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SPECIAL ISSUE: LOW INFLOW ESTUARIES

Water Releases From Dams Improve Ecological Health and Societal Benefits in Downstream Estuaries

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Abstract

This review study investigated the response of low-inflow estuaries (LIEs) to dam releases as this type of estuary is particularly sensitive to freshwater inflow modification. LIEs occur in arid and semi-arid regions and are subject to periods of little to no freshwater inflow. Case studies were used to identify ecological health and societal benefits associated with flow releases. Successful releases have been made to keep the estuary mouth open, ensure mixing, facilitate a salinity gradient and provide recruitment pulses to the marine environment for fish and invertebrates. Baseflow inputs ensured ecosystem connectivity and maintained estuary water quality gradients. Flow pulse releases in certain seasons stimulated spawning migrations of fish between freshwater and estuarine habitats. Holistic and adaptive restoration approaches were successful in terms of providing ecosystem services and societal benefits such as improved fisheries and livelihoods. Ongoing engagement, inclusion of communities, support from river users, and cooperation between multiple agencies were also important. However, this management solution for LIEs is threatened by increasing abstraction of water, competing water uses, over allocation, and frequent droughts. Moving forward, freshwater releases from dams should be considered an important restoration action that can improve ecological health, estuary function, ecosystem services, and societal benefits. This should take place within a socio-ecological system framework using an adaptive management and monitoring approach. Other key considerations for planning and implementation of future dam releases to LIEs were recommended.

Keywords Environmental flows (EFlows) · Estuary · Climate change · Freshwater flow requirements · Ecosystem process and function · Pressures · Restoration · Socio-ecological systems

Introduction

A growing global population and related demand for freshwater have increased freshwater abstraction. Dam structures built across a river or estuary are constructed to secure freshwater resources for irrigation, domestic use, flood control, generation of hydroelectricity, and navigation (Altinbilek 2002; Figueroa et al. 2022). Their accompanying irrigation systems, diversions, flood attenuation, and increases in freshwater use have fragmented and transformed the world's rivers and are impacting the functioning and health of associated estuaries (Olsen et al. 2006). The majority of dams are constructed for irrigation (~48%), while a smaller number are used to generate electricity (~20%) or for flood control (8%) (World Commission on Dams 2000). Globally, major dam construction commenced in the 1930s with more than half of the world's large river systems now affected by dams (Chen 2005; Nilsson et al. 2005). Only 23% of rivers flow uninterrupted to the sea, and it is predicted that by 2030, natural flows will be altered for 93% of river volume worldwide (Thieme et al. 2020; Kotzé 2022). This decrease in freshwater inflow will be aggravated by climate change (IPCC 2022). This increasing demand and abstraction of freshwater is threatening the health and functioning of aquatic ecosystems, such as estuaries.

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Low-inflow estuaries (LIEs) are particularly vulnerable to changes in freshwater inflow (Table 1). They occur in arid and semi-arid regions and are subject to periods of little to no freshwater inflow, with either seasonal or episodic high discharge peaks (Largier et al. 1997; Largier 2010; Walter et al. 2018). River inflow is often erratic and highly variable. Hypersaline conditions are typically present during dry periods, during which low tidal exchange, high temperatures, and long residence times result in evaporation rates exceeding rates of freshwater inflow (Largier 2010; Cira et al. 2021). Smaller estuaries that are temporarily closed/intermittently open to the sea typically occur in low inflow areas (Adams and Van Niekerk 2020). In arid and semi-arid parts of the world, where flow is often unpredictable and highly variable, irrigation and domestic water use tend to be the primary reason for dam construction. Such dams are generally not designed to release floods, or even in some cases baseflow, as water is a scarce resource in these areas where LIEs are generally located. LIEs are thus sensitive to human impacts and will be further stressed by climate-induced reductions and extremes in rainfall (Adams and Van Niekerk 2020).

Freshwater inflow to estuaries is critically important to sustain ecosystem processes and ecological function (Alber 2002; Estevez 2002; Montagna et al. 2013; Adams and Van Niekerk 2020; Chilton et al. 2021). Healthy estuaries provide the ecosystem services that we depend on, with their importance as biodiversity hotspots and migration corridors for biota being well described. Freshwater species with estuarine or marine life-cycle phases (e.g., freshwater prawns and shrimps, catadromous crabs, and eels) can be cut off from estuaries and their catchments if there is inadequate freshwater inflow (Van Niekerk et al. 2019a). It is well known that dams, weirs, levees, and other forms of constrictions affect longitudinal connectivity between catchments, rivers, and the sea. This poses a barrier to the transport of water, sediment, organic matter and nutrients, and the movements of organisms and impacts ecosystem functioning and productivity (Drinkwater and Frank 1994; Chen et al. 2016; Opperman et al. 2019; Weng et al. 2020). Dams also disrupt lateral connectivity with estuary floodplains (Bornman et al. 2002; Clark et al. 2022) and influence turbidity regimes (Figueroa et al. 2022) in both directions. For example, the Burdekin Falls Dam (Australia) caused a permanently turbid estuary downstream due to fine silt that remained suspended in the reservoir which impacted all aquatic life (Wolanski and Hopper 2022).

Further, dams have induced a series of broader environmental consequences that may not have been anticipated such as reductions in sediment delivery to the ocean, significant global erosion of deltas and coasts, and losses of coastal forests and mangroves (Giosan et al. 2014; Ezcurra et al. 2019). Construction of the Aswan High Dam on the Nile River reduced flow by over 90% which collapsed the coastal fisheries (Nixon 2003). This early case study showed the importance of freshwater inflow to the marine environment. In arid and semi-arid regions, upstream dams and freshwater abstraction lead to reduced scouring, downstream sedimentation and closure of estuary mouths to the sea (Adams and Van Niekerk 2020).

Because river inflows patterns influence the health, functioning and productivity of estuarine and coastal ecosystems (Loneragan and Bunn 1999), the planning and operation of dams and other flow regulation infrastructure should take into account the consequences of changing the timing and magnitude of flows into these systems (Sharma et al. 2022).

Table 1 Importance of freshwater inflow to low inflow estuaries

Parameter	Influence
Hydrology and hydrodynamics	Timing, magnitude, seasonality of flow determine estuary structure and function. Freshwater inflow maintains physico-chemical gradients.
Connectivity between estuary and sea	In intermittently closed estuaries baseflow keeps the mouth open and increases water levels when closed.
Connectivity with catchment and river	Freshwater inflow ensures connectivity between estuarine and freshwater environments as well as estuarine floodplains.
Sediment dynamics	Floods prevent sediment accumulation, maintain channels and reset natural processes.
Nutrient distribution and composition	Maintains nutrient processes; reduced freshwater inflow changes nutrient cycling and interrupts downstream transport.
Primary producer effects	Stimulates water column productivity; phytoplankton growth.
Salt marsh	Maintains connectivity between floodplain, supratidal and intertidal habitats. Prevents hypersaline conditions.
Upstream and downstream movement of organisms	Reproduction and abundance of anadromous and catadromous invertebrates and fish determined by freshwater inflow.
Invertebrates, fish, birds	Maintains water column and physical habitats required to sustain life cycles. Provide migratory/spawning queues. Maintains species diversity and community composition in response to changes in flows, nutrient inputs, sediment type and supply.

To mitigate the impacts of dams on downstream aquatic ecosystems, water releases are becoming an important practice around the world. In this context, a water release from a dam refers to the action of actively releasing a planned volume of water through a sluice gate or dam outlet. This is in contrast to a spill which occurs when a dam reaches a set capacity and then overflows, normally induced by a flood. Ideally, such dam releases should be incorporated in environmental flow (also referred to as EFlows) determinations for affected catchments, defined as the quantity and quality of freshwater flows—in terms of timing, duration, frequency, and intensity—necessary to sustain aquatic ecosystems to support cultures, economies, sustainable livelihoods, and human well-being (Arthington et al. 2018; Adams and Van Niekerk 2020).

The implementation of dam releases as part of EFlows and restoration programs is becoming a critical intervention to restore and manage estuaries to ensure continued provision of ecosystem services and associated societal benefits. However, to date, a critical evaluation of dam release studies on LIEs has not been undertaken to determine their effectiveness in achieving pre-defined purposes. Therefore, the objective of this study was to critically review the responses of estuaries to dam releases—as documented in the literature—and to identify key learning. Case studies were used to identify ecological health and societal benefits associated with flow releases. This assessment focuses on LIEs considered to be most sensitive to impacts from reduced freshwater inflows. As a result the study did not address high inflow systems such as the Yellow River (China), where dam construction and water abstraction have, for example, resulted in downstream erosion of deltas (Wang et al. 2017). We applied the learning gained from the study, to compose a socio-ecological systems (SES) framework for monitoring the release of freshwater inflows from dams. Finally, based on the findings of this study, we posed key considerations for effective planning and implementation of future dam release practice as part of EFlows or estuary restoration programmes. Although this investigation focuses on dam releases as mitigation for downstream environmental impacts, dam demolitions are increasingly being implemented to eliminate impacts.

Methods

A total of 11 case studies were reviewed to identify the response of LIEs to planned dam releases (Fig. 1, Table 2). The best described studies with details relating to water releases from dams and downstream estuary benefits were included in this assessment. Most of the case studies did not provide information on dam infrastructure or the operational practices pertaining to the dam releases. Additional data searches were conducted to provide such context. The

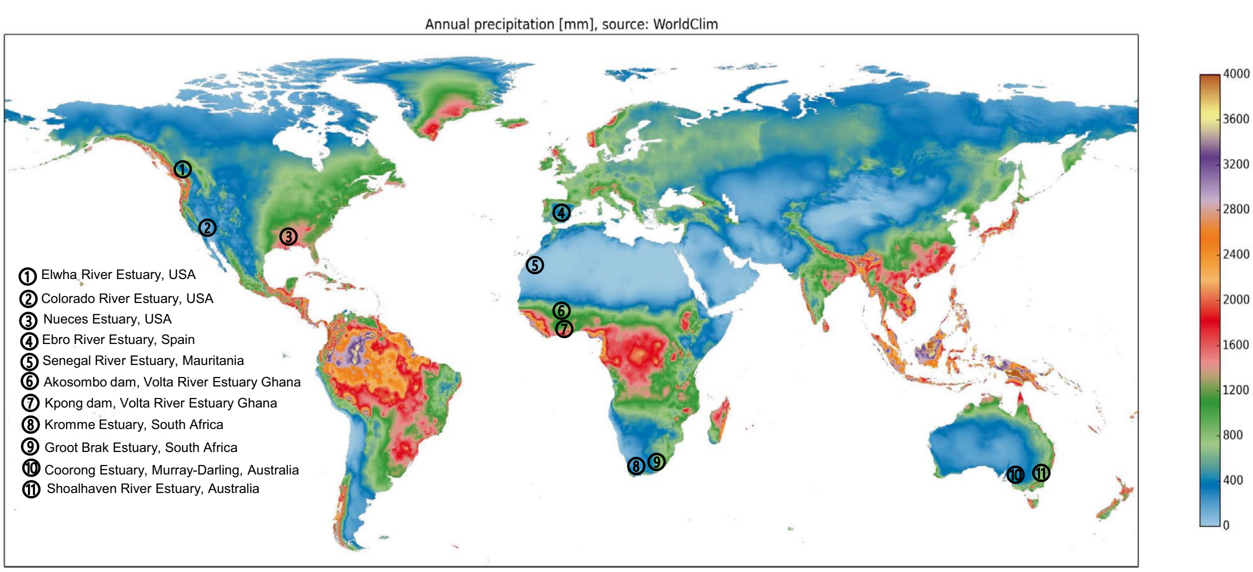

Fig. 1 Location of case studies where water has been released from dams for downstream estuary benefits in relation to the site's annual precipitation (mm) using information from WorldClim

Table 2 Summary of case studies including annual precipitation, dam purpose, storage capacity, wall height and dam length (where information available), distance from coast and associated data sources

Case study	Annual precipitation (mm)	Dam purpose	Storage capacity ($\times 10^6$ m^3)	Dam dimensions (m)	Distance from coast (km)	Source/references
Elwha River, Estuary, Washington, USA (Elwha River Dam + Glines Canyon Dam)	1000–6000 (upstream)	Hydroelectricity	50	Height: 32 Length: 64	11.2 (7.9 km distance from mouth)	• Foley et al. (2015, 2017) • Tonra et al. (2015) • Randle et al. (2015)
Colorado River Estuary, USA (Morelos Dam)	400–900	Agriculture and domestic supply		Length: 427	212	• Thomas (2007) • Harrison and Bales (2015) • Opperman et al. (2019) • Runyon, KUNC (2019) • James (2020)
Nueces Estuary, Texas USA (Lake Corpus Christi)	762–810	Domestic, recreation, and agriculture supply	332	Height: 18 Length: 167	88	• Cunningham (1999) • Montagna et al. (2009) • Hill et al. (2011)
Ebro River Estuary, Spain (Riba-roja Dam)	320–1000	Hydropower and irrigation	210	Height: 60 Length: 565	100	• Batalla and Vericat (2009) • Ibáñez et al. (2012, 2020) • Gómez et al. (2014)
Senegal River Estuary, border of Senegal and Mauritania (Diama Dam)	600–1200	Prevent saltwater intrusion, irrigation, road access between the two countries	250	Height: 18 Length: 610	9.7	• Duvail and Hamerlynck (2003) • Hamerlynck and Duvail (2003) • Degeorges and Reilly (2006) • Dumas et al. (2010) • Gebremichael et al. (2022)
Akosombo and Kpong dams, Volta River Estuary, Ghana	740–910	Irrigation use, flood control, hydroelectricity	Akosombo: 148,000 Kpong: 30	Akosombo Height: 114 Length: 660 Kpong: Height: 18 Length: 240	Akosombo: 62.7 Kpong: 41.3	• Mul et al. (2015) • Nukpezah et al. (2017) • Ohemeng et al. (2017)
Kromme Estuary, South Africa (Mpofu Dam)	700–1200	Domestic and agriculture supply	107	Height: 39 Length: 247	14.8 (4 km above tidal reach)	• Bate and Adams (2000) • Snow et al. (2000) • Strydom and Whitfield (2000)
Groot Brak Estuary, South Africa (Wolwedans Dam)	722–900	Domestic and agriculture supply	23	Height: 70 Length: 268	3 km upstream from head of estuary	• Human et al. (2016) • Slinger et al. (2017) • Van Niekerk et al. (2020)

Table 2 (continued)

Case study	Annual precipitation (mm)	Dam purpose	Storage capacity (× 10^6 m^3)	Dam dimensions (m)	Distance from coast (km)	Source/references
Coorong in Murray-Darling basin, Australia (Hume Dam and barrage system)	468–778	Agriculture and domestic supply	3083	Height: 51 Length: 1615	40	• Oliver and Webster (2011) • Thom et al. (2020) • River Murray Flow Report (2021)
Shoalhaven River, New South Wales, Australia (Tallowa Dam)	877–945	Domestic, agriculture, and hydroelectricity	75	Height: 43 Length: 520	75 km upstream of the Tasman Sea	• Reinfelds et al. (2013) • Al-Nasrawi et al. (2016) • Ji et al. (2022)

location of the case studies is shown in relation to the site's annual precipitation (mm) using information from WorldClim (Fig. 1). The image used in Fig. 1 was obtained from http://i.imgur.com/6lvzmXZ.jpg on Reddit, Inc. This presentation of global annual precipitation (mm) was generated from WorldClim that uses data layers which are generated through interpolation of average monthly climate data from weather stations (WorldClim 2022). Mean annual precipitation represented as a range (minimum, maximum) was provided for each case study from the sources indicated in Table 2.

The Elwha Estuary (USA) cannot typically be classified as a LIE as it occurs in a catchment with annual precipitation above 1000 mm per annum. However, this case study was included for comparative purposes to highlight an extreme management intervention, i.e., dam removal and the unexpected responses from this. Further details for each case study are included in the Supplementary Material.

The case studies illustrate that in semi-arid areas (e.g., South Africa, Australia, and Texas), dams were mainly constructed for domestic and agricultural use (Table 2), while the hydroelectricity dam schemes generally occurred in catchments where rainfall was 900 mm or greater. The Diama Dam was constructed to prevent saltwater intrusion upstream and supply water for irrigation—it is situated on the Senegal River with a mean annual runoff (MAR) greater than 1200 mm. However, as indicated details were not readily available on whether this and other dams had the capacity to release baseflow and floods to the downstream estuary. Dams on the Groot Brak, Kromme (South Africa) and Elwha systems (USA) occur close to the coast and head of the estuary. As a result, there is little opportunity for river tributaries downstream of the dams to mitigate impacts and contribute to natural variability in flow. Dams can store a large percentage of the mean annual runoff thus having a severe impact on the downstream estuarine environment.

To explore the effectiveness of dam releases we analysed the purpose, the release practice, and associated ecological and societal outcomes of the selected case studies. From these findings, we recommended key considerations for planning and implementation of future dam releases to LIEs. These can be integrated in EFlow or estuary restoration planning towards improving ecological health, as well as associated ecosystem services and societal benefits.

Case study outcomes then informed the composition of a socio-ecological systems (SES) framework for monitoring the release of freshwater inflows from dams (adapted from Adams et al. 2020). The framework links estuary state and well being of people through ecosystem services and is based on Ostrom (2009) and the millennium ecosystem assessment approach (MEA 2005). Examples of estuary and societal indicators, as well as ecosystem services influenced by releases of freshwater from dams, were provided. This included fisheries and nursery habitats, nutrient cycling and water quality maintenance. The concept of socio-ecological systems is an important approach for managing natural resources as it emphasizes that human populations and coastal ecosystems are interlinked. Knowledge exchange between scientists from different disciplines, decision makers, and stakeholders can take place through a shared understanding of terms, such as "sustainability" and "ecosystem services" (Hossain et al. 2017).

Results and Discussion

Evaluation and Learning from Case Studies

The purpose of dam releases spanned an array of interventions and included: improvement of sedimentary processes (e.g., Nueces Estuary), supply of freshwater to restore ecosystem and habitat (e.g., Colorado, Nueces, Volta, and Coorong), improved water quality and removing excess macrophytes (e.g., Groot Brak and Nakdong), prevention of saline intrusion and hypersalinity (e.g., Senegal, Groot Brak and Kromme estuaries), facilitation of artificial mouth breaching (e.g., Groot Brak), managing floods (e.g., Senegal, Volta), and improving fish migration and coastal fisheries (e.g., Shoalhaven). Ecological and societal outcomes for each of the selected case studies was summarized (Table 3 and Supplementary Material).

From the evaluation of the case studies, it was evident that planned freshwater releases were generally successful in moving sediment, keeping the mouths of estuaries open, allowing mixing, maintaining salinity and turbidity gradients, and triggering spawning and/or migration of fauna (Table 3). Studies showed that estuaries are resilient and, in many cases, their ecological health can improve following freshwater releases from dams. However, strong regulatory frameworks and ongoing commitment were needed to deliver environmental water over periods of prolonged droughts. In most cases, holistic adaptive management approaches required the involvement of multiple agencies to achieve environmental flow objectives as well as inclusion, and ongoing engagement, of communities and support of aquatic ecosystem users (e.g., river boat operators).

An assessment of the case studies showed that it was important to understand the *whole system* to ensure that dam releases were beneficial. In the Colorado system, if water had simply been released from the dam, the targeted lower ecosystems would not have benefited from the environmental flow as 'surplus' and would have been taken up by other users. Water was supplied through irrigation canals which bypassed dry areas (Table 3). Dam removal is an important restoration action but can result in rapid and unexpected responses and needs careful whole system planning (Table 3, Elwha Estuary study). Ecosystems and communities respond in unexpected ways frequently negating potential intended benefits. The spatial–temporal scale of impacts from dam removal and persistence of these impacts need careful consideration through dedicated monitoring and reporting particularly for LIEs.

Biota have evolved life histories based on natural cycles of flooding and drought. In long-lived species, such as riparian vegetation, desired outcomes in relation to environmental flow allocations only occur over multiple years or decades (Tonkin et al. 2021). Thus, it is key to *understand life cycles* when planning releases from dams. At the Shoalhaven Estuary *frequent pulse releases* were more effective than one large dam release in stimulating Australian bass to commence pre- and post-spawning migrations (Reinfelds et al. 2013; Al-Nasrawi et al. 2016; Ji et al. 2022). *Baseflow* establishes salinity gradients and improves biological productivity in estuaries (Bate and Adams 2000; Snow et al. 2000; Strydom and Whitfield 2000). Freshwater inflow and a reduction in salinity in the Nueces Delta increased biological productivity (Table 3). *Floods* are needed to move sediment and organics, and prevent macrophyte encroachment (Batalla et al. 2006; Gómez et al. 2014; Ibáñez et al. 2012, 2020; Human et al. 2016).

Water releases from dams improved downstream ecosystem health and ecosystem services provided by estuaries such as the nursery function and fishing opportunities (Table 3, Senegal Estuary). Releases provided societal benefits and improved livelihoods through job opportunities. An improvement in water quality increased recreational use (Table 3, Groot Brak Estuary).

Dam releases should always attempt to *mimic the natural flow patterns* as far as possible. "Novel" flow regimes often prioritize the flow characteristics that supply the most ecological benefit (Richter and Thomas 2007; Chilton et al. 2021). However, not all dams have spillways or outlets that are designed for controlled releases of water and are thus not able to mimic natural flow patterns. For example, the capacity is often there to release base flows but not the floods necessary for the effective flushing of waters and sediments from downstream estuaries. Releases are mostly made to address migratory fish populations. In impassable dams where river connectivity is completely blocked, upstream river courses are often devoid of migratory species (Fernandez et al. 2022). Some dams have fishways/passages to mitigate these impacts and although there has been an increase in the rate of construction of fishways, the performance of passing fish through these structures continues to be low in many regions (Silva et al. 2018). Legitimate constraints to environmental flow implementation include dam purpose and design, ageing water infrastructure, and encroaching development in floodplains below dams that

Table 3 Summary of case studies highlighting key purpose of dam release, overview of release practice, ecological and societal outcomes (further detail in Supplementary Material)

Case study/purpose	Release practice (mode of release)	Ecological outcome	Societal outcome	Source/references
Elwha River Estuary Washington, USA Not release but dam removal = restoration.	Removal of two dams to restore spawning habitat for endangered salmon species, to improve sediment transport, prevent ongoing erosion of coastal beaches and to allow for the movement of woody debris and nutrients.	Sediment released during dam removal resulted in over a meter of sedimentation in the estuary and over 400 m of expansion of the river mouth delta landform. Dam removal reduced the abundance of macroinvertebrates and fish in the estuary and a shift in the community composition from brackish water to freshwater-dominated species.	Large deposition of sediment to the delta and loss of the small, vital estuary habitat.	Foley et al. (2015, 2017) Tonra et al. (2015) NPS.gov (2019)
Colorado River Estuary, USA Freshwater supply to restore dry Colorado River Delta and estuary.	Re-operating of a system; not just a dam: water acquired through bought water rights was supplied as base flows to the riparian corridor. Part of the environmental flow release took place by supplying water through irrigation canals which bypassed the dry area. Success was due to water delivered by dam releases and irrigation channels. Environmental flow from Lake Mead.	Targeted lower ecosystems benefited from the environmental flow. Riparian habitat and delta undergoing restoration. Water delivered to riparian corridor as "base flows" to sustain native habitat. Water reached targeted restoration sites, maintaining growth of riparian seedlings.	Residents in riverside towns enjoyed seeing water in their river, many for the first time in their lives. Mexicali farmers, who previously viewed any water in the river as wasted, saw that the river and the farms could share the water.	National Research Council (2007) Opperman et al. (2019) Runyon, KUNC (2019) Houston (2022)
Nueces Estuary, Texas USA Ecosystem-based restoration/habitat improvement.	Water releases from Lake Corpus Christi into Nueces Estuary via reservoir spills, releases/return flows. Constructed channel to the Nuecas Delta marsh.	Increasing biological productivity of Nueces Delta by restoring freshwater flow and reducing salinity. Other areas at the time experienced hypersaline conditions.	An "adaptive" approach ensured that there was an increase or decrease in volume depending on water availability. Multiple agencies worked together to ensure the restoration of freshwater flow in the Nueces Delta.	Montagna et al. (2009) Hill et al. (2011) Montagna and Palmer (2012)
Ebro River Esuary, Spain Removal of excess macrophytes and to enhance sedimentary activity in the channel.	Flushing began in 2002 and has occurred twice a year in autumn and spring. These flood releases were managed by the dam operator (Endesa Generación S.A.) and controlled by the Ebro Basin authority.	Flushing flows enhanced ecological status and released floods showed a significant ability to transport sediment. However, the magnitude and size of floods have reduced over time.	Flushing flows were compatible with hydropower operation and cost a small fraction of the energy delivered to the market. Loss of ecosystem services due to recent reduction in floods.	Batalla et al. (2006) Gomez et al. (2014) Ibáñez et al. (2020)

Table 3 (continued)

Case study/purpose	Release practice (mode of release)	Ecological outcome	Societal outcome	Source/references
Senegal River Estuary, Mauritania Preventing seawater intrusion within valley, reservoir dam during dry seasons. Managed flood release to create artificial estuary.	Dam release was first on a trial–error basis, with sluice gates opened in 5 cm steps Water quality, water level and flooding were monitored in relation to dam releases.	Ecological benefits: Restore flood cycle, decrease salinity, increase plant diversity, improve vegetation cover including mangrove growth. Mangroves survived the harsh hypersaline drought conditions and seedlings colonized the estuary. Increase in fish catches and waterbird numbers. The nursery function of the estuary was restored.	Multiple societal benefits: fishing, gathering, livestock keeping, improved pastures and mat weaving. New job opportunities such as gardening and ecotourism.	Bousso (1997) Duvail and Hamerlynck (2003) Dumas et al. (2010) South World (2019)
Volta River Estuary, Akosombo and Kpong dams, Ghana (reoptimisation of African Dams operations) Flood control, irrigation water supply, hydropower, flow restoration	Releasing a flow pattern that closely mimics the natural variability in flows. Converting dams to "run-of-the-river" operations. Re-establishing an annual artificial flood. Reoperation of the entire water management system—not just the storage component to contribute to economic growth and poverty reduction through improvement of downstream ecosystem functions and livelihoods by re-operating and re-optimizing the Akosombo and Kpong dams.	Restoration of the natural flow and riverine ecology. Suggestion to convert dams to "run of the river" operations and to re-establish an annual artificial flood by increasing the release from dams during the rainy season to move sediments and replenish groundwater. Outlet limits at the Chaliawa Dam.	Restoration of livelihoods of residents of the Lower Volta Basin. Reduction in flood risks due to changes in floodplain management. Increased annual power output from higher average dam storage levels. Increased drought resilience due to higher average storage levels.	Nukpezah et al. (2017) Miescher (2021) Ohemeng et al. (2017)
Kromme Estuary, South Africa Prevent hypersaline conditions and establish salinity gradients to improve ecological health.	Environmental allocation released monthly but does not reach estuary (taken up illegally by farmers). Test study on release of environmental water (2×10^6 m^3) in single pulse from Mpofu dam to see if would be beneficial to estuary.	Little response in estuary, strong vertical salinity gradient but no river-estuary interface zone established. Baseflow needed to establish a salinity gradient and initiate a biological response in the water column. Two weeks after the release the estuary returned to a marine dominant state.	No reporting on benefits as it was an ecological research study.	Bate and Adams (2000) Snow et al. (2000) Strydom and Whitfield (2000)
Groot Brak Estuary, South Africa Facilitate artificial breaching, improve ecological health and water quality for recreation.	Water released (2×10^6 m^3) in spring/summer facilitates artificial mouth breaching and sustains open conditions. Estuary filled to breaching level (0.5–0.7×10^6 m^3) then neap tide releases 0.4 m^3/s for 4–6 days.	Water release opened the estuary mouth, ensured maximum fish and invertebrate recruitment from the sea into the estuary and promoted growth and germination of salt marsh. There was an improvement in ecological health.	Water quality improvement during holiday season when recreational use is high. Reduced noxious smells caused by decay of macroalgae and improve fish catches.	Human et al. (2016) Van Niekerk et al. (2019b) Van Niekerk et al. (2020)

Table 3 (continued)

Case study/purpose	Release practice (mode of release)	Ecological outcome	Societal outcome	Source/references
Coorong Estuary in Murray-Darling basin, Australia Improvement of the ecological state of Coorong.	Opening of barrages with supply of Commonwealth environmental water that was flexibly managed using a transparent approach to show how water was shared between different users.	Continuous base flow improved habitat condition for native fish and aquatic plants. Adequate water level for growth of *Ruppia tuberosa* and flows for fish life cycle completion. Breeding opportunities for many unique native fish, plants, waterbirds and wildlife. EFlows ensured connectivity between freshwater, estuarine and marine environments.	A clear and concise decision-making framework was developed that included ongoing engagement with stakeholders including conservation, NGOs and agencies such as the local irrigation trust, and agricultural representatives.	Gippel et al. (2009) Oliver and Webster (2011) Commonwealth Australia (2016a, b) Hart et al. (2020) Chilton et al. (2021) Brookes et al. (2022) DEW Technical Report (2022) Wolanski and Hopper (2022) Government of South Australia (2023)
Shoalhaven River Estuary, New South Wales, Australia Flow pulses—stimulated spawning migrations of catadromous Australian bass.	Regulated baseflow release from Tallowa Dam (release dates: Sept–Oct 2007, Mar–Oct 2008)	Declining water temperatures in late autumn to below 15°C stimulates Australian bass populations to migrate from freshwater to estuarine habitats over winter. Fish migrations associated with spill over from Tallowa Dam / flow pulse migrants.	Results from this study can be used to help inform flow and hydrograph management in other regulated river systems, for the benefit of stimulating and facilitating spawning migrations by Australian bass. Main societal benefit would be an increase in fisheries.	Reinfelds et al. (2013) Al-Nasrawi et al. (2016) Ji et al. (2022)

prevent mimicry of natural variability, especially floods (Warner et al. 2014).

Innovative methods and best practice were identified from the case studies presented such as improved irrigation practices that increased flow to the Colorado Estuary. At this system, the required environmental flows had to be attained from existing users to reduce water demand pressure. At the Coorong Estuary, water also became available from improved infrastructure and on-farm irrigation technology. Legislation that controlled the licenses/permits for set volumes of water extracted and number of irrigators in a catchment was also important (Gippel et al. 2009; Chilton et al. 2021). Purchasing water rights is a key mechanism to ensure downstream baseflow inputs to estuaries in over allocated catchments. For example, California (USA) has recently begun considering the establishment of 'ecosystem water budgets' based on the total volume of water required to satisfy environmental flow needs that consider ecosystem management objectives, current water uses, and institutional arrangements (Grantham et al. 2020; Stein et al. 2021). A similar approach is followed in South Africa where water allocated to aquatic ecosystems is "Reserved" as a water right and allocated in law (Van Niekerk et al. 2019a, b).

Socio-ecological Framework for Dam Release Management

Freshwater releases from dams are an important management or restoration action that can improve ecological health and functionality to sustain the continued provision of ecosystem services and societal benefits associated with LIEs. However, such undertakings need to take place within a *socio-ecological* systems framework using an *adaptive management approach* (Fig. 2). A SES approach can be used to track freshwater releases from dams as a restoration action in LIEs. Objectives are set, actions are implemented, and then monitored and adapted using a learning-by-doing approach. The goal/action would be to release freshwater from dams to downstream estuaries to improve estuary health and societal benefits that can be measured using a range of indicators (Fig. 2). A SES approach ensures communication and co-ordination amongst all stakeholders.

The social and cultural values associated with EFlows, including dam releases, are increasingly considered and require an understanding of ecology-culture relationships, as well as direct flow-culture relationships (Stein et al. 2021) to inform effective EFlows. These are described as ecohydrological principles that Wolanski and Hopper (2022) call for in the future management of the river basins (e.g., Burdekin River, Australia) to avoid duplicating the mistakes of the Murray-Darling River basin where water resources were not managed at the basin-scale. Notwithstanding the limitations, dam releases should be optimized as best as possible for

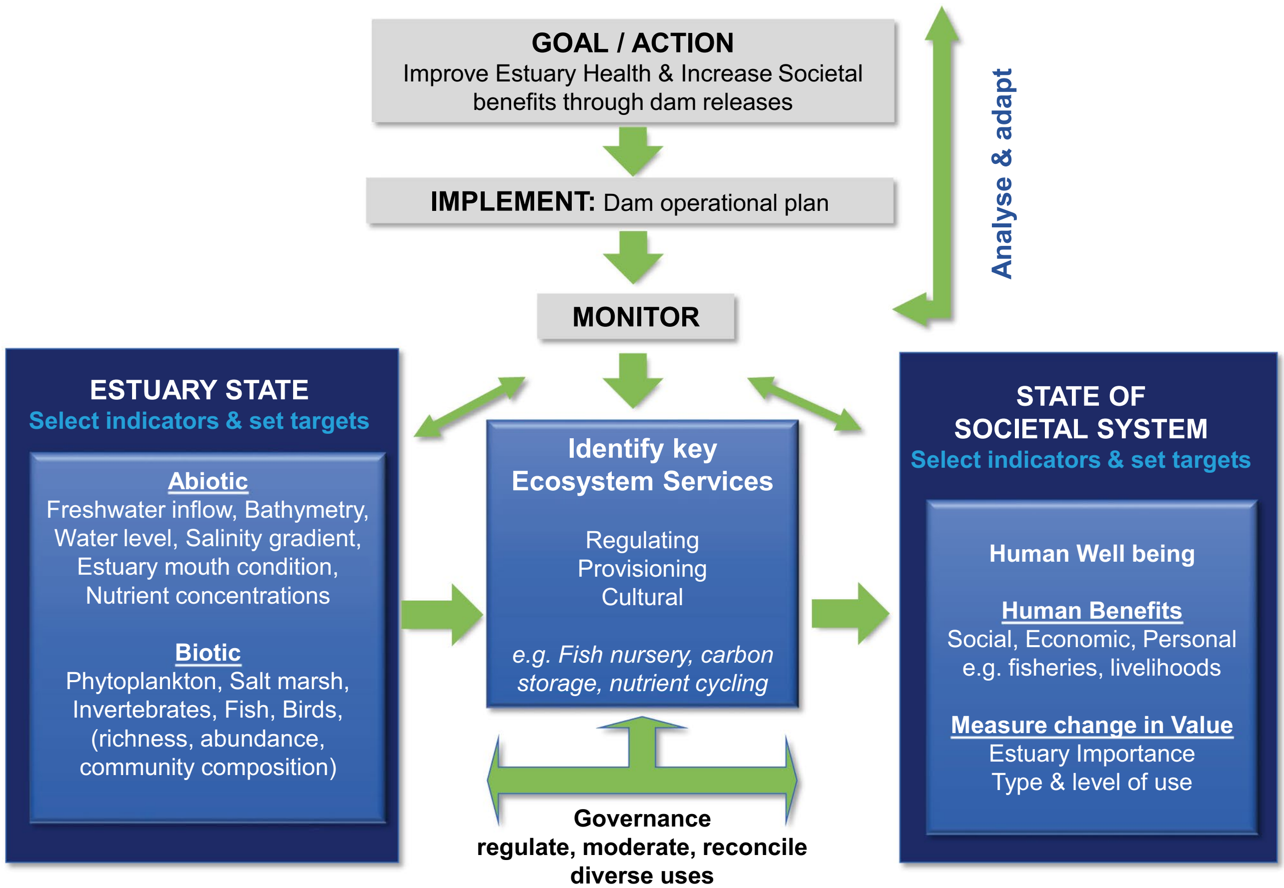

Fig. 2 A strategic adaptive management socio-ecological systems framework for the release of freshwater from dams to downstream estuaries to improve estuary health, ecosystem services and state of the societal system. Examples of estuary health and societal indicators given (adapted from Adams and Van Niekerk 2020)

ecological and societal benefits. Environmental flow assessments allow for the evaluation of a range of ecological and social outcomes as part of a series of scenarios/management options (Brown et al. 2020; Van Niekerk et al. 2019b). Governments and stakeholders can then assess options and negotiate the future they want. Engagement and inclusion of *multiple agencies*, ongoing community engagement and support from all users are essential to ensure the successful implementation of water releases from dams as indicated from the analysis of the case studies (Table 3).

Richter and Thomas (2007) proposed a similar framework for implementing dam reoperation that considers both ecological and social consequences. Addressing non-flow related impacts (e.g., land-use change, dredging, pollution, artificial breaching, over-fishing, invasive species) is also a critical consideration in holistic catchment to coast management, as well as restoration planning that aims to mitigate the risks associated with drivers of change (Arthington et al. 2018; Van Niekerk et al. 2019b; Chilton et al. 2021). New reservoir management strategies including targeted control of dam storage and flushing sediment operations, banning fishing activities, and removing unnecessary dams (obsolete or small dams) are becoming crucial tools for ecosystem restoration (Zhang et al. 2022). Water demand management through water reuse, recycling, rainwater harvesting and desalination can play a key role in the protection of baseflows to LIEs. Protection of groundwater resources against over-abstraction and/or poorly planned forestry activities are also essential for the persistence of baseflows to LIEs.

Long-term research programs are also needed to track the ecological and societal benefits of flow releases from dams to estuaries, as shifting baselines in response to climate change effects are expected. Mediterranean climates where most LIEs occur are becoming warmer and drier (Drobinski et al. 2020), potentially resulting in ecological regime shifts. Research and monitoring will improve our understanding of the role of extreme events (e.g., floods, coastal storms, and storm surges) and decadal oscillations on estuaries and how these events will be affected by climate change (Stein et al. 2021). Due to increased storminess, many estuaries along exposed, sediment-rich, microtidal coastlines will close to the sea more frequently (Adams and Van Niekerk 2020).

This will increase the need for environmental flow allocations, including dam releases, to ensure downstream estuary health and ecosystem services. Similarly, restoration of blue carbon habitats includes the provision of EFlows flows (Adams et al. 2021). An investment in long-term monitoring of catchment signals and estuary responses is essential for proactive adaptive management. Climate change is predicted to have severe impact in many regions of the world that support LIEs (e.g., Van Niekerk et al. 2022). Of key concern is the predicted decrease in river flow and the likely increase in the frequency and duration of droughts. Flow releases from dams may mask climate change impacts to some degree resulting in water resource managers becoming complacent and not taking proactive measures to secure additional flows need to contend with drought conditions in a hotter and often drier climate.

Releases from dams can provide resilience and buffer against the impacts of current and future global change pressures (Sun et al. 2013; Chilton et al. 2021). However, releases to maintain downstream estuary health are threatened by increasing abstraction of water, competing water uses, over allocation and increasing droughts in response to climate change in some regions. Although estuaries have resilience towards natural droughts and floods, changes induced by increased water use and flow regulation can artificially extend or intensify droughts putting these systems under increased stress (Oliver and Webster 2011). During droughts, the reality is that dam releases are often not made due to competing water users as described for the Groot Brak Estuary and other case studies (Supplementary Material). To ensure the provision of baseflow during droughts a strong *regulatory environment* is needed. EFlow and associated dam releases, and the monitoring thereof, are mostly only implemented if requirements have been embedded in a strong regulatory framework that compels water resource managers and users to consider such environmental matters (Brown et al. 2020). Such regulatory frameworks should be backed by investment in monitoring and auditing to track compliance (Van Niekerk et al. 2022). Appropriate dam release practices need to be formally incorporated into environmental flow planning, dam design and operational implementation, and aligned with climate change adaptation strategies (Chilton et al. 2021).

Conclusion and Recommendations

There are a few cases globally that demonstrate the efficacy of environmental flow releases from dams in maintaining downstream estuary health and societal benefits. This assessment has shown that a holistic systems approach is needed to improve downstream health of estuaries particularly in LIEs. It requires not only flow releases from dams to increase freshwater inflow to estuaries, but also the management of water infrastructure (e.g., canals and off-channel storage facilities) to provide downstream inflow.

Releases of freshwater inflow from dams have many ecological benefits; however, in most cases, current dam releases can usually only provide baseflow input for LIEs and not flood releases that are important for maintaining long-term estuary health and function. The sustained implementation of dam releases forms an important component of environmental flow implementation that should be based on adaptive management and social engagement. Flow releases should follow the natural flow regime as far as possible, mimicking floods and droughts. This will require trade-offs between different water users and stakeholders. In most cases, such releases only occur if embedded within a legislative framework and planned from the start of dam construction. Societal commitment is needed to deliver environmental water over periods of drought.

From the findings of this study, we recommended key considerations for planning and implementation of future dam releases to LIEs. These can be integrated in EFlow or estuary restoration planning towards improved ecological health, as well as associated ecosystem services and societal benefits. The recommendations for future estuary dam release studies were:

1. Understand the *whole socio-ecological system* when restoring flows as both ecosystems and the communities can respond in unexpected ways and negate potential intended benefits
2. Release water from dams to *mimic natural flow patterns* in relation to biotic life cycles.
3. *Supply baseflow* to ensure salinity and other physico-chemical gradients that improves biological productivity in estuaries.
4. Supply baseflow to maintain *marine–estuary connectivity*, while floods are important for *catchment-estuary connectivity and estuary-floodplain connectivity*.
5. Implement *flood releases* to remove sediment and accumulated organic matter, as well as prevent macrophyte encroachment.
6. Release *frequent flow pulses* as this is more effective than one large dam release in stimulating ecological response, e.g., biotic pre- and post-spawning migrations.
7. Use a *SES framework* to track freshwater releases from dams as a restoration action using an *adaptive management approach*.
8. Include *multiple agencies* to achieve outcomes; ongoing community engagement and support of users is critical for successful implementation.

9. Implement *long-term monitoring and dedicated research programs* to understand responses and inform a science-based management approach.
10. Strengthen the *regulatory environment*, especially in ensuring the provision of baseflows during droughts.

LIEs are particularly influenced by drought that will increase in frequency and duration with climate change. For many case studies, severe drought placed attention on the need for EFlows and funding was made available for monitoring and in some cases implementation of required EFlows. Unfortunately, this focus and funding are often withdrawn when the system goes back into a wet phase. In other examples, allocated and even legislated drought flows were not released from dams. It is important to monitor and report on EFlows continuously to understand responses. This study is considered timely as there are few published works integrating the responses of estuaries to dam releases so that lessons learned could be shared.

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Declarations

Competing Interests The authors declare no competing interests.

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