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REVIEW

Misplaced fears? What the evidence reveals of the ecological effects of tidal power generation

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Abstract

1. Tidal energy is a dependable and clean power source that stands as a compelling alternative to fossil fuels. Despite this promise, tidal energy projects face barriers to practical implementation, and objections to proposed schemes often stem from perceptions of adverse ecological effects.
2. Early concerns surrounding the ecological effects of tidal range energy infrastructure arose largely from the construction stages of barrages rather than from later, longer term operational stages. Though research on this was under-planned, there is now a literature base. We synthesise the available current evidence of effects that both long-established range and novel stream technologies have on marine environments through systematic and exploratory literature approaches.
3. Fifty-four articles have been included in this review and produce a nuanced picture accompanying a steep learning curve in both tidal power system construction and operation.
4. Few of the widespread concerns are substantiated by evidence or in long-term monitoring of existing projects. There is evidence of alterations in hydrodynamics and sediment flux at tidal range power plants, as well as some animal behavioural changes around tidal stream turbines, though many apprehensions either remain unsubstantiated or result in neutral effects on marine ecosystems. Several positive ecological effects are identified such as greater productivity and species diversity within tidal range basins, as well as enhanced seabird foraging hotspots surrounding tidal stream turbines. Maintaining a tidal regime as close as possible to its prior state appears key to minimising adverse ecological effects and has been a major learning point for tidal range
5. *Practical implication*. This work provides foundations for environmental impact assessments of future tidal projects and may enable more informed choices and facilitate a priori mitigation planning.

KEYWORDS
coastal ecology, estuary ecology, impoundment, tidal attenuation, tidal barrage, tidal mitigation, tidal stream, TPP

1 | INTRODUCTION

As global energy demands surge and the need to reduce dependence on fossil fuels becomes increasingly urgent, the pursuit of sustainable energy solutions has never been more critical. The International Renewable Energy Agency warns that to avoid the most severe impacts of climate change, 90% of the world's electricity needs to come from renewables by 2050 (IRENA, 2021).

Marine energy (tidal range and stream/flow) is a dependable and clean power source that stands out as a compelling alternative to fossil fuels (Neill et al., 2018). It offers key advantages over wind and solar, including increased generation efficiency owing to the greater density of water over air and reliable power production due to the predictable nature of tidal cycles (Shetty & Priyam, 2022). This reliability facilitates consistent energy output for integration with existing power networks. Furthermore, tidal energy does not compete with future land use challenges, demonstrating the technology's potential as a reliable and valuable solution in achieving energy needs and sustainability targets.

Despite such promise, tidal energy projects face barriers to practical implementation and often experience delays or cancellations due to financial, regulatory and political obstacles (Neill et al., 2018). Objections to proposed schemes also often stem from perceptions of adverse ecological impact; a topic which lacks a comprehensive evidence synthesis. Added to this is the nuance that the early evidence arises from construction stages of tidal range installations rather than from their later operational stages or from marine flow devices. The steep learning curve in both construction and operation, however, that marine energy has experienced now enables more informed choices and substantial mitigation.

A better understanding of ecological effects is now essential as marine energy has the potential to contribute to the renewable energy portfolio in several countries. Nations such as the United Kingdom, Canada, France, Norway, Taiwan and China all possess considerable tidal energy potential (Chowdhury et al., 2021). Notably, the United Kingdom could meet approximately 20% of its electricity demand (Waters & Aggidis, 2016), potentially contributing £17 billion to the British economy (CATAPULT Offshore Renewable Energy, 2022). With such immense potential, we must learn from established tidal energy projects to understand the demonstrated ecological and ecosystem effects and integrate this knowledge robustly into their planning and implementation. In doing so, negative impacts on marine ecosystems can either be avoided, minimised or mitigated, and the long-term ecological sustainability of tidal energy as a renewable source can be enhanced.

We aim to synthesise here the available evidence of effects that tidal range and stream technologies have had on marine environments through a combination of systematic and exploratory literature approaches. This evidence base will then provide foundations for environmental impact assessments of future projects. We do not mean to compare impacts between the two broad systems, but present both together here.

1.1 | Tidal energy systems—Overview

Tidal energy generation can be categorized into two distinct types: tidal range technology and tidal (or flow) stream turbines. Each relies on different mechanisms, and each is suited for different environmental conditions.

1.1.1 | Tidal range

The governing principle of tidal range power production is centred around the impoundment of water to harness the gravitational potential energy of an artificial head difference caused by tides. Tidal power plant (TPP) operation involves the release of water from a higher level to a lower level through turbines to generate energy; achieved through an ebb-only, flood-only or two-way mode of operation. An ebb-only generating process impounds water at high tide, creating an artificial head difference as the exterior water level decreases, and releases the impounded water through turbines to convert the gravitational potential energy into electrical energy. The flood-only process is similar to this but excludes water at low tide and activates the turbines at high tide. Two-way generation combines both modes to produce power on both the ebb and flood phases of each tidal cycle. Although this translates to shorter generating times each way, there is a consistent trend of greater energy production (Angeloudis & Falconer, 2017).

Tidal range technology currently only exists in the form of barrages, defined by the impoundment of an area of water within an estuary by the construction of a wall. The possibility of lagoons, describing an impounded area of water along a coastline by a much longer wall, has also been investigated, though not yet applied (Neill et al., 2018).

We focus on the five principal tidal barrages in existence globally; two of which are commercial-scale and three of which are pilot projects.

La Rance power station in France was completed in 1966 and has a 720 m barrage housing 24 turbines with a total capacity of 240 MW (Neill et al., 2018). This generates ~600 GWh annually, meeting ~0.12% of France's energy needs (Tethys, 2019a) and providing 'some of the cheapest electricity in Europe' (UK Parliament, 2021). Following completion of the plant in 1967, operation was two-way until 1975 when the mode changed to ebb only (Little & Mettam, 1994) until two-way operation was resumed in 1983 (Rétière, 1989).

The *Sihwa Lake* power station in South Korea has a capacity of 254 MW with an annual power output of 550 GWh (Tethys, 2019b). This TPP, completed in 2011, was born as a mitigation strategy for the recovery of the heavily polluted and ecologically devastated man-made freshwater lake (Kim et al., 2018), which had been created in 1994 by building a 12.7 km seawall at Gyeonggi Bay (Tethys, 2019b). Operation is flood-only with sluicing during the ebb phase (IRENA, 2014).

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TABLE 1 Search strings used to explore the tidal energy literature.

Library	Search string
Scopus and Web of Science	TS=((“tidal energy” OR “tidal power” OR “tidal barrage*” OR “tidal stream*” OR “tidal turbine*” OR “tidal lagoon*”) AND (“ecological risk*” OR “ecological impact*” OR “ecological consequence*” OR “ecological effect*” OR “habitat loss” OR “sediment dynamic*” OR “electromagnetic field*” OR collision* OR “underwater noise”))
Scopus	TITLE-ABS-KEY ((annapolis AND royal) OR (jiangxia) OR (kislaya AND guba) OR (rance) OR (lake AND (sihwa OR shihwa))) AND (tidal AND (power OR energy OR barrage*))

The *Annapolis Royal* power station in Canada has a capacity of 20 MW (Neill et al., 2018) and was built as a pilot project to ‘evaluate the operational performance of a large (7.6 m) diameter prototype straight flow (STRAFLO) turbine’ (Tidmarsh, 1984). The plant consists of an impoundment wall previously built as a dam/causeway in 1960, which was retrofitted as a TPP in 1984, and operated under an ebb-only mode until closure due to equipment failure in 2019.

The *Kislaya Guba* power station in Russia was commissioned as a pilot project for tidal range power plants on the arctic coast (Usachev et al., 2004) and was constructed in 1968. It has a capacity of 1.7 MW and operates under a two-way mode (Neill et al., 2018).

The *Jiangxia* power station in China was also constructed as a pilot project, with a capacity of 3.9 MW and a two-way mode of operation in 1985. Turbine upgrades have improved capacity to 4.1 MW since 2014 (Neill et al., 2018).

With the exception of the remediation project at Sihwa Lake, there have been no recent developments in tidal range energy, and no major tidal barrage projects have been initiated in the past 25 years (Petley et al., 2019). There are, furthermore, no imminent development plans, possibly cautioned by the experience of the Swansea Bay lagoon project, one of 27 different projects proposed for the Severn Estuary, which still ‘failed to gain governmental support’ (UK Parliament, 2021) due to financial and environmental concerns, despite having commercial viability (Neill et al., 2018; Severn Estuary Commission, 2024; WSP, 2023).

1.1.2 | Tidal stream

Recent years have seen the focus shift from tidal range to tidal stream technology, which harnesses the kinetic energy of tidal currents using turbines (Noonan, 2019). These are typically anchored to the ocean floor but can also be floating or suspended in the water column. Turbines can be either horizontal axis turbines, kites or hydrofoils; cross-flow or vertical axis turbines, with horizontal axis turbines being the most prevalent currently (Jo & Hwang, 2020).

Turbines intercept fast-moving tidal streams, spinning to generate electricity (Jo & Hwang, 2020). Ideal locations are typically found where the coastline constricts, such as narrow straits or the often shallow channels between islands where geography accelerates water flow and generates strong tidal currents (Bhatia, 2014). While turbines function well individually, like wind turbines, most are conceived to be deployed in arrays. Tidal stream projects currently require lower initial capital outlay than tidal range projects, although they also provide substantially less energy (Roberts et al., 2016).

Tidal stream technology is being explored through a number of projects, most of which are still at pilot stages. The MeyGen project in Scotland aims to achieve a capacity of 398 MW, positioning it as the largest tidal stream project in the world (Jo & Hwang, 2020). The first phase is complete, with four operational turbines contributing to the grid. Other projects, such as Nova Innovation, also have operational turbines and still more, for example, Seastar, are in planning stages (Boretti, 2020; SEASTAR, 2024), while in 2021, the Orbital O2, the most powerful tidal turbine in the world, was commissioned in Scotland (Noonan, 2019). The rapid progress of these new technologies has sparked a surge of interest in the development of tidal energy across the world.

2 | METHODOLOGICAL APPROACH

To identify relevant studies, we employed a combination of search strings tailored to capture key terms associated with tidal energy and ecological or ecosystem effects (Table 1). In addition to database searches, we used citation tracking to extend our reach. We did not restrict to publications to English and explicitly sought for Chinese, French, Korean and Russian language publications in line with the locations of TPPs.

We included only publications that reported empirical research to ensure that our conclusions were based on data, thereby avoiding potential biases that can arise from the overemphasis of certain findings in selective review articles and the assumptions made within models. We thus included all relevant publications without imposing any limitations on publication date or language, ensuring a broad and inclusive overview of the empirical evidence available on the ecological effects of tidal energy projects.

3 | RESULTS: EVIDENCED ECOLOGICAL EFFECTS

3.1 | Emergent literature

Of the 579 papers identified at title level, 54 publications that provide primary evidence of the ecological effects of tidal energy systems emerged as relevant following the full-text screening phase

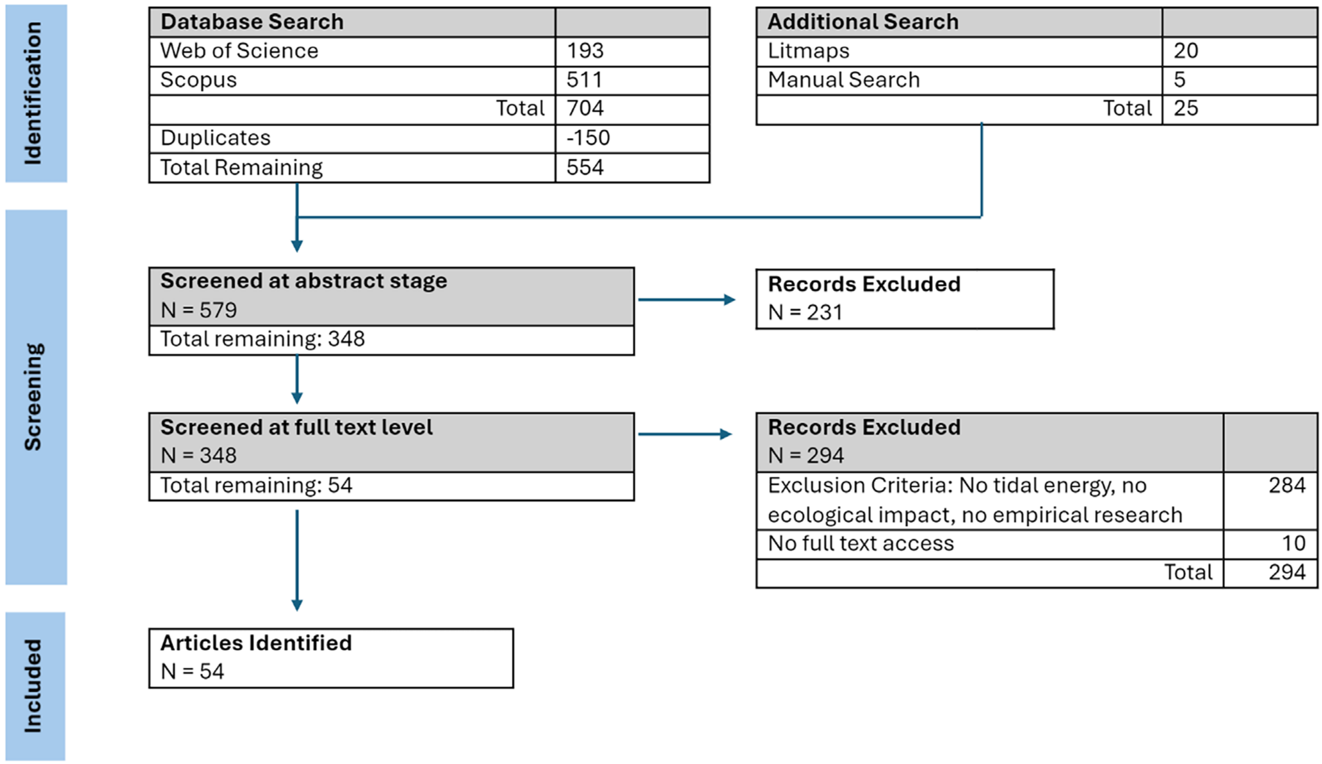

FIGURE 1 Literature identification and screening process.

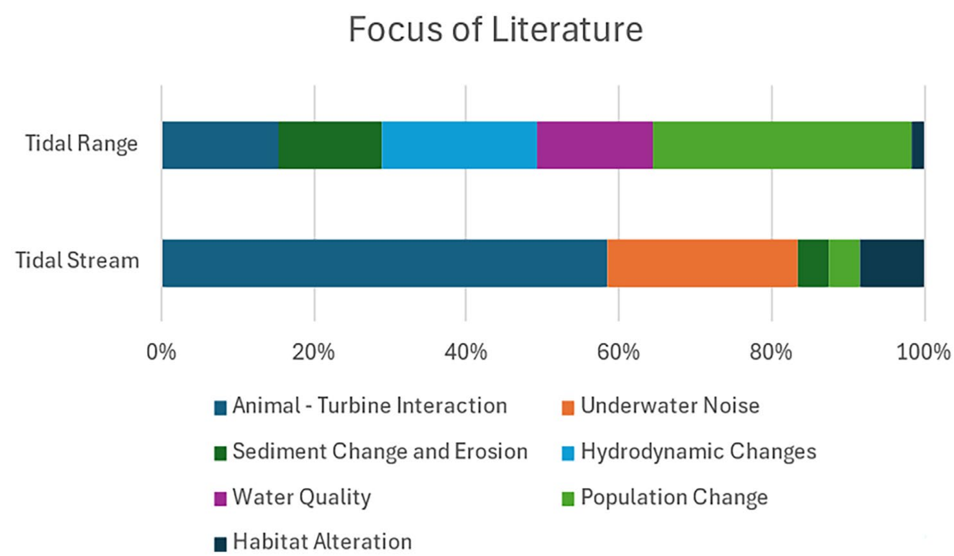

FIGURE 2 The topic foci emerging from the 54 papers included in the evidence review.

and have been included in this review (Figure 1). Of these, $N=24$ addressed tidal stream and $N=30$ addressed tidal range. The majority were in English ($N=45$), $N=6$ were in French, $N=2$ were in Korean and $N=1$ was in Russian.

The barrages themselves are unequally represented within the emergent ecological literature on tidal range, with studies of la Rance dominating ($N=17$). The other commercially operating plant, Sihwa Lake, came next ($N=5$), followed by the pilot systems at Annapolis Royal ($N=4$), Kislaya Guba ($N=4$) and no relevant ecological articles were identified for the Jiangxia power plant. The tidal stream literature largely emerged from sites in Scotland ($N=8$), with a further four from Strangford Lough in Ireland and four further studies that were informed by more than one UK site. Outside the United Kingdom, studies came from the United States (Fundy = 2, Puget = 1), Japan ($N=3$) and Tasmania ($N=1$).

The distribution of topics identified in the literature varied between the two technologies (Figure 2). These focal topics represent a combination of both the evidenced effects and a priori perceived concerns with regard to tidal power, as research was often motivated by anticipated risks and may then place unsubstantiated emphasis on preconceived concerns.

The range of concerns surrounding tidal barrages is both greater and more evenly spread; this likely stems from the age of the technology as well as its broader ecological effects. Tidal barrages are highly visible infrastructure, more physically substantial than tidal stream turbines, and they typically influence entire ecosystems. This results in a variety of concerns that centre around a wider range of posited ecological effects.

Unlike tidal barrages, which impound water, tidal stream technologies do not create solid barriers to water flow. The ecological effects associated with tidal stream projects are thus fewer, and concerns focus on the interactions between vertebrate marine life and the turbines themselves. Over 80% of the tidal stream literature examines such issues with little attention paid to ecosystem-level effects such as sediment change and alteration in water quality.

3.2 | Evidenced effects

A number of ecological effects on marine ecosystems were evidenced; there was considerable variation in these with some negative, several neutral and some positive effects (Table 2).

3.2.1 | Turbine/animal interaction (collision)

Tidal range

There is little generalisation within this literature, and different projects identify contrasting impacts on marine animal interaction with turbines. Studies at Annapolis Royal, which tracked tagged fish, showed high mortality rates due to turbine interactions (Dadswell et al., 1987, 2018; Stokesbury & Dadswell, 1991). In contrast, research from Kislaya Guba found that 99% of fish smaller than 25 cm safely passed through the turbine (Usachev et al., 2004). At la Rance, a recent study on silver eel passage reported impedance (Trancart et al., 2022); yet earlier studies indicated normal migratory behaviour and free passage through the impoundment wall, with no evidence of ecological disruption compared to nearby sites (Kirby & Retière, 2009).

The impact of different turbine models, diameters and rotational speeds also influences ecological effects. For example, high mortality of long (>1 m) sturgeon at Annapolis Royal may partly stem from the use of the STRAFLO turbine (Dadswell et al., 1987), which differs from conventional bulb turbines, as the project prioritised operational performance. Gas bubble disease, which does feature as a risk to fish in riverine hydropower literature (for instance, see Pleizier & Brauner, 2024), has not been evidenced in TPPs and these have much lower drops and system pressures. At Sihwa Lake, there is a lack of literature on fish impacts, likely due to prior ecological damage within the basin from pollution. There are also news stories recording mammals within the la Rance impoundment; for instance, a young humpback whale was ushered out in 2023 (Guellec, 2023). Dolphins are regularly seen, and seals are considered resident (Ramel, 2024). There appears to be little speculative concern regarding impacts on cetaceans and marine mammals in the range literature and even less direct evidence. These varied findings highlight the complexity of assessing ecological risks associated with tidal turbines, as outcomes are highly dependent on location, turbine design and species involved.

Tidal stream

The research on marine mammal interactions with tidal turbines appears to present consistent findings. Turbine installation did not lead to changes in the overall number of seals within a tidal channel (4 km long by 0.5 km wide) (Hastie et al., 2017), although evaluations of local-scale behaviour agree that marine mammals avoid turbines (Gillespie et al., 2021; Palmer et al., 2021), with their presence decreasing by up to 78% (Onoufriou et al., 2021; Palmer et al., 2021). While initial concerns were raised about the impact this avoidance behaviour has on species movement and habitats, literature indicates that turbines do not act as a barrier to animal transit as there is sea room for avoidance. Importantly, no evidence of sustained barrier effects was found, indicating that seals may return to the area during non-operational periods (Hastie et al., 2017; Onoufriou et al., 2021; Sparling et al., 2018). Additionally, while marine mammals generally tend to avoid active turbines, one study indicates they navigate through the rotor-swept area when the turbines are stationary (Gillespie et al., 2021). Correspondingly, there is no evidence of any mammals passing through while the rotors are in operation. This suggests a strong tendency for avoidance and indicates low collision risk during turbine operation. Furthermore, if a mammal were to encounter a turbine blade, most predicted collisions are unlikely to result in fatal skeletal trauma (Onoufriou et al., 2021).

The literature considering fish-turbine interactions similarly signalled a consensus that risk is low (Hammar et al., 2013; Shen et al., 2016; Yoshida et al., 2020; Zhang et al., 2017). Fish exhibited avoidance behaviour around turbines, reducing their movements in the area when the rotor was operational (Hammar et al., 2013; Shen et al., 2016; Yoshida et al., 2020). Mobile hydroacoustic data showed that fish initiated avoidance when they were 140 m away on average (Shen et al., 2016). Fish also approached the turbine less frequently and retreated more rapidly in dark conditions, likely due to heightened alertness from the inability to visually detect moving blades (Yoshida et al., 2020). This suggests that the risk of collision may not be greater in darkness as had been postulated. All literature found a 100% survival rate of fish, with no recorded injury or mortality in any study (Hammar et al., 2013; Shen et al., 2016; Yoshida et al., 2020; Zhang et al., 2017). The only contact between fish and turbines was reported when the turbine was stationary and did not result in injury (Zhang et al., 2017).

The primary area of concern for bird interaction with turbines is during diving-bird foraging activities (Couto et al., 2022; Johnston et al., 2021; Lieber et al., 2019). Turbines can act as aggregation sites

TABLE 2 Summary of the ecological effects for (a) tidal range and (b) tidal stream for which evidence was found in this review.

Ecological risk	Tidal range
Turbine–animal interaction (e.g. collision)	Neutral: At la Rance there is free movement of erratic or migratory organisms through the sluices and turbines, normal migratory fish behaviour and evidence that a lack of fish passes has not impaired passage of organisms. Similarly, at Kislaya Guba, most fish were able to pass through the turbine Negative: At Annapolis Royal, high levels of fish mortality (almost half) were reported through a number of experiments, with one species being entirely eradicated. At La Rance, silver eels' migratory behaviour was disrupted, likely by noise and tidal disturbance caused by the barrage
Underwater noise	No evidence of effect
Hydrodynamics	Positive: Reduced storm surge and coastal flooding risk within basin Neutral: Reduction in tidal currents in impoundment, flood and ebb currents are locally amplified upstream of sluice gates and downstream of the turbines respectively Negative: Reduced tidal range, reduced water exchange with the sea, artificial tidal regime, tidal phase shift, extended periods of slack water, fresh water discharge zone pushed upstream. Higher mean water level, decreased drainage ability and local flooding
Sediment changes or erosion	Positive: Improvement in sedimentary organic matter characteristics at Lake Sihwa—remediation from anoxic conditions Neutral: Redistribution of sediments linked to altered drainage and turbine currents and the prolonged durations of slack water Negative: Erosion of shoreline due to higher mean water level at Annapolis Royal. Displacement of sandbanks which were previously awash at low tide, erosion of riverbeds and an increase in sedimentation rates in upper estuary at la Rance. At Lake Sihwa, the total residual sediment flux remains negative (into the lake) and attributed to the mean advection processes associated with the discharge
Water quality	Positive: Destratification, reduced turbidity, and water circulation in basin improved through two-way operation at la Rance. Substantial water quality improvement at Lake Sihwa due to increased seawater exchange rates Neutral: Water quality has remained consistent and there has been a horizontal and vertical biological distribution readjustment. The freshwater–saltwater interface is pushed further upstream during summer at la Rance
Habitat alteration	Positive: Increased community richness and stability of sediments in/on sandbanks and mudflats promoted by reduced tidal amplitude and storminess Neutral: Increased sediment deposition and redistribution of sandbanks and mudflats Negative: Higher low-water level submerges portion of intertidal zones. Some portion of substrates can become permanently submerged, losing this habitat
Species/community changes	Positive: Benthic biomass, diversity and density increased (reflecting the biological penetrability of the dam). Plant plankton production downstream of the barrage and invertebrate production on mudflats at la Rance is high. Increased fish species richness at la Rance compared to other local estuaries and bays, and the basin is now designated a wetland of international importance with respect to waterbird and overwintering bird numbers Neutral: Alteration in fish community composition and distribution at la Rance, however, community structure has remained relatively stable in the long term. Novel, stable benthic community at Kislaya Guba, taking 16 years of consistent operation to establish, and corresponding to reduced water exchange with sea
Ecological risk	**Tidal stream**
Turbine–animal interaction (e.g. collision)	Neutral: Marine mammals (harbour porpoises and seals), exhibit local avoidance behaviour, though not found to alter overall population distribution. Fish interactions indicate low collision risk, no injuries reported. Turbine did not prevent transit of animals through the channel; no 'barrier' effect Overall, findings suggest minimal direct interactions and a tendency for local avoidance among marine species
Underwater noise	Neutral: Minimal physiological harm to hearing and minimal behavioural alterations. Operational tidal turbines create localized noise, unlikely to significantly affect marine animals beyond their immediate area. Acoustic emissions are below ambient levels at busy port sites Negative: Turbine noise and pile driving reduce local seal foraging success by impairing detection of prey. Operational tidal devices limit listening space for some marine mammals, local disruption of communication and navigation
Hydrodynamics	No evidence of effect
Sediment changes or erosion	Negative: At some less appropriate sites, risk of erosion likely higher due to the removal of fine sediment binding
Water quality	No evidence of effect
Habitat alteration	Positive: Anchor structures provide benthic substrate Negative: Local avoidance from seals adjacent to turbines implies habitat loss
Species/community changes	Positive: Physical structure promotes fish aggregation and a localised foraging hotspot, increasing seabird numbers

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for fish shoals, driving increased seabird foraging activity and thus collision risk. The literature, however, indicates that habitat preferences of many birds are likely to minimise collision risk as many seabirds tend to forage in areas with tidal velocities below the speeds necessary for turbines (Johnston et al., 2021). Finally, one study identified no effect on zooplankton mortality from tidal turbines (Schlezinger et al., 2013). Overall, the literature is in consensus that there is a low risk of direct interactions with tidal flow turbines for marine animals.

3.2.2 | Noise

Tidal range

No studies were identified that evidenced the effects of noise from operational barrages.

Tidal stream

The impact of noise generated by tidal energy devices on marine species presents a mixed picture, with studies revealing both neutral and negative effects. Negative effects include how turbine noise and pile driving associated with wind turbines have been shown to reduce the foraging success of seals (Hastie et al., 2021). The noise may hamper their ability to detect and pursue prey, which could affect their fitness and overall population health. Moreover, operational tidal devices reduce the listening space available to marine mammals, leading to auditory masking that can disrupt behaviours such as communication and navigation (Pine et al., 2019).

Several studies have also reported neutral effects of turbine noise on marine species. For instance, one found it unlikely to result in physiological injury to the hearing structures of invertebrates, fish and marine mammals (Lossent et al., 2018). Other evidence suggests that while operational tidal turbines do generate localized noise, it has no impact on marine animals beyond the immediate vicinity of the turbine (Schmitt et al., 2021).

While the literature generally suggests that the evidenced effects of a single turbine are manageable, concerns persist regarding potential disturbance from arrays and their cumulative impacts. The noise impact at increased scale, however, is complex as the relationship between the number of turbines and their noise level is not linear, nor do levels directly correlate with the turbine's rotational speed (Schmitt et al., 2021). Halting turbine rotation does not necessarily lead to reduced noise levels, indicating that turbine structure and braked blades can also alter the soundscape (Schmitt et al., 2021). This underscores the importance of turbine design in mitigating potential impacts. Finally, acoustic emissions from tidal turbines were found to be lower than ambient noise levels in busy port areas, suggesting that turbines in these environments contribute minimally to overall underwater noise pollution (Haxel et al., 2022). This highlights the need for site-specific evaluations, as the impact of turbine noise can vary in influence, depending on the existing background noise and the size of the turbine array at a particular location.

3.2.3 | Hydrodynamics

Tidal range

Impact on estuarine hydrodynamics was found for all barrages, with the most in-depth observations occurring at la Rance. The presence of the barrages decreased wider tidal currents within the basin, while 'flood currents and ebb currents are locally amplified upstream of the sluice gates and downstream of the turbines respectively' (Rtimi et al., 2021). Seawater exchange rates, and thus basin salinity, decreased at la Rance and Kislaya Guba, the latter experiencing rates of '30%–40% of natural exchange levels' (Marfenin et al., 1997). At Sihwa Lake, seawater exchange rates increased with the introduction of TPP infrastructure as the estuary had previously been dammed for 17 years.

La Rance and Kislaya Guba estuarine impoundments experienced reductions in tidal range and phase shifts; a delay of the natural cycle patterns by a few hours (Rétière et al., 1984; Usachev et al., 2004). Observations at La Rance also included the change to an artificial tidal regime, extended periods of slack water and the movement of the freshwater discharge zone upstream (Hillairet, 1984), as well as a rise in the basin's low-water levels (Rtimi et al., 2021). An increase in water level was also observed at Annapolis Royal (Daborn & Dadswell, 1988).

Many of these effects are not inherently negative, but can impact, for example, habitat availability, water quality and sediment dispersion, consequently influencing population dynamics and aquatic community composition. There can be land-based effects also; an example of this is the decreased drainage potential resulting from 'maintenance of a much higher mean water level', which has caused local flooding at Annapolis Royal (Daborn & Dadswell, 1988). The operation mode of the TPP also influences the extent and magnitude of these impacts as 'two-way generation utilises a lower head than for ebb-only mode, and so has less impact on the tidal regime' (Hooper & Austen, 2013). Maintaining a tidal regime as close as possible to its prior state appears key to minimising adverse ecological effects and has been a major learning point for tidal range.

Tidal stream

No studies were identified that evidenced hydrodynamic effects from tidal stream devices.

3.2.4 | Sediment changes/erosion

Tidal range

Tidal barrages have been widely found to drive sedimentary changes through their impact on hydrodynamics as current strengths affect sediment transport and deposition rates. The observed redistribution of sediment at la Rance caused by violent drainage and turbine currents and prolonged periods of slack water provides clear evidence of this (Retière et al., 1997). A change in sediment distribution is observed at all sites, regardless of operating mode, due to the inherent nature of tidal range plant function in altering the hydrodynamics of the area.

A sometimes-observed feature of sedimentary redistribution is erosion. At Annapolis Royal, 'maintenance of a much higher mean water level' meant that 'wave and ice action operating at higher levels of the shore than previously has resulted in extensive erosion up to 25 km above the causeway' (Daborn & Dadswell, 1988). At la Rance, riverbeds have been eroded (Rétière et al., 1984) and sandbanks that were previously awash at low tide have been displaced (Lebarbier, 1975).

Similarly, changes in deposition rates and locations are also common. Notably, a recent model of the estuary at la Rance without the barrage concluded that 'sedimentation rates are two times lower than those observed in the presence of the TPP' (Rtimi et al., 2022). There is also evidence of increased sedimentation rates at Sihwa Lake, where 'the total residual sediment flux was always negative (into the lake)' (Kim et al., 2021). While the deposition at la Rance was attributed to rearrangements of existing deposits, rather than new contributions (Rétière et al., 1984), it is unclear whether the changes at Sihwa Lake were caused by 'the mean advection processes associated with the discharge' from the flood-only regime, causing sediment inflow through the gates of the TPP or 'more local resuspension' (Kim et al., 2021).

The sedimentary environment at Sihwa Lake has undergone substantial organic matter improvement, transitioning 'from anoxic to more oxic conditions' (Kim et al., 2018). This is a result of the transition from a dam to a tidal barrage, which increased water exchange between the basin and the sea, facilitating improved sediment characteristics and water quality.

Sediment redistribution and erosion caused by hydrodynamic changes are influenced by operation mode. One impact noted was that 'With two-way operation, the basin level fluctuates around a slightly lower average level' (Banal & Bichon, 1982). Considering the link between increased water level and shoreline erosion, this demonstrates one element of impact reduction that two-way operation can have. Likewise, a change of modes from flood-only to two-way at Sihwa Lake could balance the advection processes associated with water discharge, reducing the inflow of sediment to the basin if this were the cause of increased deposition rates.

Tidal stream

Research on the impact of tidal stream turbines on sediment dynamics and erosion is limited, but one study suggests that turbine wakes can winnow seabed sediments by removing finer particles (Amjadian et al., 2023). This destabilises the sediment and can lead to erosion as unanchored coarser grains are more prone to being washed away under strong tidal currents (Amjadian et al., 2023). These changes in sediment characteristics may disrupt local benthic habitats, affecting nutrient cycling and resource availability for marine species (see below for findings on water turbidity).

3.2.5 | Water quality

Tidal range

Tidal barrages were found to have a cumulation of positive or neutral effects on basin water quality. At Annapolis Royal and Sihwa Lake, both previously dammed, TPP operation resulted in increased water circulation which caused destratification of the basins, improving water quality and promoting healthier aquatic ecosystems (Daborn & Dadswell, 1988; Kang et al., 2013). The impact of the TPP retrofit on water quality at Sihwa Lake was so substantial that it 'resurrected "the dead lake", which had suffered extreme water pollution due to cutoff in seawater circulation' following dam construction in 1994 (Park & Lee, 2021).

Although la Rance was not a retrofit project, construction of the barrage was conducted in dry conditions using cofferdams that fully isolated the estuary from the sea for 3 years (Rétière et al., 1984). This severance had several critical impacts on water quality; the removal of mixing desalinated the basin and allowed the build-up of organic matter (Banal & Bichon, 1982; Retière et al., 1997), largely from poorly treated wastewater from upstream conurbations (Crouzet & Boissard, 1978). These profoundly altered the ecosystems within, resulting in the almost total disappearance of marine flora and fauna (Rétière et al., 1984). Similarly, decades of inconsistent operation at the Kislaya Guba TPP resulted in desalination of the surface layer of water and a deficiency in oxygen at the bottom of the basin (Shilin et al., 1998). These impacts principally resulted from dated construction methods and highly irregular operational sequences, with weeks-long pauses in operation and are not associated with standard TPP operation.

Since two-way flow was restored in 1983, water quality at la Rance has been restored and remains consistent, indicating stable environmental conditions (Kirby & Retière, 2009). Simultaneously, there has been a readjustment of the horizontal and vertical biological distribution (Rétière et al., 1984), and most notably, a decrease in turbidity to 5% of pre-barrage levels. The freshwater discharge zone at la Rance has been pushed upstream, particularly during summer months, altering the freshwater–saltwater interface (Rétière et al., 1984; Rtimi et al., 2022).

Tidal stream

No studies were identified that evidenced effects on water quality.

3.2.6 | Habitat alteration

Tidal range

The raised low-water level due to the tidal barrage at la Rance resulted in the permanent submergence of a portion of the intertidal zone (Rétière, 1989), leading to the loss of wetland habitat for birds. Longer term monitoring has now revealed improved biological productivity of the basin, arising through reduced turbidity, leading to an increased abundance of birds, suggesting the net effect of habitat alteration is minimal (see section on population/species changes).

Tidal stream

While tidal stream turbines do not obstruct animal movement, their operation does influence behavioural patterns as animals tend to avoid them (Gillespie et al., 2021; Palmer et al., 2021), suggesting that although seals may not be permanently displaced, their interactions with the turbines do lead to localised habitat loss. This effect may grow with the expected development of arrays containing 100 or more turbines (Lossent et al., 2018). This avoidance behaviour is also likely to reduce collision risk, creating a complex interplay between habitat use and safety for marine species (Hastie et al., 2017).

3.2.7 | Species changes

Tidal range

Reports of alterations in species presence and abundance, thus of community composition, were only found for la Rance and Kislaya Guba TPPs. This is likely due to research being centred around turbine interactions at Annapolis Royal and the fact that the 'dead lake' Sihwa (Park & Lee, 2021) was thought to have a very low species diversity when operation began.

Benthic organisms feature most frequently in reports of community changes as these are indicators for ecosystem monitoring (Fedorov & Shilin, 2016). At la Rance, benthic biomass, diversity and density rapidly increased (Banal & Bichon, 1982), due to both the change in the estuary subtidal bed from 'predominantly clean, mobile sand to stable, muddy sand and sandy mud' (Kirby & Retière, 2009), as well as the biological penetrability of the barrage (Clavier et al., 1983). This rapid increase in benthos at la Rance, along with a movement upstream in the estuary, is attributed to the reduction in salinity fluctuation caused by the TPP (Banal & Bichon, 1982). Furthermore, benthic community structures remained stable within the basin at la Rance, seemingly demonstrating the stability of the environmental conditions (Desroy & Retière, 2004). Similarly, at Kislaya Guba, benthic biomass and diversity increased following the consistent operation of the plant (Usachev et al., 2004), resulting in the new restored system varying from the original due to the reduced water exchange in the basin (Fedorov & Shilin, 2016). However, during the long period of inconsistent operation, the composition of benthic life was impoverished relative to surrounding bays due to desalination of surface water, altered tidal amplitude and drying duration and oxygen deficiency in the bottom of the basin (Shilin et al., 1998).

Other changes observed at la Rance include that 'primary production of live matter has become substantially higher than average' (Banal & Bichon, 1982) and 'the production of plant plankton in the maritime sector of the Rance is two to four times higher than that observed on the Breton coast' (Retière et al., 1997). Diverse ecological communities are more stable and resilient, though a note of caution can be raised as, with raised species diversity, the likelihood of nuisance species such as those that contribute to harmful algal blooms (HABs) being present also rises. Additionally, invertebrate production on mudflats is high and provides food for both bottom-dwelling fish and wading birds (Retière et al., 1997). In 1975, Lebarbier reported changes in the species and location of fish at la Rance, while by 1984, this had developed into a reportedly richer fish population than those of similar estuaries and bays (Rétière, 1989; Rétière et al., 1984).

Indeed, the Rance estuary is now 'designated as a wetland of international importance' with respect to its numbers of waterbirds and overwintering avifauna (Kirby & Retière, 2009; Rétière et al., 1984). As explained by Le Mao et al. (1986), the increase in the surface area of the permanent body of water has been favourable to diving web-footed birds, while the appearance of new, rich and productive benthic populations has compensated for the reduction in the intertidal zone, thus allowing high densities of waders and shelducks to winter. The richer bird populations have also been attributed to the lower turbidity caused by the reduced tidal currents, which boosted primary production and hence improved the foreshore carrying capacity (Hooper & Austen, 2013).

In summary, the estuary (at la Rance) now hosts a complex and productive community which is apparently richer than the previous community in situ and which reflects 'stable environmental conditions' (Desroy & Retière, 2001, 2004).

Tidal stream

Due to the novelty of tidal stream turbines, there is no evidence of effects on population dynamics. Speculative concerns have been raised about long-term changes to local bird populations (Couto et al., 2022; Lieber et al., 2019). As the increased presence of fish around tidal turbines may enhance foraging activity for seabirds, these structures can create localised hotspots, attracting more seabirds relative to adjacent natural features (Couto et al., 2022). Additionally, as the turbines change the flow of water, they may concentrate small fish and invertebrates, effectively creating a 'prey conveyor belt' that makes these organisms more accessible to foraging seabirds (Lieber et al., 2019). Over time, alterations in prey distribution could influence the dynamics of the marine community, potentially benefiting some species while impacting others.

4 | DISCUSSION

4.1 | Evaluating ecological effects

Tidal energy has the potential to make a stable and substantial contribution to global renewable energy production. The very few tidal barrages in operation have proven consistent contributors; for instance, the la Rance barrage supplies ~600 GWh to the national grid annually and has been doing so reliably since two-way operation was re-instated in 1983 (Rétière, 1989). Despite this, the development of tidal range has stagnated, largely driven by concerns over the potential negative ecological impacts of barrage or lagoon systems.

The specific issues associated with the 'cofferdam' construction method at la Rance have long coloured the view of Tidal Range more broadly but have also been part of the learning curve for this technology. The sector now knows how not to build and install and has demonstrated one innovative method at Sihwa Lake with a floating construction approach (Park & Lee, 2021).

The legislative and technical improvements in wastewater management seen across France have helped to remedy the organic matter accumulation in the estuary (Quenet, 2023), which had also contributed to the impacts noted in the early years of operation. The lessons arising from the fish mortality recorded in Canada informed the industry about turbine design and selection, and the lessons about operational modes, particularly in using two-way flows to maintain tidal cycles and the consistency of their use emerge from all exemplar sites. Different issues have arisen in different places, but all are informative and provide components of a general understanding.

Our examination of the evidence presents a nuanced picture at odds with the generally negative public perception. While there are ecological effects, mainly from range TPPs which, when applied to estuaries rather than to lagoon systems, alter a fully tidal estuary to become a tidally-managed impounded wetland, these are a mixture of positive, negative and neutral alterations. For example, amplified rates of erosion around basins are negative, but redistribution of sediments is perceived as neutral and evidence of richer benthic, fish, and bird populations is positive (Kirby & Retière, 2009; Rétière, 1989). Furthermore, while the literature does offer valuable insights, it is a small evidence base, primarily drawn from three projects developed decades ago. This limited dataset does provide evidence of ecological effects over decades, yet its conclusions may not fully reflect current technological advancements and developments in the understanding of mitigation strategies. Issues arising in earlier installations may now be easily mitigated by modern technology and refined practices. Thus, while our findings are informative, their narrow base may not accurately represent the effects of future tidal range technology projects. Additionally, conclusions drawn from this small base may stem from specific design flaws, mechanical faults or difficulties with the project location, rather than issues inherent to the technology as a whole.

As the development of tidal range projects has stagnated, partly due to the lack of an evidence base surrounding construction and long-term operation to underpin environmental impact assessments, attention has shifted towards the more rapidly advancing field of tidal stream energy. Although stream energy only currently accounts for a small portion of global energy production, larger arrays will boost power output. This scaling-up of stream arrays may also, however, have a greater impact on local ecosystems (Roberts et al., 2016). Technological advancements in tidal stream energy are progressing rapidly (Qin et al., 2022), and commercial-scale arrays are nearing approval (TIGER, 2022). However, this approval is largely contingent upon demonstrating minimal ecological harm (Polagye et al., 2010). Current literature indicates that tidal stream turbines are not ecologically disruptive (TIGER, 2022), yet most research has been limited to single turbines or small pilot projects, and leaves uncertainty regarding the potential impacts of an increased scale (Hasselman et al., 2023). We advise here that long-term ecological monitoring should be stipulated as part of their operational permitting.

4.2 | Balancing concerns with the potential of tidal energy

In evaluating the ecological effects of tidal energy technologies, we must consider the wider context. Marine ecosystems are subject to major threats, largely due to unsustainable harvest practices, aquaculture and effects of anthropogenic climate change (Chatterjee, 2017; Halpern et al., 2007). While tidal energy does introduce risks to local ecosystems, these may be minor relative to the broader, more urgent challenges facing marine environments, such as bottom trawling, overfishing, pollution, climate change-induced acidification, sea-level rise and rising temperatures (De Dominicis et al., 2018). Recognizing and accounting for these other influences is essential for accurately determining whether local alterations in marine health are attributable to tidal energy infrastructure or are part of the broader anthropogenic pressures affecting our oceans. Improving our monitoring, gathering data for comparative cumulative effects assessments and being able to consider attribution more effectively must become part of tidal energy development pathways.

5 | CONCLUSION

Despite widespread concerns surrounding the ecological effects of tidal energy infrastructure, we find few of these are substantiated by evidence or long-term monitoring of existing tidal power projects. Although there are changes in hydrodynamics and sediment flux at tidal range power plants, as well as some animal behavioural changes around tidal stream turbines, many apprehensions either remain unsubstantiated or result in neutral effects on marine ecosystems. The literature identifies several positive ecological effects, such as greater productivity and species diversity at many taxonomic levels within tidal range basins, as well as enhanced seabird foraging hotspots surrounding tidal stream turbines. The evidence base for the ecological effects of tidal range infrastructure remains somewhat limited and is substantially more nuanced than generally perceived. This is a result of under-planned and inconsistent monitoring, despite the decades-long operational lives of the barrages. For the more recently deployed tidal stream pilot projects, risk scoping has already proceeded and trial systems of full arrays will emerge rapidly. With the plausible risks now outlined, the focus must shift towards how to effectively balance these with the considerable potential of tidal energy to contribute to sustainable energy production and thus climate change mitigation.

AUTHOR CONTRIBUTIONS

Sylvia E. Ascher led the first draft and contributed to data acquisition and interpretation. Iris M. Gray contributed to the acquisition of international literature, drafting and revision. C. M. (Tilly) Collins conceived the work, provided critical oversight and drafting. All authors have approved the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to declare.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data underpinning this work are among the papers cited in the review. Where DOIs are available, these have been listed; for other works (either older or press reports), URLs are provided.

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