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Abstract

Irrigation systems face unforeseeable changes in climate, technologies, and societal preferences during their lifetime, potentially rendering them obsolete or inadequate. To remain functional, irrigation systems need to be adaptive to changes as the future unfolds. Past approaches to irrigation system design were largely informed by engineering or economic criteria. This is increasingly recognised as insufficient. We provide examples of contemporary irrigation systems in Australia to highlight the need for planning and design approaches that recognise the complex interactions between human and water systems and embrace unknowns. We review literature on hydro-social interactions and dynamic adaptive pathways to provide insights for the development of adaptive irrigation systems.

Highlights

- Long lasting irrigation infrastructure faces unforeseeable natural and societal unknowns.
- Adaptive design approaches need to incorporate the coupled nature of human-water interactions.
- Adaptive design is a process of ongoing social learning.

Introduction

Irrigation schemes facilitate the intensification of agricultural systems and are usually associated with economic development and nation building [1]. However, contemporary irrigation schemes no longer command the unequivocal support they once did. Public policy debates now concern trade-offs between the economic potential of irrigation and the prevention of adverse environmental and social impacts. Anti-dam movements in the mid and late 20th century altered public perceptions of infrastructure development and halted the construction of many large dams [2], although recently there appears to be a resurgence [3••]. Support for existing irrigation systems is also susceptible to shifts in public attitudes. For example, in January 2019, reports of fish kills in Australia's Murray-Darling Basin intensified public debates about water management and irrigation, calling into question the effectiveness of previously negotiated arrangements of water sharing [4]. The long-term sustainability of irrigation systems is as much a social and political challenge as it is a challenge for science, engineering, and economics. Past approaches are no longer considered sufficient for the design of new infrastructure [5]. There is a growing body of literature that recognises that water systems are both natural and social and are shaped by the coupled dynamics of human-water interactions [6]. In parallel to this literature, there are repeated calls for forward-looking or adaptive decision frameworks to help deal with uncertainty about the future [7-9]. This, combined with invariably contested goals for the future we aspire to, lends significant ambiguity to water infrastructure planning.

Here, we argue that ignoring potential long-term social and environmental consequences of investment decisions can lead to suboptimal outcomes. We use examples from our research in Australia to highlight the need for adopting a long-term perspective when decisions are made about investing in irrigation infrastructure. We explore some of the challenges involved in the development of new irrigation schemes in the Australian island state of Tasmania, at a time when support for existing irrigation schemes in Australia's iconic Murray-Darling Basin is the subject of intense policy debate. How can irrigation systems be designed and managed to be adaptive to a future that will be shaped by largely unforeseeable human-water interactions? To address this question, we review and bring together insights from the literature on coupled human-water interactions and on dynamic adaptive pathways approaches to explore how no-regret decisions could be made about the design and management of irrigation infrastructure.

Contemporary irrigation infrastructure development in Australia

In 2014, the Tasmanian State Government set a long term goal to achieve an annual agricultural farm gate value of $AUD 10 billion by 2050, which was then almost a tenfold increase of agricultural production value [10]. Water is closely linked to this transformation, with irrigation investment proposals using catch phrases such as 'just add water' and 'pipeline to prosperity' [11]. The schemes are designed to last for at least 100 years and deliver water at 95% reliability. Reliability is based on modelled projections of water availability through to 2030 under wet, median and dry climate scenarios [12].

Tasmania takes a deliberate, cautions approach to irrigation infrastructure development. New irrigation schemes have to demonstrate economic benefits, ensure cost-recovery, and meet selected environmental criteria [13]. The schemes are developed as public-private partnerships, wherein farmers must commit to buying water rights to cover at least 30% of the construction cost of the scheme while the remaining 70% is funded by government. This first commitment defines the design of the scheme and the supply capacity of the irrigation pipes. As such, the long-term water availability delivered through the scheme is determined by the current willingness of farmers to invest. In research carried out by the authors, farmers with no previous experience in irrigation described how their perceptions changed as they learned what they could do with water [14]. Not only their demand for water, but also their willingness to pay for water has increased in the last few years. See the Text Box 1 for an illustrative quote.

Text Box 1. Illustrative quote of a Tasmanian irrigator about their changing perspective on the value of irrigation water, from [15]

> *"I remember when water cost $15 /ML (1000 m3) and it went to $20 /ML and we all thought it was too dear. Sometimes you have got to pinch yourself and realise that I'm about to spend $250,000 just to get access to 50 ML of water. If someone would have told me this 10 years ago, I would have thought he was living in fairyland, but perceptions change. If I tell other growers about the reality of irrigation water they often don't believe me".*

Although irrigation schemes are built with the explicit purpose of transforming the agricultural sector and rural communities, the current design strategy in Tasmania treats social change as outside its scope; it does not explore future scenarios of varying demand for irrigation water or changing attitudes, including the perceived value of irrigation water.

By designing new irrigation schemes based on current demand, (current) economic viability might be ensured, but adaptation to future changes of climate and social values is limited. This can lead to the development of infrastructure that is either inadequate or inappropriate in the future. Nowhere is this more apparent than in Australia's Murray-Darling Basin. Significant investment of public funds in large irrigation infrastructure across the basin spurred private investment and economic development of regional communities for most of the 20th century [16,17]. Towards the late 1900s however, changing attitudes towards recurrent environmental issues in the Basin altered the political commitment for large-scale infrastructure. Reforms were instituted to buy back water licenses from irrigators and allocate water for environmental purposes, but they remain mired in controversy to this day. Reflection on water resource development in the Murray-Darling Basin leads to two relevant insights: 1) during the life span of irrigation infrastructure, societal preferences and water availability are likely to change; and 2) reallocation of water is a difficult, expensive process that poses a huge political challenge. These examples highlight the need for greater recognition of the interconnectedness of human-water interactions when irrigation systems are developed.

Recognition of coupled human-water interactions

When water is conceptualised as a resource, biophysical factors such as climatic influences, flow, storage or drainage are often considered independently from human or social factors such as needs, values, or governance [18]. Likewise, when water infrastructure systems are planned, social and economic considerations are, to use Lane's [19] words, 'bolted on' to the end of hydrological assessment and design. Many argue that the arbitrary decoupling of bio-physical considerations from social, economic or political considerations has led to adverse consequences for people and the environment [8,20,21]. Malin Falkenmark [6,22], an early advocate for interdisciplinary studies of water, pointed out the extent of human influence on water circulation and made the case for a new field of hydrosociology to involve the social sciences in the study of the coupled nature of human-water interactions [22].

Studies of integrated social and environmental systems have proliferated in the last three decades, with notable contributions being made by Elinor Ostrom [23] on long-enduring irrigation systems and more broadly, the literature on resilience in social-ecological systems. The focus of the social-ecological systems literature is on the system as a whole, wherein interrelationships between components and processes are emphasized [24]. However, this literature has met with criticism from many social researchers who contest the application of functionalist ecological theories to the study of human systems, particularly for its inability to account for the role of human agency, power relationships or constructivist theories of knowledge (see [25] for a broad critique).

Focussing on studies of human-water interactions, Wesselink et al [26••] trace and contrast two approaches that have emerged from natural sciences and social sciences perspectives: socio-hydrology and hydrosocial research. Socio-hydrology has emerged as a new discipline that seeks to study the dynamics of society-water interactions to discover regularities that emerge over time in diverse contexts [27]. It aspires to capture all human-nature interactions into a holistic, quantitative model that explains and seeks to predict how human-water systems co-evolve over time [28••]. As with social-ecological systems, the main criticisms of socio-hydrology are its inability to predict human values, human behaviour or social interactions [29•,30•] and its inability to deal with knowledge controversies [19]. By contrast, hydrosocial research encompasses the work of social scientists and political ecologists who focus on the power relations that lead to inequalities in human-water systems. It sees human-environment interactions as a dialectical process that shapes both water and society. i.e., their relationship is internal. Just as the material flows of water through the landscape influence human activity, social relations – played out through hydraulic infrastructure, laws and policy narratives – determine the flow of water (for example, see [31]). Hydrosocial research is criticised for over-theorizing and not engaging as much with identifying solutions to the problems they articulate [26••].

Regardless of these epistemological differences and limitations, both socio-hydrological and hydrosocial approaches highlight the complex and coupled nature of human-water interactions. Whilst the explanatory power of socio-hydrology is useful in a historical, spatial and comparative sense, the value of hydrosocial research is in its emancipatory power, i.e., its ability to illuminate power asymmetries so that they may be negotiated and addressed.

In this regard, the two approaches could complement each other in a pluralistic or reflexive manner (see [19,25,32] for ways to do this). While this adds value to the planning and design process, it still does not address the limited ability to support forward-looking decision making. For that, the literature on Dynamic Adaptive Pathways might help.

Embracing the unknowns by exploring Adaptive pathways

Dealing with future uncertainty is increasingly recognised as a key challenge for the design and management of water infrastructure. [7,33,34]. A promising approach, applied in the long-term Dutch Delta Programme, is the Dynamic Adaptive Policy Pathway (DAPP) approach [35••,36-38]. The DAPP approach is presented as a new planning paradigm, wherein a strategic, long-term vision is developed based on consensus [39]. Commitments are made for short-term action items while the framework allows for dynamic adaptation over time, i.e., the pathways to reach the strategic vision can be adjusted or switched as the future unfolds [40]. Predefined tipping points trigger the need to redefine a strategy or to change direction [37••]. The intention of using the DAPP framework in the Dutch Delta program is to avoid making design decisions now, that will be regretted later [41].

Outside the Netherlands, similar adaptive pathway approaches have been applied in England to develop the Thames Estuary 2100 pathways [42], in New Zealand, where stakeholders explored the influence of climate scenarios in a local flood risk management context [43,44], and in Australia to develop adaptive plans to adjust to climatic changes in two local coastal regions [45,46]. In the face of uncertainty, the DAPP approach reduces path-dependencies; it is adaptive to new information; and it allows for greater distribution of costs and benefits across generations [27].

The main limitations of the DAPP approach relate to its assumptions: that participants have an understanding of (system) complexities (including externalities); that tipping points can be clearly identified; that knowledge is uncontested; and that a clearly defined unambiguous long-term objective can be agreed upon [47••,48••]. Furthermore, we find that applications of DAPP tend to focus on climatic or natural unknowns. The coupled interactions between biophysical and social phenomena are rarely explored. In some cases (for example in [49]), future changes in climate and societal perspectives are considered together to evaluate the robustness of investment strategies, but these approaches use forecasting techniques, which can be problematic for dealing with unforeseeable changes.

Insights for developing adaptive irrigation infrastructure

During the lifespan of irrigation infrastructure, unforeseeable changes in climate, the environment, technologies, and societal preference can render the infrastructure inadequate, obsolete or prohibitive to sustain. Hence, we propose a new approach (Figure 1) for developing adaptive irrigation systems that brings together insights from DAPP and the literature on coupled human-water interactions. The major difference from DAPP is that the proposed approach recognises the coupled dynamics of human-water interactions by exploring impacts on the water system, society and the environment iteratively. Fig. 1 shows this modified, iterative learning and assessment loop, adapted from Haasnoot [35••], that makes this approach applicable for other settings such as coastal or river infrastructure.

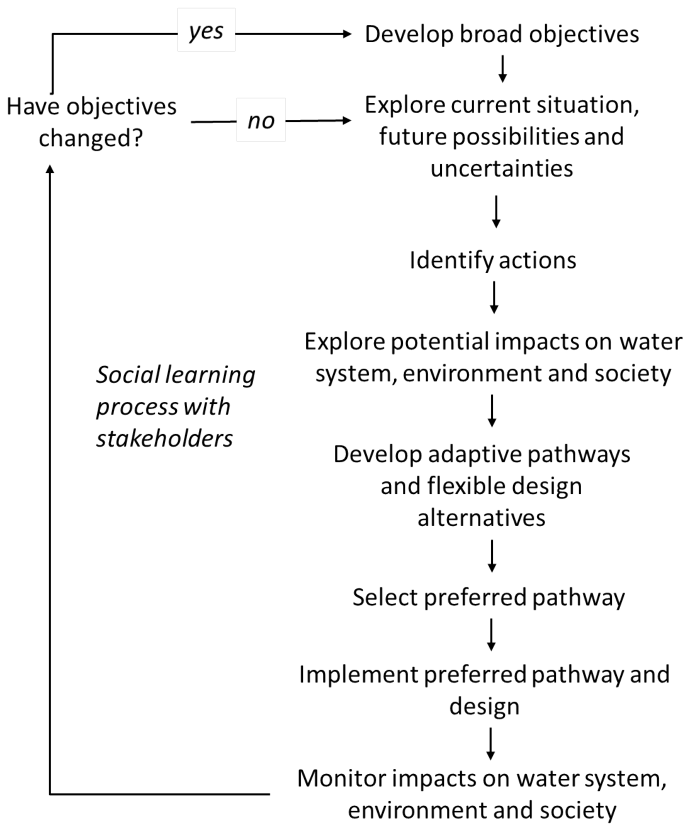

Figure 1. *Developing irrigation systems in a social learning process by linking hydro-social interactions with adaptive pathways. Adapted from Haasnoot [35••]*

Rather than attempting to predict hydro-social changes, we propose that finding the ideal pathway to manage or use water should be approached as an ongoing learning process with stakeholders. The process commences with the development of broad objectives, with the recognition that these objectives will change over time. A prerequisite for such an approach would be a culture that openly embraces and communicates uncertainty and ambiguity[1]. Social unknowns are not to be treated as exogenous but instead to be embraced, internalised, explored, and communicated. Uncertainty, ambiguity and ignorance can foster creativity, innovation and consensus building [52], but it is important to recognise that they can be used as a political tool [53,54].

Recognising the importance of the political and institutional contexts of water resource decisions [18,55,56], we suggest that as a part of the design and management process, space should be explicitly created for social learning amongst stakeholders. Social learning processes aim to facilitate cooperation among stakeholders based on shared meanings and practices [57] and provide a means to learn together to better manage together [58]. Diverse and plural knowledges are a key ingredient to such learning [59]. In the Tasmanian research study described above (see [14], further research is in progress), we found that such processes can also be useful in appreciating social change induced by changes to water systems and vice versa. Facilitated discussions between key stakeholders can create opportunities to appreciate diversity, learn from each other, and enable the identification of potential future pathways. Indeed, community-based social learning approaches to deal with future uncertainty are arguably more justifiable than top-down engineering solutions that regard social values as static and unchangeable [51,60-62]. We acknowledge that social learning processes are not immune to issues arising from power asymmetries. It becomes imperative to critically examine the framing of issues and contestations of knowledge to foster conditions for learning.

An important element of the proposed approach is the addition of flexible design alternatives when it comes to irrigation infrastructure development. Irrigation infrastructure is typically expected to last at least several decades, often centuries. Without flexibility in design, the adaptiveness of the overall system is largely constrained. Flexibility is required not only in the design of physical infrastructure (for examples, see [34]) but also in institutional arrangements and management options. We conclude by identifying adaptive design approaches for irrigation infrastructure. This includes suggestions for future

[1] Ambiguity is identified as a source of uncertainty [e.g. 50] or as a dimension of uncertainty [51]. Here, we refer to it separately to stress its significance.

research. We provide three examples of strategies that could be explored for the development of adaptive irrigation infrastructure:

1. Improving adaptive capacity through social learning processes that bring together experienced irrigators (or other stakeholders) with farmers who are considering making an investment decision in infrastructure.
2. Organising informal networks and recurring workshops between stakeholders aimed at social learning, ideally decoupled from decision making. Decoupling learning from decision making could help to overcome issues related to power imbalances, allow participants to bridge divides and improve dialogue conditions [63,64].
3. Overcoming path dependency by regulating the water market. Regulation can be done in many ways. One way is for the State to purchase water rights in the development stage with subsequent release of these rights at strategic points in time to regulate the price and allow newcomers to start irrigating. Another way to encourage learning by doing is to lower the upfront cost of water rights and increase the yearly rates. This would potentially lead to a bigger uptake of water rights and farmers pay for the water when they actually have the chance to generate the value needed to cover the costs. An additional option is to stop allocating perpetual water rights, but instead treat water rights as scarce resources such as radio frequencies, that can be bought at auction for a limited period only (say 30 years). This would allow future generations to participate in the scheme and adapt to future social and hydrological changes.

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Conflict of Interest

The authors declare no conflict of interest.

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