reality. They warn that this quantification can backfire by inducing a false sense of certainty, which can have dire consequences in a decision-making culture that highly regards crisp numbers and narratives. Hunt et al. [2007] question whether certain models are too simple, which might hide flaws by leaving out important process factors or being too rigid for uncertainty analysis. Gupta and Nearing [2014] examine model complexity and uncertainty from an information theory perspective, advocating for models to be designed in a way that maximizes information extraction and learning from data within the specific context of interest. Pomeroy et al. [2022] argue that model complexity should not be confused with model completeness and realism, which can be achieved without dramatically increasing complexity. There is evidence, for instance, that coupling the energy and mass continuity equations in cold regions hydrology can reduce uncertainty because thermodynamics are so fundamental when dealing with phase change processes such as snowmelt, ground thaw, sublimation, and evaporation. Saltelli and Di Fiore [2023] emphasize the political nature of modeling, asserting that modelers should not convey more certainty than their models warrant, and politicians should not present their policies as solely dictated by select models. Nabavi and Razavi [2023] advocate for ‘responsible modeling’, a vehicle for exploring the complexities and uncertainties beyond their technical aspects.

In the present article we contend that the holy grail of integrated modeling is to find an optimal level of complexity with an adequate characterization of uncertainty. This may be reasonably approached, for a given problem, by careful deliberation among the parties involved in the ‘social process’ of integrated modeling in the light of three fundamental questions as outlined in the following section.

2. The three overarching questions

Before embarking on the “what” and “how” of integrated modeling, it is important to take a step back and consider three fundamental questions that can be overlooked or treated lightly. These questions, which should be addressed at the outset of integrated modeling, can help ensure that the modeling exercise is well-conceived and relevant to the problem at hand. Therefore, let us first revisit these questions and reflect on their implications.

Why do we model? Broadly speaking, mathematical models may serve three general purposes: (1) nowcasting and prediction, (2) scenario analysis, and (3) diagnostic learning [Razavi et al., 2022; P Yang et al., 2022].
The first is to look into the current time or foreseeable future and predict what has recently happened or will shortly happen, for example, interfacing with a local or regional weather modeling system to enable flood warning [Shi et al., 2015]. Another example is prediction in ungauged basins, where local observations are insufficient to describe current hydrological conditions – this was the focus of a Decade for Predictions in Ungauged Basins and has particular relevance to lesser developed and sparsely populated regions of the world [Hrachowitz et al., 2013; Sivapalan et al., 2003]. This directly supports real-time operations and control, emergency preparedness, risk management, disaster risk reduction and water planning and management at different levels, from individual citizens to local, regional or global institutions.

The second takes a what-if view of the future and aims to determine how a system might respond under new or altered conditions, such as changing climate, cryosphere, water management or land-cover [Maier et al., 2016]. Thus, scenario analysis supports long-term decision-making, for example, to respond to abrupt or transient changes, and aims to build resilience in human-controlled systems [Kwakkel, 2017].

The third, conversely, is more about looking backward, using models to simulate the past and present behaviour of a system to diagnose processes and determine why it behaves as it does. This supports the development and testing of new theories [Clark et al., 2016] and exploration of causations and attributions of observed behaviors to controlling factors, for example, to examine the impact of changing rain-on-snow phenomena on mountain runoff [López-Moreno et al., 2021], to explain the observed sea level rise in past decades and attribute this in part to groundwater depletion [Wada et al., 2016], or to attribute the impacts on downstream communities of dams, diversions, hydropower operations, or shifts in hydrology due to climate change [Rokaya et al., 2019]. Diagnostic and social learning may also bring modelers and model users along a journey to generate a shared vision about the system at hand and its responses to a plausible range of controllable and uncontrollable forces [Di Matteo et al., 2017].

The modeling purpose must always be clarified and articulated up front [Hunter et al., 2018]. This avoids not only the danger of addressing a less relevant problem but also the commonly-implicit aspiration of developing a ‘model of everything’ – analogous to the ‘theory of everything’ [Hawking, 1990] – which will in most complex problem settings be unachievable given the current state of knowledge, data and computational resources. However, setting the modeling purpose for a given problem is not always straightforward and requires careful deliberations of all parties involved - scientists, modelers, and end-users - around aspects such as reliability, usability and feasibility to ensure the model is fit for purpose [Hamilton et al., 2022]. For example, for real-time flood forecasting in temperate climates, a simple empirical or machine learning-based hydrological model may serve the purpose, particularly when the underlying real-world system remains structurally unchanged in the forecasting horizon of interest. However, the same model might fail if the purpose is to diagnose possible contributions of rain-on-snow, glacier melt, groundwater, or reservoir mismanagement to a major flooding event in the past because of its inadequacy in representing the relevant physics and human actions. Similarly, that same model might be restrictive or unreliable if the purpose is to evaluate scenarios of the effectiveness of nature-based solutions to flooding under climate change - such scenarios may involve extrapolation well beyond model calibration data.

The appropriate representation of human behavior in integrated models is also closely tied to purpose. In the first instance, one must decide what types of human interactions and forcings must be represented. But then follows the choices of what level of granularity must be attributed to the various actors. Although this choice applies to institutional and policy actors, it is especially challenging to choose the scale of
aggregation (of individuals) at which human behaviors are to be represented. Consider a model that is to be used for irrigation releases and/or water use compliance, versus one for long-term planning of water availability and demand. In the former case, the representation of actors may be at the level of an individual farm, whereas in the latter it may be at the scale of an industry aggregated over space by farm type. Such deliberations around purpose may be further complicated, particularly for scenario analysis and diagnostic learning, by a second, more critical question as follows.

**What is a sound ‘boundary judgment’ for a given purpose?** Boundary judgment relates to what is to be mathematically represented as relevant components within a model, i.e., the assumptions about what is inside versus outside the model. For example, in traditional hydrological modeling, processes governing how soils store and release water are deemed ‘endogenous’, whereas processes governing precipitation formation or vegetation dynamics are ‘exogenous,’ i.e., only affect the model through boundary conditions. Most hydrological models used to assess the impact of climate change on water resources overlook the impact of the vegetation’s response to climate change on evapotranspiration and thus runoff. Cryospheric processes may be considered both endogenous and exogenous in hydrological models, depending on their assumptions about the hydrological system and inclusion of cold-region processes [Pomeroy et al., 2022; H S Wheater et al., 2022]. Boundary judgements may even dictate the details of internal aspects of a model such as the time and/or space scales at which processes are represented. For example, water management models are typically run at weekly or longer time resolutions. But, if hydropeaking in a water management problem is of interest, the model will also need to represent the sub-daily reservoir releases that are used to meet peak daily electricity demand.

Poor boundary judgment may not necessarily compromise the accuracy of the model, but it can become a key barrier to achieving true convergence in an integrated modeling exercise. In other words, if a boundary judgment used to frame a problem is not well-informed and justified, the resulting solution may lead to cascading or undesired spinoff effects and unintended consequences. For example, research has shown that a poor boundary judgment in ‘system dynamics’ modeling, which is known for its integrative capacity due to explicit representation of system archetypes and causal loop diagrams, can result in the exclusion of the most pressing and controversial aspects of water rights, leading to catastrophic unsustainability [Nabavi et al., 2017]. In principle, ‘the setting of model boundaries is not merely a technical issue—it is an ethical one’ [Nabavi, 2022]. Decisions around a model’s boundaries can be influenced by those who commission and use the model [Hassanzadeh et al., 2019]. Therefore, they may define not only what is important, but also what ought to be done.

Lastly, boundary judgment is not only about the range of responsibility accepted by modelers, which facilitates legitimation of the models they develop. Often, modelers tend to adjust the boundaries of their work to fit their own disciplinary training, available data and resources, or to avoid controversial issues. On a deeper level though, boundary judgments should be viewed as enablers for the appropriate representation of complexity, feedback mechanisms, and trade-offs, known or unknown, that are otherwise hard to capture and quantify. An illustrative instance is found in the realm of integrated food-energy-water system (INFEWS) modeling, where the discernment of boundaries and the flow of information across them hold paramount significance [Cai et al., 2018]. With this perspective, modelers may wish to work with societal actors to expand the boundaries of their model realm as much as possible. However, what runs counter to such a desire are the possible trade-offs with modeling uncertainties, which brings us to the third question below.
What are the ‘critical uncertainties’ for the modeling purpose and boundaries? Uncertainty, particularly in mathematical and engineering disciplines, has traditionally been treated through probability theory - a mathematical construct that assumes that we can describe our uncertainty or ignorance through probability distributions. Consider, for example, the case of flood frequency analysis in the design of water infrastructure. Resorting to probability theory has provided a pragmatic approach to tackle water systems problems that are complex, open, non-stationary, and only partially observable. This approach, however, may have limitations for integrated modeling problems.

One key limitation is that uncertainty and randomness may be viewed differently in different disciplines and with different political capacities, such that reconciliation within one probabilistic framework may not be feasible. For instance, traditionally, hydrologists have focused on using Bayesian statistics to determine the likelihood of parameters, initial conditions, input errors, and/or model structures, and subsequently, prediction uncertainty [Freer et al., 1996; Han and Coulibaly, 2017; Moradkhani et al., 2005]. On the other hand, atmospheric scientists have emphasized predictive uncertainty arising from chaotic behaviors within a system with much less attention to parameter calibration [Slingo and Palmer, 2011; Train et al., 2021]. Sustainability scientists, in contrast, have predominantly represented uncertainty through policy scenarios such as emissions trajectories and socioeconomic pathways [Guivarch et al., 2022; O’Neill et al., 2020]. Management scientists have addressed uncertainties through mathematical programming methods such as two-stage programming [Huang and Loucks, 2000] and fuzzy programming [C-S Lee and Chang, 2005]. Some economic analyses address uncertainty by conducting local sensitivity analysis on expected outcomes, a concept commonly referred to as ‘shadow prices,’ especially when dealing with resource-related uncertainties [Dragicevic, 2019].

Another limitation is that many modeling uncertainties are epistemic (e.g., [Beven, 2016]), in the sense that models have a poor representation of some dominant processes, interactions, and feedbacks, meaning that probabilistic distributions of model outputs do not explicitly include key sources of uncertainty, and hence probabilistic predictions may be unreliable.

There are other challenges in adopting a probabilistic framework to address uncertainty, even if all uncertainty sources across a system can be consistently described using probability distributions. In integrated models, the uncertainty space can be high-dimensional, and uncertainty characterization incurs a substantial computational burden. Moreover, there is the risk of an ‘uncertainty explosion’ when accounting for all possible sources of uncertainty in a probabilistic sense. In such situations, the range of uncertainty can increase significantly, sometimes exponentially, due to compounding or interaction effects of uncertainty sources, making the overall uncertainty much larger and more complex than the sum of individual uncertainties. Any representation of excessively large uncertainty, which might actually be a true representation of our ignorance, may render our integrated modeling efforts useless and block science advancement or decision support.

These challenges require new ways of thinking about the notion of uncertainty – e.g., through scenario discovery [M P Anderson et al., 2015; Maier et al., 2016] – that identify and characterize the uncertainty sources that matter the most, that is, the critical ones, for a particular modeling purpose and boundary judgment. We will revisit these points in Section 4 after exploring the frontiers of hydrology with some other disciplines below.
3. Convergence frontiers

With a hydrology-centric view of convergent and transdisciplinary integration, we contemplate the existing and missing links across hydrology frontiers with engineered works and social systems more generally, including socioeconomics, cultural flows and stakeholder (including Indigenous rights-holder) knowledge, as well as other interconnected natural systems, including the atmosphere and cryosphere (Figure 1). While groundwater is an integral part of the terrestrial hydrological cycle, we have dedicated a separate section to it due to its unique challenges. We further note that whereas, in principle, environmental flows require deep integration with the ecological sciences, in practice, pragmatic decisions are often made by water engineers, influenced by societal perspectives.

![Diagram of convergence frontiers with surface water hydrology](image)

**Figure 1.** A summary of convergence frontiers with surface water hydrology and associated challenges discussed.

The significance or insignificance of those links in framing the model ‘integration problem’ depends on the ‘research questions’ at hand. Identifying the right research questions, however, may not always be easy and requires careful deliberation among the parties involved, not only at the outset of the process
but also throughout. Over the course of the social process of integrated modeling, research questions (and the research pathway in general) may be refined, and new and important (but previously hidden) questions may be discovered. Accordingly, the three overarching research questions outlined in Section 2 may need to be revisited frequently to ensure the alignment of the framing with the possibly ever-evolving research questions [Zare et al., 2020].

Each of the following subsections begins with a set of sample research questions relevant to one of a set of representative frontier topics. By considering such sample questions, the interdisciplinary research team can begin to deliberate and develop a shared understanding of the problem at hand and the types of models and integration methods that might be needed to address the research questions posed. Such deliberation can help all members of the research team avoid their individual, disciplinary-focused cognitive bias. It is necessary to critically evaluate the potential limitations of one's own tools or perspectives in problem-solving, decision-making, or policy-making contexts, and emphasize the need to seek out alternative tools or perspectives when tackling complex problems. After posing the questions, each subsection delves into crucial aspects and challenges essential for converging into a broader integrated framework.

3.1. Water Resource Engineering

How can we configure a hydrology model for heavily regulated watersheds? How does a change in hydro-climatic regime affect water management? How do water diversions and irrigation change the evapotranspiration and runoff regime in a basin? How can a reservoir attenuate or amplify flood risk under climate change and new extremes?

The traditional interface between hydrology and water management for human systems has been Water Resource Engineering. Although adjacent, these disciplines have until recently been dominated by different perspectives, based on different needs and audiences. There has been increasing momentum in recent years towards integrating water engineering, including reservoirs, diversions, and irrigation, into hydrological models, including for improving the simulation of the terrestrial water cycle at regional to global scales using hydrology-land surface models (H-LSMs) [Nazemi and Wheater, 2015]. This momentum is a manifestation of a major shift in the focus of hydrological scientists and water resource engineers. Historically, the former group ignored or had a rather simplistic view of water resources management when developing their models – for example, by representing dams and reservoirs using a natural lake model [Döll et al., 2003]. The latter group tended to use rather simple hydrology models to feed into their complex water system models (WSMs) – for example by coupling a simple, lumped rainfall-runoff model with a rigorous node-link, network flow model of water resources systems [Bhave et al., 2020; Cai et al., 2003; Goshime et al., 2021; Karim et al., 2015].

The different worldviews of the two groups were perhaps rooted in their different research objectives and disciplinary backgrounds. Hydrology-land surface scientists primarily focused on understanding how natural systems work and predicting their behavior under past and future conditions. The objective of water resources engineers, however, was to focus on human-driven (engineered) systems and optimally plan, operate, or manage water resources under current or altered hydrologic and/or socio-economic conditions. However, there is increasing recognition that hydrological systems are intrinsically human-natural systems, given the pervasive effects of human activities on land use and management as well as water systems world-wide [H S Wheater and Gober, 2015]. Recently, the research objectives of the two
groups have expanded to include a more comprehensive view of the terrestrial component of the water cycle and, as such, the modeling approaches in both communities have started to converge.

The resulting synergies have led to extensive research efforts to bring the two worlds together – for example, see reviews by Nazemi and Wheater [2015] and Pokhrel et al. [2016]. The prime objective in these efforts has been to develop H-LSMs that work credibly in heavily regulated watersheds. A credible model in this context has generally been deemed one that fits both observed natural and regulated historical streamflow data. Substantial progress has been made by proposing a variety of new modules to represent components of water management in H-LSMs. These modules have been developed with varying degrees of complexity, from simple if-then rules based on standard operating strategy [Draper and Lund, 2004] to piece-wise linear relationships derived from available knowledge bases and data [Y Chen et al., 2022; Turner et al., 2020; Yassin et al., 2019], to complex purely data-driven strategies using machine learning techniques [Coerver et al., 2018; Ehsani et al., 2016; Li et al., 2022a]. Different studies report varying degrees of success in reproducing observed streamflow across local, regional, or global domains.

However, it has been shown that an H-LSM even with no representation of water management can be calibrated to data from a regulated watershed and generate ‘acceptable’ performance in the eyes of hydrologists [Dang et al., 2020a]. This performance is partly because model parameters associated with soil storage capacity can be manipulated to represent (at least partially) the controlled store-and-release mechanisms of reservoirs. After all, we have known for a long time that our highly-parameterized computational models can be tweaked to reproduce virtually any desired behavior, as articulated by Hornberger and Spear [1981] more than four decades ago in the context of models that were substantially less complex than the models of today. So, perhaps, there is now a need to shift attention from a curve-fitting exercise on historical records for simulating reservoir releases to a more holistic platform that enables emerging research questions facing society to be addressed. In doing so, six major challenges require immediate attention:

1. Embrace systems approaches. The design of modules representing reservoirs and water withdrawals in H-LSMs is generally based on an assumption (explicitly or implicitly) that such operations are ‘point-based’ and independent from other components in a watershed system. For example, to simulate releases from a reservoir, these modules do not account for the linkages between the management of other reservoirs and infrastructure in a basin. This is despite the fact that WSMs have for decades used systems approaches to study water management as a whole and consider the interactions and interdependencies between various components, rather than focusing on individual parts in isolation. Recent progress has been made to develop software for incorporating reservoir operation optimization into H-LSMs [Dang et al., 2020a; Dang et al., 2020b; Peñuela et al., 2021; J Wu et al., 2020]. However, more work is required to move away from ‘linear thinking’ in the integration of natural hydrology and water management towards integration paradigms rooted in ‘systems thinking’ [Newman et al., 2019; Simonovic, 2012; Williams et al., 2017].

2. Account for non-stationarity and changes in hydrology, water policy, and human-water feedback. The operational strategies for reservoirs and diversions that are built into H-LSMs are generally assumed to remain stationary over time. These strategies may work acceptably when calibrated and tested on historical data, but they lose their credibility under future scenarios that are different from the past. This is because real-world water operations are generally dynamic and respond to changes in hydro-climatic and/or socio-economic conditions. For example, a set of reservoir rule curves derived based on the status quo may result in frequent, unrealistic flashy spills under a possible wetter future scenario. On the other
hand, water policy and regulations may change abruptly or gradually over time to respond to changing socio-economic needs. For example, in the wake of the catastrophic floods in Alberta in 2013, the operation of the hydropower Ghost Reservoir dam upstream of Calgary was changed to provide flood control capacity for spring high flows [Fletcher, 2016]. Or in Queensland, Australia, the operational purpose of the Ross River dam has gradually shifted in recent decades from flood protection in the 1970s towards water supply of the downstream city of Townsville [Razavi et al., 2020]. Another example to consider involves the complex feedback between humans and water, often referred to as the “levee effect”, concerning the increase in development due to a false sense of security stemming from disaster mitigation projects [Burton et al., 1968; Di Baldassarre et al., 2018]. Or, in the Ningxia Yellow River irrigation district, China, conversion of rice-growing land to wheat or urban areas since 2012 reduced irrigation, lowering the water table and streamflows [Li et al., 2022b]. Accounting for such abrupt or gradual changes requires proper mechanistic representations of operational decision making under deep uncertainty in future climate, technological, and societal changes, through discovering and using plausible future scenarios [Maier et al., 2016; Wu et al., 2023].

3. Resolve numerical incompatibilities of H-LSMs and WSMs in space and time. These two different groups of models have historically evolved based on different ontologies and conceptualizations. As a result, there exist at least three typical sources of incompatibilities between the two groups of models: spatial discretization schemes, time scales, and numerical solvers. The first is about the fact that natural process representations in H-LSMs have historically been raster-based (e.g., grids) while the representation of human-driven processes in WSMs is typically vector-based (e.g., nodes and links). Often, multiple human-driven features such as reservoirs or irrigation districts may fall within a single grid cell of an H-LSM, complicating the interfacing of the two conceptualizations. The second arises from the fact that H-LSMs run on daily or sub-daily time resolutions whereas WSMs typically run on weekly, monthly, or longer time resolutions. The third is that H-LSMs simulate one discrete data window at a time (as dictated by the temporal resolution of the forcing data), while many WSMs (e.g., based on dynamic programming) look for operational solutions that are ‘optimal’ in a longer-term sense, spanning several time steps, through strategies such as ‘hedging’ to mitigate the risk of water shortages or excesses in the future. Therefore, the exchange of information between the two requires interfaces that can reconcile such incompatibilities. Cai [2008] provides insights and recommendations on how to ‘match’ different scales in hydrology and economics.

4. Revisit approaches to estimating water demands, actual abstractions, and return flows. A range of water uses may exist in a basin arising from domestic, industrial, or agricultural demands. These demands typically change in time and space in response to changes in climate, economy, technology, and demography of a region. However, current methods for estimating these demands are often ad-hoc and highly uncertain [Puy et al., 2022]. Traditionally, external functions have been used to estimate these demands for H-LSMs based on approximate variables and assumptions such as irrigation demand being primarily driven by potential evapotranspiration and irrigated crop acreage. Consequently, water use is often overestimated in these models because they either assume that demands are always satisfied or fail to incorporate appropriate constraints on water availability for abstraction [Zhou et al., 2020]. In reality, different water demands may compete, and their supply may be via complex connected surface water supply systems through storage and diversion, and/or via conjunctive use of surface water and groundwater. Return flows to main water bodies can be significant but are very difficult to estimate, as they depend on terrain, cropping pattern, irrigation approach, available drainage, and treatment technologies [Li et al., 2022b]. These return flows could play a crucial role in multi-district water
management. Over- or under-estimating return flows may lead to potential violations of transboundary water agreements. Therefore, it is essential to develop new approaches to estimate and represent water demands, actual abstractions from groundwater and surface water bodies, and return flows within H-LSMs accurately. Such future developments can take advantage of the information and capabilities built in H-LSMs, such as irrigation volume, simulated moisture and energy available in the root zone, enabling estimation and representation of water demands in an online manner.

5. Formalize regional differences in water management. Water management practice is inherently region-specific as people in different parts of the world may follow different philosophies, values, and rules, unlike natural processes such as evaporation that may be based on somewhat universal processes and principles. For example, different countries or states may have different systems of water rights, licensing and allocation, and priorities, and may view benefits and costs (monetary and non-monetary), tradeoffs between competing objectives, and transboundary water issues differently [Apurv and Cai, 2021]. Therefore, it is non-trivial to transfer knowledge from one region to another or to implement a WSM for large areas with a heterogeneous water management landscape. This is in contrast to typical H-LSMs that can scale to cover large areas relatively easily, even the global land area. Such heterogeneity in human processes – further complicated by different extents of data availability in different parts of the world – limits the functionality of a single approach everywhere. It is crucial to account for the diversity of water management practices by classifying regions based on their water management structures and data availability. This can enable the development of mechanistic, region-based water management modules that are tailored to the unique characteristics of each region, thereby enhancing the accuracy and applicability of H-LSMs.

6. Move beyond reservoirs to include other socio-economic factors. The vast majority of research on integrating water management into H-LSMs focuses on the representation of reservoirs and diversions. While they are perhaps the most prominent features of water management, they provide only a partial view on possible interactions of water-human systems. Simulating reservoir operation merely based on optimization to meet water demands may ignore human behavior under uncertainty by assuming that dams and other engineering works are operated in a completely rational way [Coerver et al., 2018]. In reality, the operation of reservoirs is connected to a vast array of socio-economic factors, including those that are not directly dependent on water [Eamen et al., 2021]. These factors may include political decisions, cultural beliefs, and power dynamics, and water pricing policies, that affect how water is allocated and managed. Understanding these factors and how they affect each other is particularly important, as these interactions are likely to change into the future as a result of social, environmental, economic and technological changes [Cominola et al., 2023; W Wu et al., 2020; Yao et al., 2023]. Therefore, a socio-economic lens is required to broaden the scope of linking water engineering and hydrology, as outlined in the next section.

3.2. Socioeconomics

What are the economic impacts of changes in availability and timing of flows? How may water shortage due to climate or policy change affect non-water-using industries? How may inter-sectoral and cross-regional transactions control water demand and management? How may a change in water policy affect the hydrology of a basin and/or rural communities? How can the hydrology of a region affect global trade and policies and vice versa? How do values and norms affect human behavior and decision making in water use?
Water is a component of a complex coupled human-natural system where water demand and availability are mutually influenced and strongly affected by population growth, economic development, food and energy production, land-use change, carbon policy, and climate change. Recognition of the socio-economic aspects of hydrology to address growing challenges pertaining to water security dates back at least to the Harvard Water Program in 1955 [Reuss, 2003]. Since then, the field of water resources systems analysis has gradually evolved to account for coupled human and hydrologic processes, with the aim of advancing scientific understanding and informing decision making [Iwanaga et al., 2021; Marston and Cai, 2016; Rosegrant et al., 2000; Simonovic, 2012; Simonovic and Fahmy, 1999]. While there has been notable advancement in this field, progress has been slowed by the differing disciplinary backgrounds of hydrologists, economists, and social scientists.

Engineering economics has been a part of the curriculum at engineering schools for decades. Consequently, many hydrologists are accustomed to incorporating various ‘economic (production) functions’ into water system models (WSMs) to estimate revenues and costs associated with decisions related to water resources. These economic functions typically focus on hydropower and irrigation, deterministically quantifying the benefits and costs of operations based on exogenous inputs such as electricity price, water trading benefit, and crop pattern and prices [Harou et al., 2009; K Li et al., 2019; Nguyen et al., 2017]. With such economic functions, WSMs can not only estimate financial implications of different management options but also facilitate the identification of trade-offs between economic and environmental and social objectives. These models aim to provide optimal solutions within a specific domain. However, the economy may be striving for ‘equilibrium’ across various domains, including supply, demand, investments, and labor — a state where forces are balanced, leading to stability in these economic facets. Therefore, it is important to fully understand how decisions derived from WSMs interact with other sectors.

On the other hand, economists have a long history of developing hydro-economic models based on general or partial equilibrium theories [Calzadilla et al., 2011; Rosegrant et al., 2002]. The former analyzes the behavior of the entire economy, taking into account the interdependencies between different markets and sectors, whereas the latter focuses on analyzing the behavior of specific markets or sectors in isolation. A major shortcoming of these models is that they primarily involve monetary flows, which do not necessarily account for the complexities of hydrology and the physics of the water system involved. Simplistic assumptions are often made to introduce water flows to hydro-economic models, which can limit their accuracy in capturing the full range of interactions between the economy and water systems. For example, input-output economic models may account for water by assuming sectoral production is linearly proportional to the existing sectoral water-use data. This assumption is generally deemed acceptable when there are no changes in the amount of available water supply. However, it may become misleading in cases of alterations in water availability due to factors such as climate change or policy interventions [Eamen et al., 2022].

Further, optimality theory, an assumption that individuals make decisions that maximize their utility or profit, is still a mainstream assumption among water researchers in the simulation and management of water resource systems. Other behavioral models, however, have been developed by social scientists to analyze how individuals make decisions, e.g., around water consumption and efficiency, under psychological factors and changes in policy and the environment, for example, based on prospect or bounded rationality theories [Du et al., 2020; Dziubanski et al., 2020; Ghoreishi et al., 2021b; Haer et al., 2019]. Prospect theory tries to explain how individuals are more sensitive to losses than gains, which may
have implications for how water-related risks are perceived and managed [Noël and Cai, 2017]. Bounded rationality, on the other hand, suggests that individuals are limited in their ability to process information and make rational decisions due to cognitive and time constraints, which may affect their ability to adopt more sustainable water use practices or respond to changing water policies.

Furthermore, it is well-known that the redistribution of water through engineering works and relocation of people through migration have major limitations when compared to the redistribution of water and land in their virtual form. Virtual water and land, which are embedded in food and agricultural products, flow along socioeconomic gradients through global trade networks, crossing national and continental boundaries. This cycle is human-induced and can be seen as a socioeconomic counterpart to the natural hydrological cycle [Abdelkader et al., 2018]. The variability in water and fertile land around the world has resulted in a global food trade network, with each region acting as both a virtual water and land exporter and importer [Allan, 2003]. Despite the recognition of the interdependency between local/regional water systems and the socio-economy of the rest of the world, a vast majority of efforts for water resources systems analysis overlooks such interdependencies in their boundary judgments, often for practical reasons.

By bridging socio-economic theories, scopes, and associated standards with those of the conventional, engineering-oriented solutions, water managers and policymakers may be better equipped to design interventions and policies that respect the complexity of socio-economic systems and decision-making processes at different scales. This endeavor may be pursued along the following six dimensions:

1. **Address scale incompatibility between hydrology and socioeconomics.** The processes of data collection and attribution around hydrology and socioeconomics have traditionally been developed independently, serving fundamentally different purposes. Hydrologic datasets follow watershed boundaries with a relatively fine-resolution in both space and time, often representing flows at every stream with time resolutions ranging from sub-daily to monthly scales. On the other hand, economic data are generally framed and collected at coarse spatio-temporal resolutions, generally respecting political boundaries such as provinces, states, or countries and at annual or longer-term scales. The resulting models of hydrology and socio-economy have historically been serving different purposes. The former group addresses questions around hydrologic understanding and water management at the hillslope or catchment scale in the face of flood and drought, while the latter is concerned with questions, for example, related to the impact of a policy on income distribution and poverty rate, of a technology on labor markets and employment patterns, or of regulations on trade and commerce. As such, integrating current-generation models of hydrology and socio-economy is not straightforward and demands extensive, often unverifiable, assumptions to reconcile their scale incompatibility in data collection, synthesis, and processes representation [Eamen et al., 2022]. Investments are needed to develop socio-economic data collection campaigns that support integrated modeling at scales relevant to water resource systems analysis [Cai, 2008; Rosegrant et al., 2002].

2. **Broaden the perspective beyond primary water-using economic sectors.** The common practice in WSMs tends to narrow the boundary judgment to the main socio-economic sectors that directly use water, such as hydropower and irrigation, with increasing attention to cultural and environmental needs. This practice, however, does not account for the fact that water-using sectors may be closely tied to other economic sectors, even those that are seemingly water-independent, through inter-sectoral and inter-regional transactions. For example, only around 30% of economic sectors across the Saskatchewan River Basin in Canada directly depend on water, while the indirect contribution of water to the rest of the...
economy is quite significant [Eamen et al., 2021]. The benefit and cost of water availability and allocation can reach distant sectors such as information and cultural industries. To capture this complexity, water resources systems analysis needs to broaden its boundaries and develop interfacing mechanisms that bridge local-scale water operations to larger-scale economies and seek equilibrium across sectors and regions.

3. Refine industry classifications to better match water use and economic sectors. Different countries may possess different systems of national accounts on which basis the economy may be disaggregated into sectors. These systems may not always adequately align with direct water-using sectors at the scales needed for water management. In such cases, simplistic assumptions are often made to map different industry classifications. For example, the Canadian System of National Accounts does not distinguish between irrigated and rainfed agriculture in most economic datasets, such as input-output tables. To align with the classifications of water-using sectors in WSMs, we need to make certain assumptions to partition agricultural production into irrigated and rainfed categories. One such assumption could involve splitting agricultural production based on the proportion of irrigation production in comparison to the total agricultural output [Eamen et al., 2020]. Even though such assumptions may be verified and improved at specific times and on a case-by-case basis, revisiting and recasting industry classifications based on their level and shape of dependency to water will provide the groundwork for improved integration of WSMs and economic models.

4. Identify and enable the representation of feedback loops between water management and socioeconomic actors. The integration of models representing water and those representing socioeconomic agents have typically been one-way, primarily hydrology and water policy influencing water use and economy. While it has long been known that the influence can be bi-directional, it remains a major challenge to identify, characterize, and represent the possible emergence of feedback loops between water and society [Di Baldassarre et al., 2015; Loucks, 2015]. One example of such feedback loops is the rebound phenomenon, also called Jevons paradox, which describes a situation where policy instruments designed to improve water-use efficiency may counter-intuitively lead to higher water use in the long run [Ghoreishi et al., 2021a]. Efforts have been made to model existing feedback mechanisms. For instance, to illustrate the feedback between farmers’ decision-making processes and hydrology, Esteve et al. [2015] combined a socio-economic model, which simulates how farmers alter cropping patterns based on economic factors, with a WSM, which simulates the availability and distribution of water under various scenarios. Such studies provide valuable insights; however, the fundamental challenge lies in identifying complex behaviors and effectively encapsulating them within integrated models as the mere amalgamation of various models does not guarantee the emergence of real-world behaviors.

5. Connect models of local/regional water systems to the global economy, national and international policies, and trades. The boundary of a vast majority of water problems is set to be limited to watershed divides, assuming external trades and prices as exogenous scenarios that may or may not change over time. While such a boundary judgment is generally deemed valid for a range of water problems, it may undermine important feedback mechanisms between local water systems and the rest of the world. For example, the Canadian Prairie Provinces are the world’s largest exporter of peas, lentils, durum wheat, mustard seed, canola, flaxseed, and oats, yet their population, collectively, is far less than 0.1% of the world’s population. Therefore, international trade plays a major role in the region’s economic volatility, with possibly significant two-way feedback mechanisms [Rosegrant et al., 2002].
Recognizing such broader, often global, socioeconomic dynamics that surround local water systems, Integrated Assessment Models (IAMs) provide unprecedented opportunities to understand important feedback mechanisms, synergies and trade-offs, and critical interdependencies [Van Beek et al., 2020]. IAMs are process-based computational models that integrate knowledge and interactions across sectors over long time-scales (i.e., decades to century) to inform decision making under changing socioeconomic and climate conditions in different contexts, such as climate mitigation [Guivarch et al., 2022], food production [Bodirsky et al., 2022], land-use change [Popp et al., 2017], and sustainable development [Moallemi et al., 2022]. IAMs have been the backbone of projections and response strategies in the Intergovernmental Panel on Climate Change, EU Commission Climate Target, and the International Energy Agency Energy Outlook, among others [Koasidis et al., 2023]. These models have different types of structures such as general or partial equilibrium [Cantele et al., 2021], or system dynamics stock-and-flow [Q Liu et al., 2023]. They may provide a range of sectoral coverage such as food-land or energy-climate at different scales and spatial resolutions (e.g., national or global).

Beyond climate change mitigation, IAMs are versatile tools with potential applications in tackling a broad spectrum of complex challenges within the water sector, of which three avenues are outlined, each with an example in the following: (1) Water demand and supply dynamics. Dolan et al. [2021] enhanced the hydrological component of a global Integrated Assessment Model, called GCAM, to capture the diversity and complexity of water demand (i.e., for irrigation, livestock, municipal, manufacturing, primary energy, and electricity generation) and water supply (i.e., surface water and renewable groundwater, nonrenewable groundwater, desalinated seawater). (2) Economic impacts of water policy change. Birnbaum et al. [2022] used an IAM to analyze how water scarcity and its economic impacts vary in Latin America and the Caribbean under different global scenarios of multisector dynamics across systems and scales. (3) The impacts of global policy actions on local water systems. Giuliani et al. [2022] used an IAM to investigate how water, energy and food systems are interconnected and how global climate mitigation policies impact African river basins locally.

6. Account for possible shifts in the global socio-economy. The global virtual water and land trade, which had been considered a reliable means of balancing global food supply and demand for decades, has come under scrutiny due to a series of crises. The COVID-19 pandemic and the Russia-Ukraine war are just two examples of events that have disrupted global trade networks and raised concerns about disruptions that could compound the negative consequences of natural disasters, such as droughts, which can impact producer countries. Consequently, the concepts of food self-sufficiency and food system resilience are gaining more attention than traditional food security in a fully connected global network. Preparing for such possibilities requires integrated modeling systems that can envision and account for such relatively rapid dynamics towards new global equilibriums. While the use of IAMs may prove useful in this context, further research is needed to generate and discover a range of plausible future scenarios that must be considered in planning and decision making.

3.3. Water Quality, Ecosystem, and Cultural Flows

How can water quality dynamics be integrated into large-scale hydrology-land surface models? How does a change in river flow regimes due to climate change or water management affect the health of aquatic systems? What operational or structural interventions can be taken to restore and enhance the health of downstream biodiversity and ecosystem resilience? How can flow properties be attributed to cultural needs, particularly in Indigenous and local communities?
Water researchers and practitioners have a long history in estimating and maintaining environmental flows - defined as the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being [Arthington et al., 2018] - primarily based on either natural flows or ecosystem service paradigms [Alexandra et al., 2023]. However, the approach to incorporating environmental flows into water management policies and practices is often limited to minimum thresholds of acceptability primarily based on flow percentiles - an approach that has long been in use (e.g., [Tennant, 1976]) - although there have been some exceptions [J Szemis et al., 2013; J M Szemis et al., 2014]. This is despite the fact that there has been substantial research progress to relate the health of aquatic ecosystems to signature properties of flows [Monk et al., 2006; Poff et al., 2010; Schnier et al., 2016; Y Yang et al., 2008] and water quality variables [Vaughan and Ormerod, 2014].

In addition to the quantity of environmental flows, the water quality pressures on ecosystems are an additive pressure due to economic development, urbanization, climate change, and political modifications [Hannah et al., 2022; H Wheater and Gober, 2013]. Climate and human factors influence water quality through various mechanisms; solar radiation and cloud cover controls water temperature and photosynthetically active radiation. Wind speed and direction leads to sediment and nutrient resuspension in the water column. Ice cover blocks the wind stress and oxygen exchange. Hydrology is equally dependent on climate, and impacts water quality in both natural and regulated systems. Flow rate influences waterbody residence time, nutrient cycling, and oxygen concentrations. Precipitation brings nutrients in runoff that is heavily dependent on land use in the catchment. Air temperature determines the magnitude of freshet flows from snow melt, and in turn sediment transportation. Climate, hydrology, and land use combine to regulate which aquatic species have competitive advantage and shifts species composition going forward.

A parallel concept called ‘cultural flows’ has been gaining attention in recent years, based on a recognition that water is not only a physical resource, but also a cultural, social, and spiritual entity, that is central to the well-being, livelihoods, and identity of many Indigenous and local communities around the world [E P Anderson et al., 2019; Sofi et al., 2020]. Cultural flows are relational, and often linked to specific places, such as rivers, lakes, and wetlands, that hold cultural significance and are associated with stories, ceremonies, and practices that have been passed down through generations. Although cultural flows are related to environmental flows [Finn and Jackson, 2011; Sharma et al., 2020], their estimation is considerably more complex, requiring a collaborative and participatory approach between modelers and research participants rooted in observations, oral history and storytelling of Indigenous peoples and local communities - methodologies that are not typically part of the toolbox of modelers. To better identify and integrate environmental and cultural flows into the modeling process, further work needs to be pursued across the following interconnected dimensions.

1. **Identify indicators of ecosystem health.** Riverine and floodplain biota are adapted to capitalize on specific aspects of the flow regime to complete their life cycle and enable sustainable populations [Bunn and Arthington, 2002]. As such, environmental flow assessments identify key indicators of flow regimes that maximize growth, performance and reproduction of a group of indicator species deemed sensitive to flow changes; or they attempt to reconstruct a natural flow regime, assuming that the local biota were adapted to a particular set of flow features. Ideally, local measurements are carried out to establish flow-ecology relationships for the organisms and ecosystem of interest [Poff et al., 2010]. This is difficult in practice because of the resources required to establish such relationships. Instead, proxy hydrometric
indicators are used to infer likely biotic responses. These include the Index of Hydrologic Alteration [Richter et al., 1996] and presumptive standards approaches [Richter et al., 2012] that need only flow data to identify deviations from natural conditions. Physical models, such as the Physical Habitat Simulation (PHABSIM) approach that estimates depth and velocity for a river reach, are also often used to assess the environmental flow regime in the context of instream flows [Jorde et al., 2020; Luo et al., 2021]. These physical models need site-specific depth and elevation data, and are therefore employed less often, especially in large-scale integrated models [Casper et al., 2011]. Furthermore, they cannot simulate the interactions of abiotic or biotic processes, and they often ignore water quality impacts.

2. Integrate water quality into large-scale hydrology-land surface models. Traditionally, large-scale hydrology-land surface models have primarily focused on simulating the movement and distribution of water through the hydrological cycle, overlooking the complexities of water quality dynamics. Integrating factors such as nutrient concentrations, pollutant loads, and microbial contaminants into these models can offer a more comprehensive understanding of how hydrological processes interact with water quality dynamics, thereby influencing ecosystem health. However, despite advancements, this effort faces challenges such as spatiotemporal mismatches between landscape and instream processes [Rode et al., 2010], lack of calibration and validation data across different water quality variables, and uncertainties in data and process representations by models [Tscheikner-Gratl et al., 2019]. Moreover, accurately representing system feedback, such as the increased potential for nutrient loading during precipitation runoff on ground saturated from earlier storm events, remains underdeveloped. Limited data availability to capture nutrient pathways and water movement through soil further hampers model accuracy [Jackson - Blake et al., 2017]. Additionally, there is a need to address the impact of climate change-induced changes in snowpack regimes on water quality variables. Integrated modeling platforms combining hydrology and water quality will enable the assessment of various management strategies and interventions to combat water quality degradation and promote environmental sustainability. Further, including vegetation dynamics and carbon-pool processes [Chadburn et al., 2015; Melton et al., 2019] is of significance particularly when these models are coupled with atmospheric models in a two-way manner.

3. Attribute flow signatures to cultural needs. Indigenous and other local communities have a long history of observing and managing waterways and hence are capable of sustainably governing their waters without intervention [O’Bryan, 2018]. However, upstream development of water resources has disrupted the relationships that many communities have developed with rivers [Jackson et al., 2022], prompting the need for collaborative approaches in assessment and modeling to enable simulation of future states in the face of climate change and other development pressures. Cultural needs include those directly linked to biological indicators such as the abundance of important harvested fish species [Finn and Jackson, 2011], and others that would exemplify good relations between people, water, and the living world [Laborde and Jackson, 2022]. Defining what might constitute good relations in such a context, and how they could be applied in integrated models, is the subject of long-term interpersonal dialogue. In cases where model outputs have direct relevance for communities, identifying environmental or cultural categories and thresholds requires a commitment to relationship building, a co-learning process involving time spent together on the land and water [Jardine et al., 2023; Mohammadiazar, 2022]. The significant effort required here is akin to that of site-specific biophysical measurements used to calibrate hydraulic and flow-ecology models, elucidating why this human element is often lacking in large-scale integrated models.
3.4. Indigenous Knowledge

How can water management uphold Indigenous values of water and the environment? What can the knowledge and experiences of Indigenous communities offer integrated modeling, and vice versa? How can mathematical models and Indigenous knowledge be applied together to enhance understanding?

Indigenous knowledge refers to the collective wisdom, practices, and beliefs that have been developed and passed down through generations within Indigenous communities [Von Der Porten et al., 2016]. It encompasses an understanding of the environment, culture, spirituality, and peoples in sustainable interactions with their surroundings. When Indigenous knowledge is applied to an ecological context, it is often referred to as Traditional Ecological Knowledge (TEK). Indigenous knowledge emerges from different traditions than those of Western scientific modeling. Modeling is largely quantitative, such as when focusing on physical properties of water, whereas Indigenous knowledge is more holistic, incorporating psychological, cultural, and ecological values [Berkes and Berkes, 2009; Grenier, 1998]. Indigenous knowledge is multidisciplinary in nature, encompassing interactions within systems in an approach akin to systems thinking [Ali et al., 2022]. In this way, Indigenous knowledge comes ‘pre-integrated’ with multiple disciplines, making braiding more complex than simply selecting those pieces which align, for example, with hydraulic modeling parameters. In addition, historical extraction of water resources and Indigenous knowledge by colonizers have fractured trust between Western and Indigenous institutions and erected barriers to Indigenous involvement in water management [O’Donnell et al., 2023].

Typical approaches to integrated modeling - coupling, data assimilation, data fusion - are ill-equipped to embrace Indigenous knowledge without compromising its legitimacy. Therefore, modeling that involves Indigenous knowledge requires integration at the design level and throughout the modeling process [Duffy et al., 2024; Mantyka-Pringle et al., 2017]. When Indigenous place-based and cultural insights are respectfully included alongside mathematical models, the modeling process itself becomes effectively integrated. This is also known as taking a ‘braided’ approach, which is a collaborative process where western and Indigenous expertise work in harmony and equal partnership, often on matters of natural resources and co-led from the proposal stage of projects. This approach has proven viable, for example, within fields of plant ecology [R Kimmerer, 2013], geomorphology [Koppes, 2022], and mountain and river systems [Abu et al., 2019; Kassi et al., 2022]. The following three sequential dimensions will contribute to the development of a braided approach in the context of integrated modeling.

1. Learn the merits of Indigenous knowledge. The traditional adaptation pathways that have sustained communities over generations provide valuable insights for contemporary challenges. Parallels have been drawn between TEK and adaptive management, including principles of feedback learning, uncertainty and ecological unpredictability [Berkes et al., 2000]. Already, TEK provides evidence and guidance in ecosystem management, conservation biology, and ecological restoration [R W Kimmerer, 2002]. However, depending on one’s familiarity with Indigenous cultures, a level of awareness is required before braiding can be conducted. Indigenous knowledge systems are being increasingly recognized and taught within colonially-established institutions of research. During colonization efforts, previous generations of western society tended to disregard Indigenous traditional knowledge as pseudo-science [Ellen, 2004], a conditioning that has proven not only incorrect but damaging to water resources [O’Donnell et al., 2023]. To classically trained Western scientists, the validity of traditional knowledge is (ironically) novel and may be difficult to accept without experiencing an Indigenous community’s landscape and culture first-hand. Subsequently, the act of braiding Western knowledge with Indigenous knowledge requires a level of respect, relationship-building, social learning, and time commitment from all involved.
2. Balance the merits of each knowledge system. The experiences and narratives of Indigenous communities highlight resource management options that are appropriate for the context and based on lived experience [Martin et al., 2010], which is especially valuable in northern and other regions that feature considerable heterogeneities and uncertainty under climate change [Woo et al., 2007]. By drawing upon generations of place-based knowledge, resulting management options exhibit resilience to change, and can include adaptive planning [Abu and Reed, 2018], ecosystem-based approaches [Atlas et al., 2021], increased capacity to respond to events in remote locations, and development of efficient early warning systems. Observations of downstream impacts can also indicate important basin-wide change.

In turn, integrated modeling can support communities in assessing vulnerabilities to climate change impacts [Thapa and Upadhyaya, 2019]. Assessing vulnerabilities can lead to targeted adaptation strategies, which may be explored by modeling scenarios of extreme events and other shocks [Henly-Shepard et al., 2015]. Integrated modeling can also be utilized to evaluate the potential effectiveness of these strategies, at a local context [McDonald et al., 2022] but also the policy level [Hassanzadeh et al., 2016]. This can include assessing the impacts of specific climate scenarios on ecosystems, livelihoods, and cultural practices, and identifying appropriate measures to enhance resilience. Modeling can also help assess the impacts of upstream activities or climate change on traditional food systems, transportation infrastructure, or access to healthcare and sanitation during flooding events. This knowledge can inform the development of strategies to maintain or restore these vital systems and secure many interconnected aspects of local life including but not exclusive to water resources.

3. Co-create new knowledge with Indigenous and other local communities to inform and evaluate models. Coupling cultural knowledge with broader hydrological and water resource models is difficult because the former is often provided as qualitative data and observations and the latter take an almost exclusively quantitative approach. Many would also argue that combining such information is inappropriate because it imposes dominant paradigms on a group of people whose knowledge exists independently of those paradigms. However, there are mechanisms by which these knowledge systems and worldviews can be carefully braided throughout the modeling process. For example, categorical indicators can be used by individual experts to describe desired states, that can then be compared with quantitative model outputs to determine if the system is meeting expectations and whether it will continue to do so in the future [Mantyka-Pringle et al., 2017; Tipa and Teirney, 2006]. Māori flow indicators range from ‘cannot see movement’ to ‘broken/white water’ along a scale of undesirable to desirable [Tipa and Teirney, 2006], while water vitality indicators described by Dene, Cree and Metis range from ‘dead’ to ‘full of spirit’ [Mantyka-Pringle et al., 2017]. In other cases, clear demarcation of required water levels at particular times of a year can be indicated based on important reference points along the riverbank that are needed for rituals and other cultural practices [Lokgariwar et al., 2014]. Evaluation of and learning from the models [Sabokruhie et al., 2024] also connects well with an element of critical reflection that characterizes many transdisciplinary research initiatives [Cockburn, 2022].

3.5. Groundwater

How resilient are groundwater systems to stresses, and what signals their failure? Which rivers, lakes, and wetlands depend on groundwater for flows and quality? Where and when do groundwater systems exchange water/nutrients/chemicals with surface water? What are the ecological, cultural, and economic impacts of groundwater abstractions? At what extraction volume does groundwater quantity and quality reach a tipping point? How does climate change impact groundwater resources and with what time lag?
**How much complexity must be included for an adequate representation of the groundwater system for integrated modeling?**

Over 90% of available freshwater is groundwater, and groundwater is the dominant source of water for municipal, industrial, and agricultural economies in many parts of the world. Moreover, many surface manifestations of groundwater such as springs and fens are revered by Indigenous and non-Indigenous people worldwide. However, groundwater systems are typically unseen and sparsely sampled, and investments for groundwater characterization, monitoring, and prediction lag the more visible surface water and atmospheric components of the water cycle \[A.J. Jakeman et al., 2016\]. For meaningful forecasts and trade-off analyses, a quantitative framework provided by modeling is vital \[M.P. Anderson et al., 2015\]. Yet, the mismatch between importance and investment creates challenges for integrated modeling.

Another challenge lies in the fact that, in many surface water, water-engineering, and climate models, groundwater is either omitted or coarsely represented. Such simplistic models aim to emulate what groundwater flow systems contribute rather than capturing the forecast-salient characteristics of the groundwater system itself such as the fact that groundwater may be recharged by surface water \[Döll et al., 2016\]. Worse, these simplistic models fail to capture the groundwater system’s response to abstraction, and thus, for example, cannot recognize that pumping will deplete surface water features within the system unevenly, which can be crucial for translating pumping effects to minimum streamflows and ecosystem services. Thus, such simplifications typically cannot represent the interactions, interdependencies, tipping points, and thresholds essential for integrated water availability decisions where groundwater is important.

Groundwater models have been integrated into several more holistic models. For instance, the widely applied water allocation model Water Evaluation and Planning (WEAP; https://www.weap21.org) can invoke the groundwater flow model MODFLOW \[Niswonger et al., 2011\]. However, coupling may not ensure enhanced simulation quality. Presently, the majority of connections involve coupling groundwater models with surface water models, which has facilitated assessments of the impact of climate warming on groundwater, lakes, and streams and cold-water fisheries \[Hunt et al., 2013\]. There is also a considerable body of work dedicated to linking economic aspects to groundwater systems, policies, and usage, as well as to ecology, particularly groundwater-dependent ecosystems.

Such work notwithstanding, the subsurface remains challenging to characterize, with measuring the groundwater system typically requiring costly wells and estimation of groundwater recharge and discharge being very uncertain \[Flint et al., 2002\]. Especially challenging is the parameterization and upscaling of small-scale processes and conditions at the interface of groundwater and surface water \[Gleeson et al., 2021\]. A notable example of the challenges in integrated surface/groundwater hydrological modelling, and the associated potential for model misuse, is reported by \[H.S. Wheater et al., 2024\]. Consequently, we identify the following major challenges to the appropriate inclusion of groundwater systems in integrated modeling and decision-making.

1. **Find appropriate spatial and temporal scales for groundwater interaction with surface water and ecosystems.** Groundwater-surface water interaction has been increasingly recognized over the past few
decades and has become a focus of many integrated models. Capturing these interactions is challenging because groundwater systems often require consideration of different spatial scales than those used for surface water systems. Groundwater flow boundaries do not necessarily align with watershed boundaries [Fan, 2019]. The placement of the lower boundary in groundwater flow models is also debated, as permeability contrasts, water chemistry shifts, and environmental tracers can suggest different boundary positions [Condon et al., 2020]. A global analysis of chloride ions (Cl) fluxes in streams and groundwater indicates that groundwater below 500 meters contributes negligibly to global streamflow [Ferguson et al., 2023], a depth similar to the lower boundary in some global and continental-scale hydrologic models [de Graaf et al., 2015; C Yang et al., 2023].

Understanding groundwater flow systems often necessitates consideration of various temporal scales. Groundwater residence times commonly range from decades to millennia [Jasechko et al., 2017], with million-year timescales occurring in some large regional aquifers [Kim et al., 2022; Ram et al., 2020; Sturchio et al., 2004]. Groundwater systems also take considerable time periods to respond to shifts in boundary conditions due to climate change or other drivers. Shallow aquifers typically take decades to centuries to respond to climate shifts [Cuthbert et al., 2019]. In contrast, large regional groundwater systems may require millennia to millions of years to equilibrate to climate shifts, often existing in transient states due to response times exceeding climate cycle timescales [Rousseau - Gueutin et al., 2013].

Questions of interest in integrated modeling often span large areas, with modeling extents typically best considered at the watershed or sub-watershed scale. However, within these larger extents, a relatively fine discretization of the model domain is necessary to accurately represent crucial processes, such as interference from pumping wells, streamflow depletion, and the effects of water table changes on ecosystem services. For instance, it has long been acknowledged that well interference and conjunctive groundwater-surface water use cannot be adequately simulated when the interfering wells and streams are located in the same model cell or adjacent cells [M P Anderson et al., 2015]. Temporal discretization is typically less problematic because the unsaturated (vadose) zone commonly acts as a low-pass filter that dampens highly transient processes at the land surface. However, this underscores the need to include some level of these unsaturated zone processes to appropriately link land-surface processes to groundwater systems [Hunt et al., 2008].

Addressing multiple scales in groundwater modeling has been tackled through various approaches, such as inset models and unstructured grid methods [M P Anderson et al., 2015], as well as hybrid modeling techniques combining gridless and gridded approaches [Abrams et al., 2016; Hendrik M Haitjema et al., 2010]. However, as integrated modeling expands to encompass broader human and socioeconomic dimensions, reassessing these challenges becomes essential in the context of decision-making and stakeholder perspectives. Rather than focusing solely on high-fidelity representations of individual interfering wells, it is essential to understand the underlying reasons for well interference and cumulative impacts. Achieving an integrated model that balances sophistication and practical utility poses a significant challenge [Henk M Haitjema, 2015], requiring consideration of stakeholder needs, available resources, and time constraints.
2. Recognize prolonged lags in groundwater system’s response to unsustainable stress. Groundwater use is acknowledged as unsustainable in many parts of the world. Even in areas where it currently appears sustainable, the situation might change if all wells were operated at their permitted capacity, especially during extreme droughts. However, widespread failures of groundwater-supported systems are only recently gaining attention. These failures include unacceptable pumping impacts on irrigation wells, springs, calcareous wetlands, and other groundwater-dependent ecosystems.

The lag between unsustainable use and widespread degradation stems from groundwater stored in the aquifer. Initially, when a well is turned on, this storage provides all the water pumped [Theis, 1940]. As pumping continues, an increasing amount of water is drawn from streamflow capture, which includes recharge that would have discharged to streams and streamflow drawn into the subsurface where hydraulic gradients have been reversed [Konikow and Leake, 2014]. The response times of groundwater systems to pumping can be long, often much longer than the human timescales used in decision making [Bredehoeft and Durbin, 2009]. Thus, to an observer, groundwater mining may not be immediately evident. Consequently, there is a tendency to assume that the amount of groundwater pumped today will be what can be pumped tomorrow. This misunderstanding is likely to escalate with the widespread adoption of high-capacity pumping technology, which began in the 1950s and continues to deplete groundwater reserves worldwide.

3. Build trust and address inequity in modeling, particularly in transboundary systems and trading markets. Groundwater systems are at best only partially observable, posing challenges in understanding and developing intuition for their operation, limits, and response to stress. Much of this intuition - or “hydrosense” [Hunt and Zheng, 2012] - is cultivated through active engagement in groundwater modeling involving many unknowns, yet to be discovered [Hunt and Welter, 2010]. Additionally, post-audits of groundwater models often reveal poor performance in prediction [Konikow and Person, 1985], typically because of unanticipated future conditions or human activity that uncertainty analyses are unable to capture regardless of their sophistication. These factors can result in low levels of trust in groundwater predictions.

Trust is particularly crucial when addressing issues related to transboundary aquifer systems, equity, and trading markets. In transboundary systems, political boundaries often play a significant role in integrated modeling, yet they may not align with groundwater flow patterns. Stakeholder interests and available datasets vary depending on surface location, but groundwater systems integrate cumulative stresses over space and time. These factors affect equity, with many underserved communities lacking resources for modeling, resulting in less vetted models and unexplored uncertainties. In trading markets, confidence in the resource representation is essential to avoid unforeseen consequences and ensure both buyer and seller trust in the transaction. If a groundwater model fails to accurately simulate stakeholders’ systems, decision-making based on that model is likely to face significant trust issues.

4. Include groundwater in informing decisions involving water quality. Each of the above challenges to incorporating groundwater into integrated modeling becomes more critical when the focus moves from groundwater quantity to groundwater quality simulations. Fu et al. [2020] provide an extensive discussion of the underlying issues, some of the most salient are briefly described here. Problems of scale and dearth
of observations are more problematic and simulations of solute transport in groundwater are more dependent on small-scale preferential flowpaths that are more difficult to characterize than in simulations of water quantity. Likewise, there are typically fewer water quality observations available for a groundwater system than for groundwater elevation. In addition, the source history - location and timing - is critically important to understanding where a solute plume is moving to and how long it will take to get there; yet adequate information on source history is rarely (if ever) available.

Contamination, which can include non-aqueous phase liquids that either float or sink in the groundwater system [Zheng and Bennett, 2002], follows hydraulic gradient directions or geologic structures within the aquifer. Stationarity assumptions may also undermine water quality forecasts; for instance, changes in permafrost melting rates can significantly impact water quality dynamics [Langer et al., 2023]. Moreover, contamination may involve human pathogens, necessitating separate theoretical formulations for their transport [Hunt and Johnson, 2017]. These water quality concerns are further compounded when transitioning from conservative transport to reactive transport, where contamination changes nature during its journey through the aquifer from source to discharge area. Indeed, water quality changes at interfaces, such as where groundwater discharges to surface water, can be much more significant than those occurring over the longer groundwater flowpath distance [Schindler and Krabbenhoft, 1998].

3.6. Atmosphere

How is evapotranspiration affected by the response of vegetation to climate change? How do hydro-climatic regime shifts influence land cover changes, and how do these changes in land cover reciprocally affect hydro-climatic regimes? How does soil adaptation to new ecohydrological or climate conditions impact hydrology? How does irrigation change micro-climate and consequently local hydrology, as well as impact the global climate?

Climate change, accompanied by an increase in atmospheric CO2 concentrations, affects vegetation, and the vegetation’s response to these changes modulates the direct impact of altered climatic conditions on evapotranspiration and runoff. While climate change may alter land cover types, changes in land cover, such as deforestation or urbanization, can also affect the hydro-climatic regime by altering temperature, soil moisture, and evapotranspiration [Y Li et al., 2019]. Abrupt landscape changes from fires or other events can significantly impact hydrology and water management [Partington et al., 2022], with consequential effects on the atmosphere. Fires remove vegetation, creating impervious surfaces that increase runoff, reduce infiltration, and accelerate erosion. These changes can alter local atmospheric conditions, potentially affecting precipitation patterns and creating a feedback loop that influences both water and atmospheric dynamics. Soil adaptation to new ecohydrological or climate conditions significantly impacts hydrology. Soils can adjust to new conditions by altering their physical properties, such as permeability and water-holding capacity, which can reshape the hydrological cycle by changing evaporation, transpiration, and runoff processes.

1. Incorporate vegetation responses to climate change in hydrological impact studies. Almost none of the existing hydrological models used to quantify climate change impacts on water flows and storage consider vegetation responses, operating under the assumption that models accurately simulating historical
conditions are also suitable for future climate change assessments. However, with higher atmospheric CO\textsubscript{2} concentrations, the leaf stomata close, thereby reducing transpiration. Conversely, higher CO\textsubscript{2} levels may enhance plant growth, increasing transpiration. Furthermore, changing climate conditions impact the growing season and overall plant growth, resulting in biome changes. These complex processes are typically captured in dynamic vegetation models and some land surface models that are part of Earth system models (ESMs). Unfortunately, ESMs exhibit no consensus regarding the overall hydrological response to the increase in CO\textsubscript{2} concentrations [Canadell et al., 2021]. On the other hand, many dynamic vegetation models and regions demonstrate that incorporating CO\textsubscript{2} effects results in a relative decrease in evapotranspiration, leading to increased runoff or groundwater recharge [Pourmokhtarian et al., 2017; Reinecke et al., 2021], as well as a relative decrease in irrigation water demand [Deryng et al., 2016]. Hydrological models either need to include dynamic vegetation modeling to compute actual evapotranspiration or use simpler approximations of the impact of vegetation response on potential evapotranspiration. Given the uncertainties of simulating the vegetation response, an avenue forward could be an ensemble approach for hydrological climate change impact assessments with hydrological models lacking a dynamic vegetation component, as suggested by Peiris and Döll [2023].

2. Capture reciprocal relationships between land cover changes and hydro-climatic changes. Land cover changes significantly influence hydro-climatic conditions due to their impact on local air temperature, evapotranspiration, soil moisture, and albedo, all of which drive climate processes through land-atmosphere coupling [Z Zhang et al., 2022]. When land cover changes, particularly due to deforestation or urbanization, the process of evapotranspiration is disrupted, leading to changes in atmospheric humidity levels and potentially altering precipitation patterns [Huo et al., 2021]. Changes in land cover can affect the Earth’s albedo, impacting the amount of solar energy absorbed by the land, which can subsequently influence local and global climate conditions. Land cover changes, specifically changes to vegetation cover, can affect soil moisture levels. Plants help retain water in the soil, so when land cover changes by processes such as deforestation, it can lead to drier soil conditions. This change can influence local weather patterns, as soil moisture contributes to atmospheric humidity through evaporation [Zhe Zhang et al., 2020]. These impacts underline the reciprocal relationship between land cover and hydro-climatic changes, necessitating sustainable management and policies to mitigate potential negative effects on climate and the environment.

3. Improve representation of precipitation and phase-changes. One challenge with the prediction of precipitation by atmospheric models is to accurately predict the precipitation phase [V Vionnet et al., 2022]. Furthermore, hydrological models should rely on the predicted amount of rain and snow to conduct hydrological prediction. This information is critical for accurate hydrological modelling in cold regions. Existing empirical methods discriminating the precipitation phase can lead to different results [Birk et al., 2021; Harder and Pomeroy, 2013; Harpold et al., 2017; Jennings et al., 2018]. Such differences produce uncertainties in snowpack estimation and, in turn, in estimates of water storage during the melt season [Harder and Pomeroy, 2014; Jennings and Molotch, 2019; Wayand et al., 2017]. The warming climate may lead to further uncertainties as near-0°C Celsius conditions may become more frequent during the cold seasons in historically cold regions [Stewart et al., 2023]. Hence, developing and using accurate representations of the processes producing clouds and precipitation in atmospheric models are crucial.
These processes are intricate, involving numerous hydrometeor categories and phenomena [Morrison et al., 2020]. Significant progress has been made recently in enhancing the representation of mixed-phase precipitation in models [Cholette et al., 2019; Cholette et al., 2023], contributing to the more accurate prediction of rain, snow, and mixed precipitation. The subsequent steps could involve integrating these models of precipitation with hydrological models. Currently, hydrological models disregard the phase partitioning of precipitation from atmospheric models and conduct their independent calculations [Harder and Pomeroy, 2014; Harpold et al., 2017].

3.7. Cryosphere

How do seasonal and long-term changes in snow, river ice, frozen soils, permafrost, and glaciers interact with hydrological systems? How will climate change, which reduces the cryosphere, impact hydrology, water management, ecosystems, and socio-economies? How does snow's interaction with shifting vegetation dynamics affect its redistribution and sublimation? Does reduced mountain snowfall and increased rainfall-runoff lead to less efficient runoff generation mechanisms?

The cryosphere encompasses snow, glaciers, permafrost, seasonally frozen ground, lake and river ice, solid precipitation, ice caps, ice sheets and sea ice [Barry, 2011]. The cryosphere is especially vulnerable to climate change [Kloenne et al., 2023], a fact that has attracted significant research attention in recent years [Adler et al., 2019]. Within this realm, seasonal snow cover, glaciers, and perennial snowfields serve as linchpins for upland and cold regions, contributing essential runoff to rivers that sustain nearly half of humanity [Viviroli et al., 2020]. However, these cold regions pose formidable hydrological challenges, spanning from the redistribution and ablation of snow to soil infiltration in frozen conditions [Pomeroy et al., 1998a; Pomeroy et al., 2007]. Yet, the modeling of these processes lags behind our understanding, highlighting the urgent need for further research to integrate them into hydrological models, especially in light of the ongoing challenges posed by climate change.

Another pressing concern lies in the detection of significant permafrost thaw in recent decades [Barros et al., 2014; Harris et al., 2009; Meredith et al., 2019; Pan et al., 2016] and projections that indicate an acceleration of the thaw in response to climate change [Burke et al., 2020; Chadburn et al., 2017; McGuire et al., 2018]. Permafrost, defined as ground material that remains at or below 0°C for at least two consecutive years [van Everdingen, 1998], underlays approximately 14% [Obu, 2021] to 25% [Y Zhang et al., 2008] of the Northern Hemisphere’s land. It is overlain by the ‘active layer’, a soil layer subjected to seasonal thawing/freezing and influenced by the insulative properties of snow cover on the ground and/or organic composites in the topsoil [Dobinski, 2011]. These factors collectively moderate the impact of external climate on permafrost dynamics.[Barros et al., 2014; Burke et al., 2020; Chadburn et al., 2017; Harris et al., 2009; McGuire et al., 2018; Meredith et al., 2019; Pan et al., 2016] Permafrost thaw alters the dynamics of the active layer, affecting energy and water exchanges, hydrological processes, natural hazards, carbon dynamics, and plant communities over vast areas, and subsequently, impacting the global climate system [Walvoord and Kurtylyk, 2016; Woo et al., 1992]. Modeling and predicting such dynamics requires accurately representing the coupled evolution of water and heat – considering phase change and phase-dependent thermal conductivity – and possibly carbon, across interfaces of the atmosphere, vegetation, and soil [Jafarov et al., 2012; Riseborough et al., 2008].
To address these challenges, future research should explore several key dimensions outlined in the following.

1. **Incorporate comprehensive snow redistribution and ablation processes in hydrologic models.** Processes like blowing snow redistribution and sublimation by wind, as well as gravitational transport by avalanches in steep terrain, are crucial for calculating snowpack accumulation and variability [Vincent Vionnet et al., 2021] and estimating snow cover depletion during the ablation period [Pomeroy et al., 1998a]. Snowfall interception by forests leads to significant sublimation losses, influenced by forest characteristics and meteorology in continental climates [Pomeroy et al., 1998b]. Snow ablation depends on coupled heat and mass transfer relationships, involving energy fluxes from radiative to conductive to turbulent transfer, impacted by terrain exposure to wind, stability, slope, aspect, and forest cover [King et al., 2008]. Yet, many models lack this comprehensive representation, leaving the hydrological cycle in cold regions inadequately addressed. Calibration and validation in such environments remain uncertain due to data scarcity and the complex behavior of catchments in response to these relationships. Incorporating the full suite of snow redistribution and ablation processes (see, e.g., [Pomeroy et al., 2022] and H S Wheater et al. [2022]) will significantly enhance predictive performance in cold regions.

2. **Refine hydrologic models for improved representation of permafrost processes.** The typical depth of soil column ranges from 2m to 4m in most H-LSMs. A deeper soil depth, typically greater than 30m, is essential to minimize the influence of uncertain lower boundary conditions and to enable representation of the long thermal and hydraulic memories of permafrost [Alexeev et al., 2007; Nicolasy et al., 2007]. Furthermore, improving surface insulation representation through the integration of multi-layer snow algorithms [Chadburn et al., 2015] and explicit parameterization for organic soils like peat and moss [DM Lawrence and Slater, 2008; Letts et al., 2000; Y Wu et al., 2016] facilitates impact assessments of atmospheric changes on land thermal and hydraulic regimes [Dobinski, 2011]. Additionally, addressing small-scale features such as lateral taliks and microtopographic changes in polygonal regions [Aas et al., 2019; Devoie et al., 2019] further refines model accuracy in capturing cold-region processes.

3. **Overcome data scarcity in cold regions through targeted data collection efforts.** Progress in representing permafrost dynamics in integrated models remains challenging due to insufficient data. Currently, the existing monitoring network in the Northern Hemisphere consists of only a few hundred borehole/thaw-tube sites across the entire permafrost region [Aalto et al., 2018; Obu, 2021]. Furthermore, scaling up point-based measurements to larger scales has proven to be elusive due to the significant heterogeneity and non-uniformity of permafrost thawing, both vertically and spatially [Farquharson et al., 2019; Morse et al., 2016; Smith et al., 2012]. Current remote sensing technologies remain incapable of detecting permafrost features, such as the active layer depth and soil ice content [Westermann et al., 2015]. Existing modeling-based permafrost presence/occurrence maps [Aalto et al., 2018; Chadburn et al., 2017; Gruber, 2012; Obu et al., 2019; Ran et al., 2021] are largely inconsistent, specifically in discontinuous-sporadic regions, owing to their differing estimation philosophies/assumptions [Abdelhamed et al., 2023]. Moreover, the existing ground-based meteorological data network is extremely sparse, especially in higher latitudes and altitudes, imposing major challenges to representing phase-change-dependent responses around the zero-degree isotherm [Asong et al., 2020; H S Wheater et al., 2022; Wong et al., 2023].
Snow interception, where snow is ‘caught’ in the canopy of subalpine forests, is another cryospheric process hindered by data scarcity, limiting our understanding and modeling capabilities [Lundquist et al., 2021]. As snow interception alters the water balance, energy balance, and albedo of subalpine forests [Stähli et al., 2009; Strasser et al., 2008; Suzuki and Nakai, 2008], misrepresenting this process can be detrimental to understanding of snow dynamics in these ecosystems. Snow interception is often an initial parameterization in H-LSMs, with influence on other parameterizations [Roesch et al., 2001], causing cascading errors throughout the model.

4. Improve representation of long-term thermal memory of permafrost. Unlike hydrologic modeling in warm or temperate climates, proper initialization of state variables in permafrost-enabled models often requires running the model over centuries-long (historical or synthetic) data periods. This imposes substantial computational burden and subjectivity in defining the initial profiles for soil temperature and moisture content [Abdelhamed et al., 2022; Ji et al., 2022]. Notably, improper model initialization can introduce significant biases in the evolution of model states and fluxes, exerting a long-lasting effect on model response [F Chen and Dudhia, 2001; Rodell et al., 2005]. Furthermore, there are additional processes that can influence thermal and hydraulic regimes yet are under-represented in the current generation of models; these include the presence of excess ground ice [H Lee et al., 2014], land subsidence associated with permafrost thaw [Streletskiy et al., 2017], and the effects of salinity on freezing point [Dobinski, 2011].

5. Anticipate and model ice-jam flooding. In addition to the changes in hillslope hydrology, the regimes of river flows are also changing in cold regions under climate change. The most notable example is the change in the timing and magnitude of ice-jam flooding in the northern rivers. Developing models and modeling techniques for ice-jam flooding in the context of flood forecasting and long-term trend prediction is difficult due to the chaotic nature of ice-jam formation. Even small shifts in ice-jam location can drastically change the morphology of ice-jams and the backwater staging they induce. Once formed, ice-jams are also prone to collapse and release, forming ice jams further downstream at locations that are hard to predict. Hence, research questions arise on how such chaotic behavior in flooding can be modeled to provide reasonable accuracy and skill in forecasting and predictions. New modeling techniques are needed to provide some order to these chaotic systems [Prigogine and Stengers, 2018].

4. Piecing it all together

Since the pursuit of inclusivity of processes, disciplines, and perspectives knows no bounds, a fundamental undertaking revolves around scoping of the integration problem according to the specific research questions, and then designing the process of integrated modeling to achieve as sound a research outcome as resources will allow. As challenges accumulate, the integration problem can swiftly grow in magnitude and complexity, potentially reaching a point where it becomes intractable without careful consideration and thoughtful application of appropriate instruments. Time is well-spent on this journey, especially in the initial stages of integrated modeling projects, with substantial deliberations such as those centered around the three overarching questions introduced in Section 2. Subsequently, the realization of successful convergence and transdisciplinary scholarship requires a strategic blend of technical methods, in particular, sensitivity analysis, multi-fidelity modeling, and stress-testing, as outlined below. This blend
should be crafted in a dynamic, iterative, and adaptive manner, continuously auditing and questioning the process to navigate the complexities of integrated modeling.

4.1. The law of the “vital few”: Apply sensitivity analysis to balance complexity, uncertainty and computational demands

The Pareto principle, also known as the 80/20 principle or principle of factor sparsity, highlights that the vast majority of the consequences in a system result from a small minority of the causes or inputs, emphasizing the disproportionate impact of a small subset of factors, the “vital few” [Box and Meyer, 1986]. The underlying concept of this argument, first noted within the realms of economics and business, demonstrates its extensive applicability as it spans across a multitude of diverse natural systems, such as hydrology, ecology, climate science, geology, and biodiversity, as well as various complex social systems, including human behavior, sociology, and organizational dynamics. This concept proves highly instrumental in integrated modeling, enabling us to concentrate our attention on the most crucial pieces that bear the greatest significance for the research questions at hand.

A key question therefore is: how can we identify the most important pieces in practice? The answer is through sensitivity analysis (SA). Although a relatively young discipline for systems modeling and policy support, SA is concerned with the study of how the ‘outputs’ of a ‘system’ are related to, and are influenced by, its ‘inputs’ or the ‘assumptions’ we hold about it [Razavi et al., 2021; Saltelli et al., 2021]. SA can help us navigate the heterogeneity across various disciplines, such as varying perceptions and definitions of uncertainty, and reconcile the uncertain properties of a myriad of factors to answer the critical question: when, where, and how does uncertainty matter? Within an SA framework, some variables may possess clearly defined units and distributional properties, whereas others could be qualitative and represented through a set of possible narratives around uncertainty sources and plausible effects. SA can identify the factors and/or assumptions that primarily control the system’s dynamics under different conditions, thereby guiding modelers to the most significant sources of uncertainty.

SA needs to be an integral part of integrated modeling and be resorted to iteratively throughout the modeling processes. It serves several fundamental purposes in systems analysis and modeling: (a) supporting scientific discovery by exploring causalities and understanding how different processes, hypotheses, parameters, scales, and their interactions impact a system [Gupta and Razavi, 2018; Mai et al., 2022]; (b) facilitating dimensionality reduction to identify and remove non-influential factors in a system, streamlining subsequent analyses [Cuntz et al., 2015; Larabi et al., 2023]; (c) conducting data worth assessment to pinpoint processes, parameters, and scales that dominantly control a system, guiding targeted data acquisition to reduce uncertainty significantly [Guillaume et al., 2019; Partington et al., 2022]; and (d) providing decision support by quantifying the sensitivity of expected outcomes to different decision options, constraints, assumptions, and uncertainties [Baroni and Tarantola, 2014; Tarantola et al., 2002].

SA can and should be applied not just to the integrated model as a whole but also to its component models (submodels). Thus, the analysis can be broken down to identify the factors in a parent submodel controlling the output(s) needed as input(s) to a child submodel. This also provides understanding of what is most critical in a submodel. Once submodels are parametrized downwards, such information can be taken into account in performing SA on the integrated model. In the SA process, one can also investigate different scale hypotheses in the models, the subject of the next section.
4.2. Scale incommensurability: Exploit multi-fidelity modeling to address appropriate scaling representation within and between model interfaces

What is the ‘right level of fidelity’ for component models (i.e., sub-models) in an integrated modeling framework? A model’s fidelity refers to how closely it approximates the real-world system it represents, ensuring that the model accurately captures the essential behaviors and characteristics of the actual phenomenon. A particular challenge here is that different processes may operate at vastly different speeds and involve various spatial extents. Therefore, important dynamics pertaining to a research question might emerge at distinct characteristic time and/or space scales in different systems. For illustration, consider ‘characteristic time scale’ to be the time lapsed after a perturbation to a system’s response. For instance, the characteristic time scale of a catchment’s streamflow response to a storm event might be on the order of minutes to hours, while the characteristic time scale for changes in groundwater response may be months to years, and that for the catchment’s active layer thickness due to warming and permafrost thaw could be on the order of decades. Or, the characteristic time scale of reservoir operation for hydropower generation may span minutes to hours, whereas the processes altering reservoir rule curves in response to water re-allocation policies or economic changes may extend over years or decades. Similarly, ‘characteristic space scales’ pertain to the spatial extent, distance or area, at which a perturbation can evoke a discernible system response. For instance, the characteristic space scale of convective storms may be on the order of a few kilometers, whereas the characteristic space scale for the crop pricing response to a perturbation in international trade could extend to the country or global scale.

How should we handle model fidelity amidst scale inconsistencies? In an integrated modeling framework, models should not, or indeed cannot, necessarily operate on uniform spatio-temporal discretization or exhibit identical levels of process detail. The right level of fidelity depends on the specific research questions the modeling exercise is assisting with answering and the trade-offs between accuracy, computational efficiency, and available data. In some cases, high-fidelity models that capture intricate details of the system might be necessary to gain precise insights and predictions for certain components. However, using high-fidelity models for the entire integrated framework may lead to excessive computational costs and inefficiencies, making it impractical for real-time simulations or large-scale analyses. Conversely, using overly simplistic low-fidelity models may result in inadequate representations of the system, leading to inaccurate results and limited understanding of complex interactions between components.

To strike a balance between accuracy and efficiency in integrated modeling, multi-fidelity modeling is essential. Multi-fidelity modeling is an approach that uses multiple models of varying levels of complexity to represent the same system or different components of the system, enabling a balanced trade-off between accuracy, computational efficiency, and data demand [Razavi et al., 2012]. Models representing the same system but exhibiting different levels of fidelity can take various forms, including statistical or process-based [Forouhar et al., 2022], and can be run at diverse space/time resolutions [Fraehr et al., 2023]. When integrated modeling incorporates multi-fidelity modeling, modelers can seamlessly switch between models with varying levels of fidelity, ensuring that the processes and their interactions of interest are accurately and appropriately represented. Modelers, however, should only operate within the ‘trust region’ of a model, acknowledging the model’s limitations and assumptions. For instance, when a model is formulated based on linear assumptions around a particular equilibrium, as is the case in input-
output economic models [Eamen et al., 2020], the model’s results are likely to be trustworthy only when perturbations to the system are small in proximity to that equilibrium.

4.3. Model evaluation and coupling: Undertake an eclectic range of stress-testing to comprehensively understand model strengths and weaknesses

Model evaluation is a critical step in the modeling process, as it is a check to see if the model is fit for its intended purpose. A classic feature of evaluation is assessing how well the model performs in predictive mode against observational data on the system [Bennett et al., 2013], by employing various methods to partition the available data into subsets intended for model calibration and evaluation [Maier et al., 2023]. Model evaluation is typically challenged by data scarcity or even limits in observability. This challenge becomes more pronounced in the context of integrated modelling, wherein diverse models from various disciplines are interconnected and feed into one another. Running the models after integration may lead to the emergence of complex dynamics, and individual models might be extended beyond the boundaries of the data originally employed for their development, venturing well into the realm of extrapolation.

The development and potential calibration of individual models can occur independently of other models. Naturally, these individual models might undergo partial evaluation in isolation, using disciplinary approaches available for assessment. But, how should these models be interconnected and evaluated collectively? A spectrum of approaches could be employed to couple different models, including those of varying system fidelities. At one extreme, two models could be fully and seamlessly integrated, possibly within a unified software implementation, where each receives inputs derived from the outputs of the other. This approach proves valuable when aiming for a quantitative representation of potential feedback loops. Alternatively, at the opposite end of the spectrum, the integration of two models could take a sequential or one-way approach, possibly even being ‘soft’ in nature - for example, a specific output from one model might trigger the execution of a scenario in another model. The challenge lies in the fact that modelers might not possess foreknowledge about the most suitable integration method, and their perspective could undergo revisions as they advance in the integrated modeling process.

A key approach in such situations is stress-testing the model via an explorative-then-adaptive integration lens. Stress-testing or assumption hunting entails speculating and exploring a variety of forcing scenarios and/or model assumptions, whether hypothetical or not, to rigorously assess the integrated model. When, where, and how may the integrated model break down? What intriguing dynamic behaviors might manifest under novel conditions? Can we explain the emergence of these new dynamics using our existing knowledge base? Is the appearance of these dynamics genuine or merely a result of modeling artifacts? How might the outcomes of stress-testing vary when employing different approaches for the integration of individual models? Posing these questions while designing the stressors can provide guidance to modelers as they navigate the complexity of model integration and evaluation. Stress-testing embodies a ‘learning endeavor,’ as enabling the interactions across diverse phenomena may lead to a wide array of complex dynamics, encompassing strong non-linearities, hysteresis, positive feedback loops, multiple equilibrium states, and possibly even chaotic behaviors.

5. The bottom line

Ideas and aspirations for convergent and transdisciplinary integration are not new to water scientists. Progress in this important endeavor, however, has been slow due to the complexity of the integration
problem, and disciplinary and epistemological barriers – see Table 1 for a summary. Instead, there has been momentum towards increasing ‘computational complexity’ of models, for example, pertaining to heterogeneity, numerics, and solvers within hydrologic models [e.g., hyper-resolution watershed models, [Bierkens et al., 2015]]. However, solely increasing computational complexity may not reproduce true, real-world complex dynamics as the resulting models often under-represent ‘systems complexity,’ which relates to holism and boundary judgments. Complex, but under-represented, interactions in natural and human-natural systems are manifest in interdependencies and feedbacks, nonlinear dynamics and thresholds, hysteresis, time lags and legacies, with unintended consequences for policy making.

Exploring systems complexity through integrated modeling and determining the appropriate level of complexity for a given problem requires a shift in modeling perspective—from viewing models as predictive tools to seeing them as exploratory instruments. Naturally, this shift introduces new challenges to the ‘social process’ of modeling. One such challenge involves navigating the ‘decision chain’ of the modeling process and formulating sound ‘reasoning’ for those decisions, necessitating careful deliberation among all involved parties. Another challenge is effectively managing the multitude of sources of uncertainty in integrated modeling and communicating those uncertainties to scientists, policymakers, and the public. At the heart of the social process of modeling is the aspiration that a well-developed model will profoundly influence policy making, ultimately serving the greater good of society.

The pursuit of convergence and integration equally demands a transformative approach to educating and training the forthcoming generation of scientists and practitioners. This entails fostering interdisciplinary learning environments that cultivate a grasp of complex systems, collaborative problem-solving acumen, and effective communication across disciplines. We must envision instructional methods that steer young researchers away from a ‘computing too-much, thinking too little’ [Emanuel, 2020] or a ‘matematistry’ [Box, 1976; Razavi et al., 2021] mindset, towards an attitude grounded in transdisciplinary curiosity and exploration. This further facilitates the transition from a ‘science for society’ to a ‘science with society’ paradigm, engaging diverse perspectives and expertise, including community members, to promote inclusive decision making for addressing pressing real-world climate, water, and interconnected environmental challenges.

Table 1. A summary of challenges and pathways for convergent and transdisciplinary integration across frontiers of surface water hydrology with other disciplines

<table>
<thead>
<tr>
<th>Convergence Frontier</th>
<th>Challenges and Pathways</th>
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<tr>
<td><strong>Water Resource Engineering</strong></td>
<td>A more systematic representation of dependencies across water infrastructure systems will greatly enhance hydrologic modeling platforms.</td>
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<td></td>
<td>Dynamic modeling approaches will be essential to adapt to the evolving conditions of non-stationarity in water policy and human-water feedback.</td>
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<tr>
<td></td>
<td>Improving numerical compatibility in space and time will facilitate seamless integration between hydrological and water system models.</td>
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<tr>
<td></td>
<td>Customized modeling approaches, tailored to specific geographical contexts, will address regional differences in water management practices effectively.</td>
</tr>
<tr>
<td><strong>Socioeconomics</strong></td>
<td>Addressing scale incompatibility between hydrology and socio-economics will streamline integrated modeling efforts, enabling smoother reconciliation of data and processes across various spatial and temporal resolutions.</td>
</tr>
</tbody>
</table>
Incorporating currently missing links to non-water-using economic sectors will pave the way for a comprehensive assessment of the indirect impacts of water management decisions, ensuring a more accurate estimation of their broader economic repercussions.

Addressing the complex feedback across water management and socio-economic agents will involve identifying and representing bidirectional influences, such as rebound effects and policy-induced behavioral changes, within integrated models.

Capturing intricate interactions between global socio-economic systems, national and international policies, and trades with local water systems within integrated models will enable more effective policy formulation and management strategies.

<table>
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<tr>
<th>Water Quality, Ecosystem, and Cultural Flows</th>
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<tr>
<td>Defining environmental flows should embrace differing perspectives on the quantity, timing, and quality of freshwater necessary to sustain aquatic ecosystems and support human cultures.</td>
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<tr>
<td>Advancing our understanding of the complex relationships between environmental flows and ecosystem health will involve considering factors such as flow regime characteristics, habitat requirements, and species interactions.</td>
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<tr>
<td>Exploring water quality dynamics will entail recognizing the intricate connections with hydrology and climate, and comprehending the complex relationships governing factors like nutrient cycling, sediment transport, and contaminant dispersion.</td>
</tr>
<tr>
<td>Incorporating cultural flows, which represent the cultural, social, and spiritual significance of water, will involve greater inclusion of diverse perspectives and values in modeling efforts and water resource management practices.</td>
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<th>Indigenous Knowledge</th>
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<tr>
<td>Harnessing synergies between mathematical models and Indigenous wisdom will involve skillful integration of quantitative and qualitative approaches.</td>
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<tr>
<td>Recognizing alternative ways of knowing will address historical biases and cultural barriers, fostering mutual respect and understanding between Western scientific perspectives and Indigenous knowledge systems.</td>
</tr>
<tr>
<td>Achieving balance amidst differing values will entail acknowledging and reconciling diverse perspectives and priorities inherent in Western scientific modeling and Indigenous wisdom, fostering collaboration and mutual learning.</td>
</tr>
<tr>
<td>Co-developing outputs will involve engaging in participatory processes that respect Indigenous sovereignty, culture, and knowledge systems, ensuring that modeling efforts are inclusive, culturally appropriate, and beneficial to Indigenous communities.</td>
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<tr>
<th>Groundwater</th>
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<tr>
<td>Achieving alignment between spatio-temporal scales of sub-surface and surface processes will enhance the integration of groundwater dynamics into more holistic models.</td>
</tr>
<tr>
<td>Properly modeling delays in groundwater response to stressors, such as pumping, will improve recognition of both immediate and long-term impacts of unsustainable groundwater use.</td>
</tr>
<tr>
<td>Building trust through enhanced observability of groundwater systems will bolster confidence in modeling predictions, particularly in transboundary aquifer systems and trading markets.</td>
</tr>
<tr>
<td>Overcoming challenges in groundwater quality investigations will involve innovative approaches to navigate heterogeneous subsurface geology, improve data availability, and better understand contaminant transport processes in aquifers.</td>
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</table>
**Atmosphere**

- Integrating the response of vegetation to climate change in hydrological impact studies is essential yet challenging, as is evaluating the local to global impacts of land management—including land cover, land use, and water use—on climate.
- Enhancing precipitation prediction models in near zero-degree conditions, particularly in historically cold regions, will be pivotal for accurate hydrological forecasting and the implementation of effective water management strategies.
- Landscape changes resulting from fires can have profound effects on hydrology, including increased surface runoff, soil erosion, and degradation of water quality, highlighting the importance of effective post-fire management strategies.
- The expansion of irrigation can alter local land surface properties, leading to changes in atmospheric processes such as cloud formation and precipitation patterns, thereby influencing regional climate dynamics.

**Cryosphere**

- Advancements in snow, glacier, and permafrost representation within hydrology-land surface models will significantly improve predictions of cryosphere processes, leading to more accurate modeling of the hydrological cycle.
- Addressing data scarcity in cold-regions processes will unlock opportunities for modeling cryosphere dynamics, enabling the development of accurate representations of key variables and processes through expanded observations.
- Modelling long-term memory in cold-region processes poses challenges for initialization and forecasting, demanding extensive historical data and comprehensive consideration of complex interactions to accurately simulate the hydro-thermodynamic behaviors.
- Developing innovative techniques to capture the complex, chaotic behavior and impacts of ice-jam flooding events will overcome modeling challenges, leading to more effective management of river systems.

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42


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