A meta-model of socio-hydrological phenomena for sustainable water management

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Overemphasizing technological solutions in water management without considering the broader systems perspective can result in unintended consequences. For example, infrastructure interventions for drought adaptation may inadvertently increase flood risk, illustrating a socio-hydrological phenomenon. We propose a systems meta-model that reveals the complex mechanisms and feedback loops underlying the critical human-water interactions. We show that the unintended outcomes of water management decisions result from the lack of integration and coordination of the feedback loops. The insights highlight the importance of considering environmental capacity in water management, as well as the necessity for integrated assessment and coordinated solutions for long-term sustainability.

Main

The global community faces substantial challenges in achieving water-related Sustainable Development Goals (e.g., clean water and sanitation, sustainable cities, etc.), including the need for considerable infrastructure investments[1] and cooperation on climate change[2]. These challenges may be caused by the complex socio-hydrological phenomena that describe interactions in coupled human-water systems (CHWS)[3]. The socio-hydrological phenomena provide a conceptual framework to understand how water management interventions can result in various unintended outcomes (Table 1). These outcomes include trade-offs between management goals, such as socio-economic development and environmental health[4] and different water uses, for example, urban-rural water use trade-offs[5]. This highlights the necessity for a comprehensive understanding of water management decisions, policies, and interventions by multiple stakeholders. We take a systems perspective on socio-hydrological phenomena to challenge conventional water management decisions and plans, which have often been developed using linear thinking and a goal-focused approach that may overlook system-wide interactions[6].

To comprehensively address socio-hydrological phenomena from a systems perspective, it is essential to understand their underlying mechanisms, including the ways in which human interventions impact the state of the environment. The concept of archetypes, which represent common structures that produce a characteristic system behaviour[6], can enhance our understanding of complex socio-environmental interactions. Many CHWS problems have been analysed through a range of well-known archetypes. For example, the ‘limits to growth’ archetype describes the overuse of common natural resources impairing sustainable and equitable development[7] while the ‘green-red loop’ approach illustrates how different resource dependence on the environment to support social development may lead to environmental degradation and potential system collapse[8]. Conceptual and systems dynamic models have been developed to explore socio-hydrological phenomena as forms of archetypes, focusing on specific water management aspects such as groundwater depletion[9], flood protection[10] and wetland degradation[4]. However, a generalisable representation that encompasses the drivers and feedback mechanisms defining multiple socio-hydrological phenomena is currently lacking. This creates a need for a framework to analyse and inform integrated solutions for complex human-water system interactions.

To explore the potential for a unified framework we select the six phenomena included in Table 1 that are described by eight selected case studies explaining the drivers and dynamics of complex socio-hydrological interactions in CHWS. The case studies show that socio-hydrological phenomena can be observed in all aspects of water management (floods, droughts, water infrastructure, technology, and governance) and across multiple spatial scales (local, catchment to regional) from the Global North to South. We hypothesise that socio-hydrological phenomena are ultimately unintended outcomes of water management caused by external driving forces (e.g., climate change) and internal feedback mechanisms (e.g., social development drives water infrastructure development, which in return provides water supply for further social development), which are inconsistent with what water managers would expect and their own planning and allocation decisions. The focus is on man-made changes to the natural environment and their consequences, and how systems-level analysis can support stakeholders in water management decisions and planning. To test the hypothesis, we develop a unified systems framework that generalises the socio-hydrological phenomena. We refer to this framework as a CHWS meta-model, which we first describe and then use to show how complex socio-hydrological phenomena could be better analysed from a systems perspective. The meta-model application has the potential to provide insights that will enable the anticipation of unintended outcomes and the development of more robust and sustainable water management plans.

Coupled human-water system meta-model

To conceptualise the CHWS meta-model, we analyse example case studies in Table 1 to reveal *components* and feedback loops that describe the socio-hydrological phenomena. Components are defined as high-level elements of the meta-model that can be evaluated through a set of indicators. The meta-model feedback loops are conceptualised as causal (positive or negative) links between the components informed by the socio-hydrological phenomena mechanisms (Fig. 1). We recognise that real-world systems involve a range of complex interactions. The meta-model can serve as a high-level representation of key CHWS mechanisms that, once mapped, can be further expanded to capture context- and problem-specific water management decisions, and select relevant indicators that can be used for water management systems-level analysis.

CHWS meta-model components

Case studies in Table 1 reveal a reliance on *water infrastructure* to support development by managing the *environmental state* and balancing the water *resources demand-supply.* In the adaptation effect phenomenon, perpetual development enabled by water infrastructure (e.g., flood defences[11] and water supply reservoirs[12]) eventually negatively impacts the *quality of life* (e.g., increased damages from subsequent flood and drought events). The economically driven growth manifested through the *level of development* is characteristic of the safe development, supply-demand cycle and rebound effect phenomena, which define the human system's reliance on natural resources without considering long-term impacts on the environmental state. This can result in increased social vulnerability due to the perceived security provided by flood protection[13] and increased water use enabled by water transfers[14] and water-saving technologies[15]. The notion of limits to growth within the pendulum swing phenomena describes how the environmental system's ability to provide resources and *ecosystem services provision* is impacted by human activities' *environmental footprint*. If environmental protection becomes the priority for decision-makers, economic activities may be shifted from, for example, reducing the water used for food production towards mitigating riparian environment degradation[4]. Finally, examples of the aggregation effect phenomenon reveal undesirable outcomes of water management decisions across different spatial scales, such as causing environmental degradation due to over-abstraction of common groundwater resources between countries[16] and prioritising urban water use while reducing irrigation supply within a catchment[5] In Table 2 we generalise the description of seven CHWS meta-model components and give examples of potential evaluation indicators. We note that each component can be described by a set of indicators, which should be defined based on the meta-model application and selected method of analysis.

Feedback loops in the CHWS meta-model

The CHWS meta-model proposes that the quality of life, as a measure of societal priorities for prosperity and wellbeing[17] is a function of both the level of development and the ecosystem services provided directly (e.g., land use for agriculture) and indirectly through water infrastructure (e.g., water supply for irrigation). The meta-model is designed to help us understand how to coordinate water infrastructure management, development, and environmental protection. We achieve this goal by creating three hypothetical feedback loops which show how these components interact. (Fig. 1).

For the level of development to improve the quality of life, there must be a sufficient supply of commodities, disposable household income and accessible public services[18], which can be measured by socioeconomic indicators (e.g., GDP per capita). However, improved quality of life also leads to increased demand[19], use of local natural resources, and dependence on distant ecosystems[20]. In the CHWS meta-model, the perception of increasing quality of life through water intensive level of development creates a resources dependence (RD) loop. The RD loop creates a disconnect between water services and the environment, as can be seen through urbanisation where cities create virtual and actual water footprints that exceed urban boundaries[21].

Exploiting natural resources to support development reduces the integrity of ecosystems and diminishes their ability to provide services[22]. In the CHWS meta-model, the natural environment's role in increasing quality of life is defined by the environmental capacity (EC) loop. A wide range of human activities (e.g., food production and land management) can damage the environmental state, which can be quantified through an environmental footprint[23]. The EC links are caused by dependence on water and land resources, e.g., land degradation caused by irrigation-induced salinity leading to decreased agricultural production and livelihood[24]. However, the damage to the ecosystem services delivered by the EC links can be potentially reduced via proactive environmental management (e.g., nature-based solutions to manage floods and water pollution[25]). Therefore, ecosystem services provision is needed to evaluate the quality of life, and the environmental state is a critical indicator for socio-economic system performance in the RD loop. Changes in the environmental footprint should be used to manage and adjust this RD loop.

Understanding the role of water infrastructure as a link between the RD and EC loops is key to aligning development with the level of environmental change. Economic growth and population-dense urban environments require water infrastructure to deliver water supply, surface water management and wastewater treatment, while agricultural areas expansion with increasing irrigation demand requires intensive canal and well systems. By interacting with the water systems, society has become detached from the local environment. Water infrastructure fulfils a dual role, serving as a provider of services like water supply and as well as performing environmental management functions such as river protection from the wastewater pollution[26]. Water management decisions, such as wastewater treatment plant operations and flood protection, are designed to create a positive link between the water infrastructure and environmental state components. However, they also create an infrastructure management (IM) loop that buffers the signals of environmental degradation. Water infrastructure systems are necessary to support development, but their buffering effect enables the EC loop mechanisms to be either ignored, allowing development in the RD loop to continue despite pressures on and from the natural environment.

Meta-model and socio-hydrological phenomena

By understanding key drivers and feedback mechanisms in the meta-model, we can explain the socio-hydrological phenomena described in Table 1. We argue that the phenomena are influenced by feedback loops in the meta-model, and can be grouped into three distinct CHWS archetypes based on whether these loops are considered, integrated, or coordinated (Fig. 2). Detailed explanations of the socio-hydrological phenomena mechanisms informed by the meta-model, which create feedback loops in case study examples, is provided in Table 3.

Within the CHWS meta-model, two socio-hydrological phenomena can be described as a process when the EC loop is not fully considered in water management analysis, which we refer to as an 'environmental capacity ignorance'. The adaptation effect occurs when, to mitigate extremes (e.g., floods and drought management) by an enthusiastic investment into infrastructure, technology or efficiency, interventions can have unintended outcomes caused by increased resource use[12] and socio-economic development[27] within CHWS. When this form of infrastructure investment is mapped onto the CHWS meta-model, it creates an unstable, perpetually increasing IM loop (Fig. 2A). This perpetual loop highlights that it is not possible to expect infrastructure investment to continually improve the quality of life without also considering the environmental footprint and development impacts on the system. Environmental capacity ignorance also occurs when only IM and RD loops are considered. Fig. 2B maps safe development, supply-demand cycle and rebound effect phenomena. The mapping highlights that these phenomena do not properly consider the EC loop by failing to account for the environmental footprint arising from e.g., increased urbanisation incentivised by water infrastructure service provision. Again, ignoring the environmental footprint in this manner results in persistent deterioration of the environmental state and ecosystem service provision, which typically accumulates and becomes evident over time. This formulates a perpetual feedback loop that is unstable in the long term.

The second archetype characterises systems where the environmental capacity is taken into consideration, but proposed development and water management options cannot support continuous growth, which we define as a ‘water systems segregation’. As an example, Fig. 2C maps the pendulum swing phenomenon onto the meta-model. The phenomenon occurs when, over time, priorities swing between the EC and the IM loops to pursue better living standards. Viewed in the context of the meta-model, activating the IM and RD loops only results in the same perpetual loop as in Fig. 2B. Meanwhile, activating just the EC and RD loops results in a coordinated system but potentially with low economic growth, since any increase in local resource use will decrease ecosystem service provision[22]. This highlights why it is necessary to consider the entire meta-model in development planning to improve quality of life.

Finally, socio-hydrological phenomena occur when all meta-model loops are activated, but the systems that they represent are not properly coordinated, resulting in a ‘water management discord’ archetype. Two instances of the aggregation effect phenomenon across different spatial scales fit this process and cause undesirable outcomes without adequate systems coordination. In Fig. 2D, we depict an example of the water management discord, commonly referred to as a tragedy of the commons[3]. The conceptualisation shows how two stakeholders, for example, water utilities drawing groundwater from the same regional aquifer[16] have separate infrastructure management and resource dependence loops but a shared environmental capacity loop. For two individual stakeholders who consider their EC loop in isolation, their impacts may appear negligible. However, this setup will only function in a stable manner if stakeholders understand that their EC loop is shared.

In Fig. 2E, we depict how the environmental footprint of catchments, regions or countries can be exported to other parts of the system via the CHWS meta-model[20]. This exportation enables what appears to be a perpetual loop of increasing quality of life, from the perspective of the system that exports impact. For example, at a catchment scale, such exportation of the environmental footprint can happen when urban systems obtain benefits through expansion and increased resource use, with less water and land availability and more pollution taken by rural systems[5]. However, this is not a fair situation and one that is unfavourable for the impact-receiving region when the environmental capacity loop is considered. Viewing this phenomenon in the context of the meta-model also reveals how, if proper infrastructure were installed and feedback into a level of development were enabled, this setup could be made to work in a stable manner. Examples of sustainable footprint export show that cities imposing their environmental capacity loop onto rural areas in developed nations could be an acceptable situation provided that the rural areas receive support for sufficient infrastructure and development[28].

Principles for water system sustainability

The insights from socio-hydrological phenomena analysis using the CHWS meta-model can be used to define guiding principles for sustainable water management that aims to prevent future unintended outcomes and utilise ecosystem services in supporting quality of life. We propose three principles that need to be included in the water management system conceptualisation and integrated into the qualitative and quantitative analysis of CHWS, which we support with examples from recent studies on water systems integration.

Develop within the environmental capacity

The environmental capacity ignorance implies that solutions relying on water infrastructure expansion and operation (IM loop), and more broadly any technology to support development (RD loop) need to include analysis of maximal allowed resource use in an environmental system to minimise the environmental footprint and prevent environmental state decline (EC loop). Within the CHWS meta-model, we suggest that future development and water infrastructure systems should be designed and operated to achieve the goal of water neutrality. The water neutrality concept sets targets for the environmental state component (e.g., river flow and pollutant concentrations) to guide design and options for land planning and water management[29]. By defining the water neutrality targets based on either the current or desired environmental state (EC loop), the impact caused by development decisions linked to the RD and IM loops can be quantified and explicitly accounted for in future planning. This will enable answering three questions: (i) how far the current environmental state is from the desired targets, (ii) how ambitious we want to be in achieving these targets, and (iii) how achieving water neutrality could impact our development decisions. An example study applied the water neutrality concept to London, UK and found that to offset the impacts of the proposed new housing and maintain the current state of the environment, almost the same number of existing homes should be retrofitted with water-efficient and green infrastructure solutions[29]. The water neutrality concept highlights the need to monitor and regulate the environmental impacts, which will help to prevent the system from approaching the maximal limit of resource use and pollution and avoid potential significant damage from unintended outcomes caused by environmental capacity ignorance.

Provide evidence for integrated planning

The CHWS meta-model highlights the importance of an integrated assessment of environmental state indicators to address the trade-offs between resources-intensive development (RD loop) supported by water infrastructure (IM loop) and environmental protection (EC loop), identified by the water systems segregation. We propose that for water planning, environmental state indicators should be defined across three key aspects of water management: water supply, quality, and flood protection, for which integrated water management models are needed to capture interactions between system components and indicators. A study that implemented integrated modelling to a regional rural-urban water system demonstrated the value of quantifying systems-level objectives for water planning analysis[30]. An integrated model was coupled with multi-objective optimisation algorithms and the results showed potentially significant trade-offs between water availability, water quality, and flood management objectives when developing a set of optimal portfolios of nature-based solutions. Water planning analysis could also expand the set of indicators by accounting for the link between, for example, water systems and ecology. Applying regression modelling on land use and water quality data to predict the presence/absence of species showed a great potential to use ecological indicators to inform water planning decisions that promote biodiversity protection[31].

Coordinate solutions for long-term sustainability

The CHWS meta-model can highlight the connections among multiple systems to support holistic decisions. A water management discord showed that integration of water infrastructure and environmental footprint analysis to support socio-economic development within one system (e.g., urban, or rural) may not be sufficient if coordination has not been achieved across the water planning decisions that can result in aggregated impacts on the environment and, consequently, on quality of life. Two examples showcase the value of coordination for the long-term planning of water systems. An example of catchment coordination can be found in the application of the integrated water system analysis to reveal how pollution management can be designed to specifically target periods of low water quality by combining fertiliser reduction (rural environmental footprint) and wastewater treatment upgrade (urban water infrastructure) interventions[32]. These interventions are efficient at improving water quality because urban measures target dry seasons (when wastewater concentration in rivers is high) while rural measures are designed for wet seasons (when erosion and other hydrological processes which mobilise pollutants are strong), enabling the natural system to maximise the regulating ecosystem services provision potential. Another example of water infrastructure coordination, in an urban metropolis setting (London), demonstrates that reducing abstractions (supply infrastructure) during intense rainfall events increases the in-river dilution capacity of combined sewer overflow spills (wastewater environmental footprint), ultimately improving river water quality at levels comparable to expensive hard infrastructure solutions[33].

Given the ever-increasing complexity of water systems and the urgency of moving onto a sustainable development path, the CHWS meta-model provides a systems-level perspective on integrated water planning that includes resources development, environmental capacity, and infrastructure management feedback loops and uses environmental state indicators to guide land and water infrastructure planning. As such, this approach can be used to inform the framing and modelling of CHWS. This in turn will lead to the creation of an evidence base, through case studies, addressing socio-hydrological phenomena from a systems perspective. By considering the three feedback loops of the CHWS meta-model and using integrated modelling approaches, we can move towards the planning and design of water systems that enable long-term sustainable development in the face of an uncertain future.

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Author contribution

A.M. conceived the idea and designed the meta-model. A.M., L.L., J.O.K, B.D and K.P.C. designed and carried out analysis and developed proposed principles. A.M. and L.L. wrote the paper. All authors discussed the findings and contributed to the manuscript.

Competing interests

The authors declare no competing interests.

Manuscript tables

Table 1. Selected socio-hydrological phenomena with example case studies from the literature

Socio-hydrological phenomena	Description	Example case study with a reference
Adaptation effect	Frequent extreme events increase coping capacities thereby reducing social vulnerability	The reinforced flood defenses reduce protection failures and 50% monetary damage in 2013 after the 2002 flood event in Elbe and Danube, Germany[11]

	Adaptation to drought can worsen flood losses, and vice versa	Long-term droughts affect reservoir operations for more water storage, which enhances the severity of the 2011 Brisbane flood[12]
Safe development paradox	Protection measures generate a false sense of security that reduces coping capacities thereby increasing social vulnerability	Raising levees over decades to protect a growing urban area in New Orleans has led to low probability but catastrophic flooding[13]
Supply-demand cycle	Increasing supply enables growth that in turn generates higher demands	Inter-basin water transfer projects increased water demand in the Zayandeh-Rud River Basin, Iran[14]
Rebound effect	Increasing the efficiency leads to higher consumptions	The application of water-saving technology increased total water consumption in Xinjiang province, China[15]
Pendulum swing	Changing priorities from pursuing economic prosperity or environmental protection	Shift from water use for food production into mitigating riparian environment degradation in the Murrumbidgee River basin, Australia[4]
Aggregation effect	Undesirable outcomes at the system scale from aggregated optimal decisions at the individual scale	Unprecedented regional groundwater level decline in Disi aquifer shared by Jordan and Saudi Arabia[16]
	Desirable outcomes at the system scale from aggregated inequalities at the individual scale	At a catchment scale, urbanisation in Hyderabad, India, drives more water from a reservoir allocated to urban use so that

		farmers’ access to canal water for irrigation is reduced[5]

Examples of socio-hydrological phenomena reported are from Di Baldassarre et al.[3]

Table 2. CHWS meta-model components and potential indicators

Component (abbreviation)	General description with relevant references	Examples of potential indicators
Water Infrastructure (WI)	The status of infrastructure that is specifically designed, engineered, and operated for water management purposes, including water supply (e.g., reservoirs), water quality (e.g., wastewater treatment plants), and flood mitigation (e.g., levees and dikes)[34]	Access to safe drinking water[35]
Environmental State (ES)	The physical conditions of ecosystem components (e.g., soil, atmosphere, water, species) as well as their interactions (e.g., hydrological processes and nutrient cycles)[36]	Environmental Performance Index[37]
Resource Demand-Supply (RDS)	The quantity of natural resources that is demanded and supplied for supporting socio-economic development and human wellbeing, including water, food, and land[20]	Food production and consumption[38]
Quality of Life (QoL)	The degree to which human basic needs for well-being are satisfied. Such needs include physical needs (e.g., natural resources demand) but also a	Poverty headcount ratio[39]

	mental health support (e.g., safety when facing hazards)[17]	
Level of Development (LoD)	The degree to which a society can provide public goods (e.g., commodities) and services (e.g., land development) as socio-economic benefits[18]	GDP per capita[40]
Ecosystem Services Provision (ESP)	The benefits that ecosystems can provide for human well-being, such as resources provision, pollution purification and aesthetic values[22]	Biocapacity[41]
Environmental Footprint (EF)	The impacts on natural environment by human activities, such as land cover change, resource extraction and pollution[23]	Ecological[23] and water[42] footprint

Table 3. Socio-hydrological phenomena examples informed by the CHWS meta-model.

Phenomenon	Case study location	Meta-model informed mechanisms driving unintended outcomes
Adaptation effect	Elbe and Danube, Germany[11] (Successful adaptation)	**IM loop:** After significant monetary damage and fatalities (QoL) by a flood event in 2002, the local community demanded better regulation of water resources (RDS) during high rainfall events, which triggered construction of new flood defences (WI). This increased the carrying capacity of the rivers (ES), which enhanced the flood mitigation ecosystem services (ESP). As a result, the next flood event in 2013 affected fewer people and significantly reduced the damage (QoL).
	Brisbane, Australia[12] (Unsuccessful adaptation)	**IM loop:** Prolonged drought conditions had threatened the residential water use (QoL), who demanded sufficient water supply (RDS). This resulted in the operation of the reservoir (WI) to store more water, which increased the water availability for supply (ES). Water provision ecosystem services (ESP) were thus improved, but the ability for flood mitigation (ESP) was decreased. Consequently, the system failed to cope with the flood in 2011 which caused remarkable monetary damage and fatalities to the local community (QoL).

Safe development paradox	New Orleans, USA[13]	**IM loop:** To reduce monetary damage and fatalities (QoL) caused by frequent flood events, local society demands better regulation of river flows (RDS), which results in levees' rising (WI). This increases the carrying capacity of the river (ES) and enhances the flood mitigation ability (ESP), which reduces the frequency of flooding and the damage caused to the society (QoL). **RD loop:** With the enhanced flood security and population growth (QoL), more land resources are needed (RDS) for urban area expansion that supports socio-economic development (LoD). Such development in return generates more benefits for improving well-being (QoL) such as an increased income. **EC loop (neglected):** However, the expanded urban land (RDS) influences local hydrological processes (ES) by increasing stormwater generation and occupying low areas (EF), which undermined the regional flood mitigation ability (ESP) and increased flood exposure. Without fully recognising these impacts, more catastrophic fatalities (QoL) were caused when low-frequency flood events happened that overtopped the raised levees.
Supply-demand cycle	Zayandeh-Rud River Basin, Iran[14]	**IM loop:** Increased population in the basin (QoL) generated more water demand for domestic use and production (RDS). To satisfy increased demand, canals, and tunnels (WI) were built and operated for inter-basin river transfer, which increased the water resources within the basin (ES) and enhanced the water provision (ESP). The increased water provision helped to secure residents' daily water use (QoL).

		RD loop: Securing the supply of water resources (RDS) supported economic development in agriculture and industry sectors (LoD), which generated social benefits such as more job opportunities (QoL). **EC loop (neglected):** However, the increased population (QoL) demanded more water (RDS) that was satisfied via increased water abstraction (EF), which decreased the quantity of water resources in the local water bodies (ES) and the water provision (ESP). Ignoring this loop could potentially lead to a water supply reduction, with direct effect on the local quality of life.
Rebound effect	Xinjiang province, China[15]	**IM loop:** To increase the crop yield that generates better income (QoL), farmers in the dry Tarim River Basin demanded sufficient water resources for irrigation and better soil conditions (RDS). They installed water-saving irrigation appliances (WI), which managed groundwater levels and reduced soil salination (ES). Soil health then favoured crop growth and increased crop yield (ESP), which generated more profits for farmers (QoL). **RD loop:** With the increased income and subsidies from the government (QoL), farmers demanded more water and land (RDS) for expanding the agricultural activities (LoD) to generate increase their income (QoL). **EC loop (neglected):** However, the expanded total water demand for irrigation (RDS) increased the total amount of water abstractions (EF), which decreased groundwater storage within the region as a whole (ES)

		and undermined the overall water provision (ESP). Neglecting this loop caused the total water abstraction for irrigation to rebound and constrain farmers' crop yield and income (QoL).
Pendulum swing	Murrumbidgee River basin, Australia[4]	**Early eras:** **RD loop:** With the population growth (QoL), more water and land resources (RDS) were needed to expand the agricultural activities (LoD), which enhanced food security and income via crop sales for the local community (QoL). **IM loop:** To increase the water supply for irrigation (RDS), new dams were constructed (WI) to increase water storage capacity (ES), which enhanced the water provision (ESP) and increased water security for domestic use and irrigation (QoL). **EC loop (neglected):** Increased supply of water resources (RDS) encouraged a wide expansion of irrigation (EF), which caused soil salinity and reduction in environmental flows and wetlands degradation (ES). The overall ecosystem services for ecological maintenance were reduced (ESP), which a negative impact on the local QoL.
		Late eras: **RD loop:** After recognising the role of environmental degradation for local well-being (QoL), communities' attitudes shifted more towards environmental protection and demanded better regulation of water resources

		for ecological maintenance (RDS). As a result, the 'green lobby' and the diminishing role of agriculture changed the Australian economy, and water markets were built (LoD). Rice growers then diversified their income sources such as creating profit (QoL) by selling water during dry periods. **IM loop (neglected):** To better regulate water resources for ecological protection (RDS), water infrastructure for irrigation (e.g., farm dams) (WI) was restricted through licensing. The development of this loop previously for irrigation water abstraction was suspended in this era. **EC loop:** Demand for regulating water resources for ecological protection (RDS) resulted in the implementation of measures to reduce the water allocation for agriculture (EF). This helped to restore environmental flows and improve ecological conditions (ES), which enhanced the ecological maintenance (ESP) that benefited social well-being (QoL).
Aggregation effect	Disi aquifer shared by Jordan and Saudi Arabia[16]	**IM loop:** To enhance water security (QoL), satisfying water demand for domestic use and irrigation (RDS) drove new borehole construction (WI) in both countries, which initially changed the hydraulic conductivity of groundwater bodies (ES) and increased the water availability for both countries (ESP). **RD loop:** Enhanced water supply (RDS) increased socio-economic development, especially in agricultural sector (LoD), which generated benefits (e.g., more income via cereals export) for improving well-being in both countries (QoL).

		EC loop: However, increased demand (RDS) increased water abstraction (EF) across the whole regional system, which decreased the groundwater levels (ES) and endangered overall water provision (ESP). A lack of coordination between the three loops in both countries may further deteriorate groundwater resources and lead to a collapse of a shared water resources system.
	Hyderabad, India[5]	**IM loop:** Increased urban population (QoL) generated more water demand (RDS), which changed reservoir operation (WI) to allocate more water for urban use. The reservoir water storage capacity was increased (ES) and the water provision for urban residents (ESP) was enhanced. **RD loop:** Increased water supply (RDS) stimulated urbanisation and boosted economic development (LoD), which generated benefits for urban residents such as a growth in income (QoL). **EC loop:** However, increased urban water abstractions (EF) decreased the available water resources in the catchment (ES) and water provision for irrigation (ESP), while the increase in impervious land (EF) reduced the agricultural area available for farmers (ES) and land provision for agriculture (ESP). Prioritising urban development significantly impacted the rural system and farmers' well-being (QoL). A lack of coordination between these urban and rural systems has a potential to accelerate the water use inequity.

Figure captions

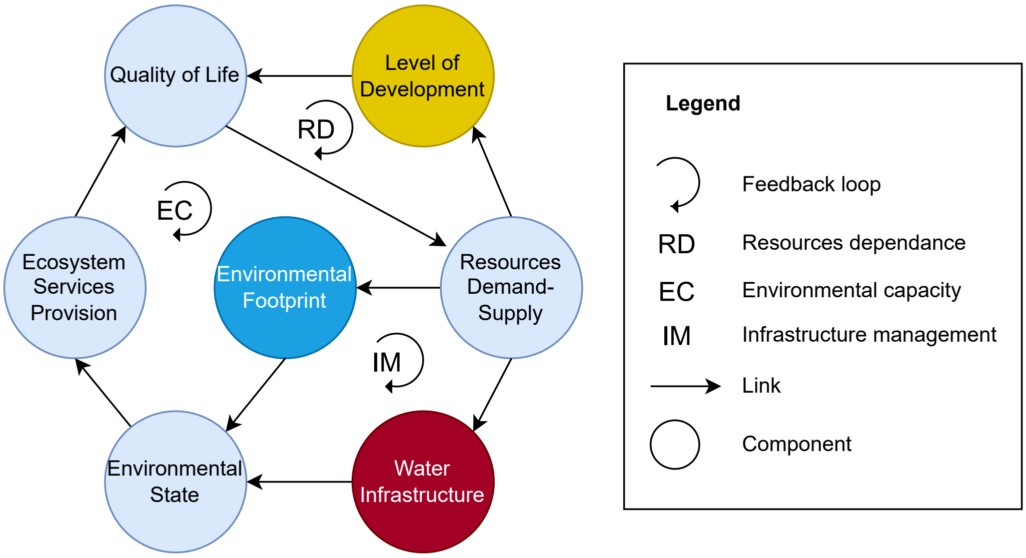

Fig. 1. Coupled human-water system (CHWS) meta-model. The meta-model includes seven components, whose interactions are conceptualised as causal (positive or negative) links informed by the socio-hydrological phenomena case studies (Table 1). The components interact at a systems level via three feedback loops. Human reliance on the natural environment (e.g., water and land) to support quality of life through a level of development is driven by the **resources dependence (RD) loop**. The environmental state is defined by two loops; (i) an **environmental capacity (EC) loop** that depicts a functioning natural environment and associated footprint and (ii) an **infrastructure management (IM) loop** that includes the role of water infrastructure in managing supply, pollution, and flooding. The meta-model suggests that the proposed level of development (yellow component) should be coordinated with water infrastructure management (red) so that impacts on the environment via footprint are minimised (blue), leading to the long-term sustainability of integrated water management systems.

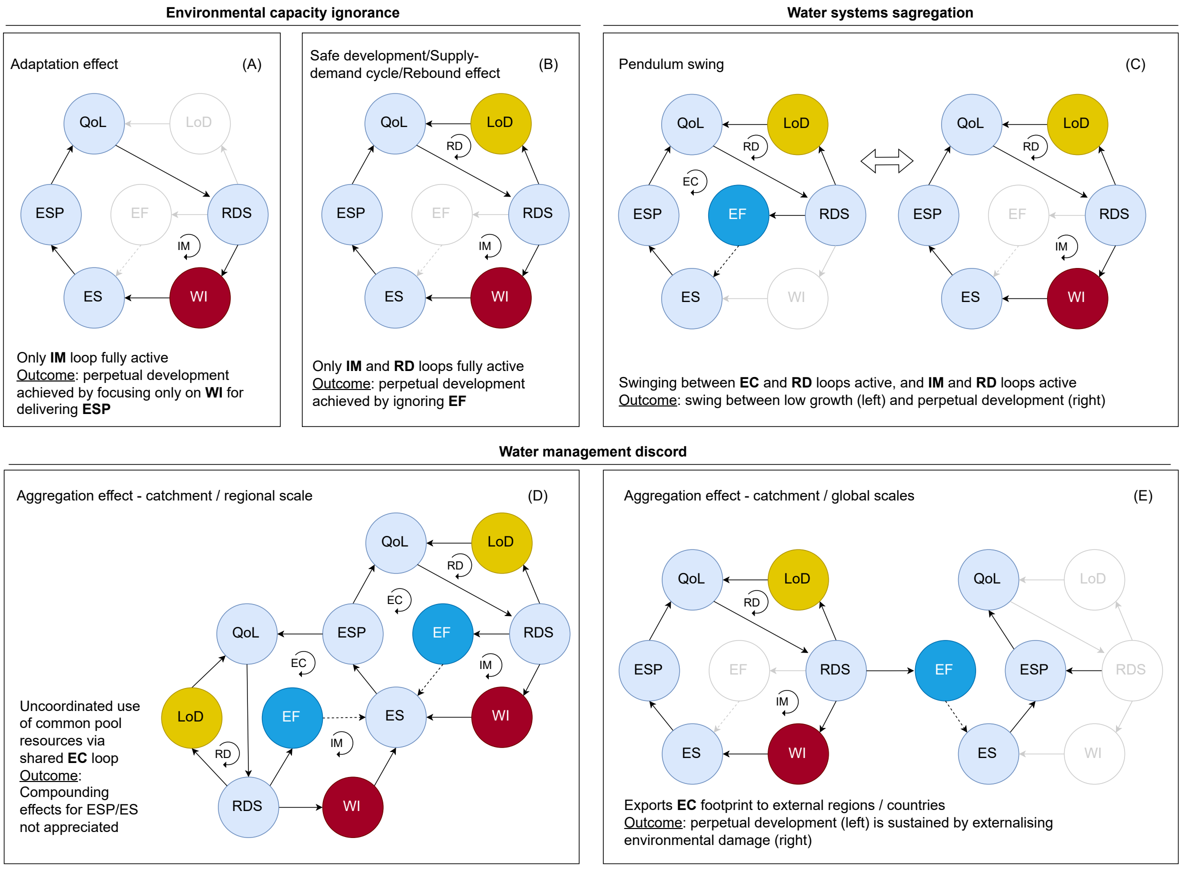

Fig. 2. Analysis of socio-hydrological phenomena with CHWS meta-model. Phenomena are identified to occur as a different combination of CHWS meta-model components and links (positive – solid line or negative – dashed line) that create feedback loops. Environmental capacity ignorance is assumed when either IM (A - adaptation effect) or IM and RD loops (B - safe development, supply-demand cycle and rebound effect) are considered, thus ignoring feedback mechanisms that affect the long-term environmental state. Water systems segregation (C - pendulum swing) can occur when two loops are considered, but not a third, causing an inability to develop integrated water management plans. Water management discord (D, E - aggregation effect) can happen when all loops are considered, but not coordinated, causing impacts beyond the system in question. For components notation please refer to Table 2.

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