Sustainability Science (2022) 17:1695–1714
https://doi.org/10.1007/s11625-022-01176-1

SPECIAL FEATURE: ORIGINAL ARTICLE

Synergies and Trade-offs between Sustainable Development Goals and Targets

Place-based interpretation of the sustainable development goals for the land-river interface

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Received: 28 September 2021 / Accepted: 4 May 2022 / Published online: 27 June 2022

Abstract

The land–river interface (LRI) is important for sustainable development. The environmental processes that define the LRI support the natural capital and ecosystem services that are linked directly to multiple Sustainable Development Goals (SDGs). However, existing approaches to scale up or down SDG targets and link them to natural capital are insufficient for the two-way human–environment interactions that exist in the LRI. Therefore, this study proposes a place-based approach to interpret the SDG framework to support sustainable land/water management, by (i) identifying key priorities for sustainable development through a normative content analysis of the SDG targets, and (ii) illustrating these priorities and associated challenges within the LRI, based on a literature review and case-studies on human–environment interactions. The content analysis identifies three overarching sustainable development priorities: (i) ensuring improved access to resources and services provided by the LRI, (ii) strengthening the resilience of the LRI to deal with social and natural shocks, and (iii) increasing resource efficiency. The review of the current state of LRIs across the world confirms that these are indeed priority areas for sustainable development. Yet, the challenges of attaining the sustainable development priorities in the LRI are also illustrated with three examples of development-related processes. Urbanisation, dam construction, and aggregate mining occur within specific zones of the LRI (land, land–river, river, respectively), but their impacts can compromise sustainable development across the entire LRI and beyond. The existence of these unintended impacts highlights the need to consider the geomorphic, hydrological, and ecological processes within the LRI and how they interact with human activity. Identifying the place-based priorities and challenges for sustainable development will help achieve the SDGs without compromising the functions and services of the LRI.

Keywords Sustainable development priorities · Land–river interface · Human–environment interactions · Hydrology · Geomorphology · Ecology

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Introduction

Throughout human history, settlements and civilisations have developed along rivers. Rivers and the surrounding land provide flat, fertile soils for agriculture and accessible transportation corridors in close proximity to a range of natural resources (e.g. water, fish) (Smith 2020). As a result, many of the world's major cities and new developments are located near rivers. Hence, rivers and the surrounding land, termed the land–river interface (LRI), is an essential zone for sustainable development (Grabowski et al. 2022). The LRI must be considered, as a whole, when proposing and evaluating measures to achieve sustainable development goals and targets. However, these areas of the landscape are dynamic and highly connected via hydrological, geomorphic, and ecological processes (Fryirs 2013; Wohl et al. 2019). With strong interconnections and feedbacks between environmental processes in a space with deep social and economic importance, unintended consequences and trade-offs between sustainable development priorities are common (Di Baldassarre et al. 2013; Fader et al. 2018). Therefore, approaches are required that more explicitly consider linkages between these human–environment interactions and sustainable development priorities within the context of the LRI.

Balancing environmental, social and economic needs is the basis for sustainable development. As originally defined in the Brundtland report of the World Commission on Environment and Development in 1987, sustainable development is the need for development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987, p. 16). The report is considered as the first framework that integrates environmental conservation with social and economic justice objectives (Edwards 2005). The term was later adopted in the 7th Goal (Ensure sustainable development) of the United Nations (UN) Millennium Development Goals (MDGs) (United Nations 2015a), and eventually in the 2030 Agenda for Sustainable Development consisting of 17 interlinked Sustainable Development Goals (SDGs) (United Nations 2015b).

While the SDG framework is globally defined, it can be used to identify development priorities at regional to local scales and even at the level of specific ecosystems. For example, the SDGs have been used to identify management needs in urban centres (Maes et al. 2019), river basins (Ge et al. 2018), and wetlands (Jaramillo et al. 2019). Interlinkages between SDGs and associated targets and indicators have also been identified for specific contexts; e.g. (i) between goals in relation to climate and energy policies in Swedish municipalities (Engström et al. 2019), (ii) between targets in relation to priorities for wetland management (Jaramillo et al. 2019) and in the context of the energy system (Nerini et al. 2018), and (iii) between indicators in relation to climate change adaptation strategies and contrasting Shared Socioeconomic Pathways in Europe (Papadimitriou et al. 2019). Furthermore, studies have reformulated general SDG targets to new metrics appropriate to the scale of interest; e.g. River Basin Sustainable Development Goals (RiSDGs) with associated targets and indicators linked to the SDGs (Ge et al. 2018).

The above examples have contributed greatly to an improved understanding of the interlinkages between SDGs and targets over multiple spatial scales (e.g. global to municipality), and how the SDGs relate to specific contexts (e.g. river catchments). Yet, these approaches easily become unworkable on a practical level. It is challenging to downscale a globally defined framework to local scales without the risk of being too conceptual (e.g. negative or positive interaction between two SDGs) or too complex (e.g. very detailed data requirements for context-specific indicators) (Maes et al. 2019). These arguments are especially important in the context of the LRI. While the LRI undoubtedly plays an important role in supporting multiple SDGs (Daam et al. 2019; Funk et al. 2019), it is challenging to capture the interacting hydrological, geomorphic, and ecological processes that underpin many SDGs in the LRI into a set of concrete and practical indicators (Grabowski et al. 2022). To identify LRI-specific sustainable development priorities, an approach is required that explicitly considers these processes and interactions while also maintaining a practical level of methodological complexity.

Therefore, this study proposes a place-based approach to interpret the Sustainable Development Goals framework to support integrated, sustainable land/water management in the LRI. To this end, the objectives are to (i) identify key priorities for sustainable development in the LRI through a normative content analysis of the SDG targets in relation to the LRI, and (ii) illustrate these key priorities and challenges based on existing literature and specific development-related case-studies on human–environment interactions within the LRI.

Place-based interpretation of the SDG framework

Defining the LRI

The LRI is the area of the landscape in which river and terrestrial processes interact. It is a term based on concepts from hydrology, geomorphology and ecology, and encompasses a wide area of the landscape (river channels, floodplains, etc.). It is defined by strong two-way process interactions, spatial connections, and varying temporal responses (Grabowski et al. 2022). In general, the LRI is characterised by four components: (i) the hydraulic active zone (i.e. river channel), (ii) the geomorphic active zone, adjacent to the river that experiences erosion and deposition (i.e. gravel bar formation and river bank migration), (iii) the surface water connected zone (i.e. active floodplain), and (iv) the soil moisture zone, in which rivers sustain aquifers along the valley and hillslopes adjacent to the river (Fig. 1).

The processes operating in the four zones of the LRI support ecosystems and human communities. The hydraulic active zone is characterized by flowing water and sediment transport (Grabowski et al. 2022). It is a critically important zone for ecological habitats and provides important natural resources (e.g. fisheries; water for consumption, irrigation, and power generation; sand and gravel for construction) (Giupponi and Gain 2017). The geomorphic active and surface water connected zones are areas of the land surface that are directly impacted by fluvial erosion and flooding, processes which drive physical habitat complexity, regulate the transport and deposition of minerals and aggregates, and influence global hydrological, carbon and nutrient cycles. The ecology and land use of the surface water connected and the soil moisture zones are strongly influenced by rivers, through the quantity and timing of water availability. These areas are commonly used for agriculture, housing, commercial and industrial activity, and corridors for transportation networks, due to their physiographic and soil characteristics (i.e. flat areas and fertile soil) and the linear nature of river networks. Across all four zones, the LRI provides recreational and cultural benefits and uses (Brown et al. 2018; Kumar 2017; Shukla et al. 2019). Finally, while estuaries are important components of river systems, which deliver essential ecosystem services (e.g. flood protection), they are not included in the definition of the LRI, because their form and dynamics are often strongly influenced by different coastal processes.

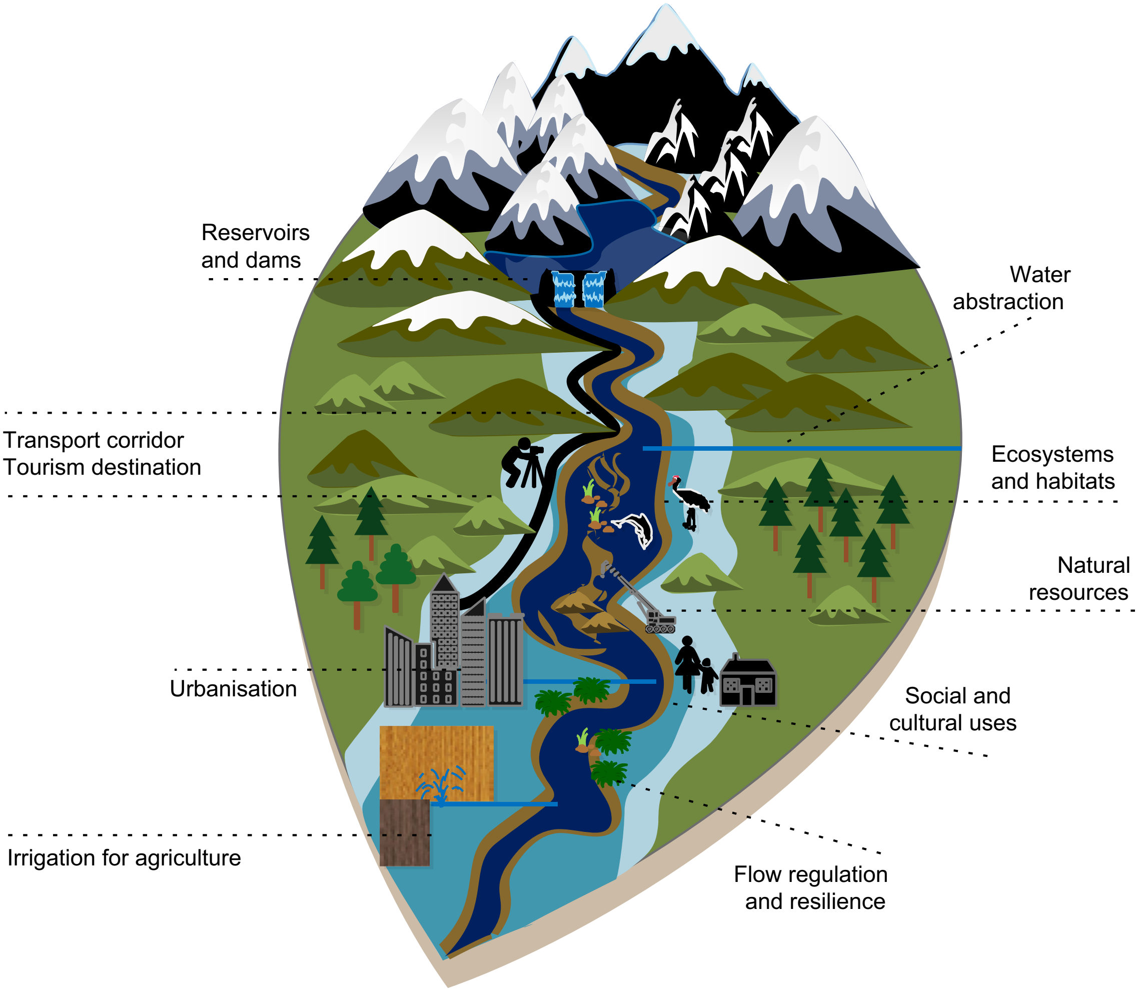

Fig. 1 Illustration of the land-river interface zones (hydraulic active zone (dark blue), geomorphic active zone (brown), surface-water connected zone (grey–blue), and soil moisture zone (light blue), and examples of resources and services provided by the LRI (Grabowski et al. 2022)

While links between the SDGs and the LRI appear straightforward (e.g. food production links to SDG2, aquatic ecosystem services to SDG6, etc.), it is challenging to directly apply the framework to identify priorities for sustainable development in the LRI. To contextualise the 2030 Agenda and take into account the interlinked dimensions of the LRI, a systematic content analysis of the SDGs was performed. This analysis aimed to identify all SDG targets that stipulate specific action in the LRI. The approach is based on the work of Maes et al. (2019) who identified the implications of the 2030 Agenda for management of urban ecosystems through a normative content analysis to identify which SDG goals and targets are explicitly interlinked with urban ecosystems and to formulate context-specific principles for sustainable development. The methodology consists of two main steps: (i) identification of all SDG targets that call for action in relation to the specific context (here: the LRI), and (ii) a three-stage consensus-based qualitative content analysis to identify key normative themes for sustainable development in that specific context.

Identification of SDG targets that call for action

First, SDG targets were identified based on expert knowledge of the involved international research team (UK, Belgium, China, India), which is composed of researchers with up to 25 years of expertise in geomorphology, hydrology, agronomy, ecosystem services, resource management and policy. To this end, SDG targets were selected that answered to the question: "Does this SDG target call for specific action in relation to the LRI?" To ensure the analysis starts from the specific processes that define the LRI (Grabowski et al. 2022), a criterion was set to include only targets that focus on actions that relate directly to hydrological, geomorphic and ecological processes within the LRI (Table 1). For example, target 11.5 aims to "*significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses by disasters, including water-related disasters*". This target is directly related to hydrological processes (e.g. flooding) within the LRI, thus would be included. Conversely, target 5.A ("*Undertake reforms to give women equal rights to economic resources, as well as access to ownership and control over land and other forms of property…*") is also applicable to people living in the LRI, but it does not call for action specifically related to hydrological, geomorphic, or ecological processes of the LRI, thus would not be included.

Based on this criterion, ten SDGs were identified in which at least one target stipulates a specific action related to LRI processes (Fig. 2, Table 1). More specifically, SDG 6 (water) and SDG 15 (life on land) are most strongly linked to the LRI. These two goals have the greatest number of targets that stipulate actions in the LRI that contribute towards sustainable development. Nevertheless, a range of other SDGs include targets that call for specific action in the LRI, such as target 7.2 ("*increase substantially the share of renewable energy in the global energy mix*") that includes hydro-electricity (driven by hydrological processes), or target 12.2 ("*achieve the sustainable management and efficient use of natural resources*") that includes resources provided by the LRI such as water and aggregates (driven by hydrological, geomorphic and ecological processes) (Table 1).

Three stage consensus-based qualitative content analysis

A normative content analysis was conducted based on the methodology proposed by Maes et al. (2019). As is standard practice within qualitative content analyses (Elo and Kyngäs 2008), the methodology aims to progressively summarise the normative content of the SDG targets by systematically selecting categories and creating new categories based on consensus between the involved researchers.

Three stages were followed: (i) summarize the wording of all identified SDG targets individually into a maximum set of three themes per target (either a word or a short sentence), (ii) summarise the themes in stage one into a maximum set of three themes for each SDG (either a word or a short sentence), (iii) identify three final themes for all SDGs together based on the themes of stage two (Maes et al. 2019).

SDG targets were summarized, for the subset of targets that relate directly to LRI processes (Stage 1), and then common themes identified by SDG (Stage 2) (Table 1). Through this process, three overarching themes were identified: (i) access and control, (ii) resilience, and (iii) resources. In stage 3, these themes were reformulated and expanded into sustainable development priorities for the LRI: (i) management of the LRI must promote improved rights for all to control and access land, natural resources, reliable infrastructure, and river-related ecosystem services (including water provision, energy, leisure and cultural); (ii) resilience must be strengthened in the LRI's communities and ecosystems to increase capacity to deal with social and natural shocks, primarily through protecting, conserving and restoring land and important ecosystems; and (iii) resources within the LRI must be managed sustainably through increasing resource efficiency and reducing water and soil pollution in different industries, by better management and innovative infrastructure and technology.

Sustainable development priorities

The content analysis helped to identify high-level sustainable development priorities specifically targeted at the LRI by contextualising the global SDG framework using an

Table 1 Links between SDG targets and the LRI: the targets that call for action in the LRI are shown, together with the related hydrological, geomorphic and/or ecological processes

SDG	Target	Related LRI process	Stage 1 (per target)	Stage 2 (per SDG)
SDG 1	1.4 By 2030, ensure that all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, as well as access to basic services, ownership and control over land and other forms of property, inheritance, natural resources, appropriate new technology and financial services, including microfinance	Hydrological, geomorphic and ecological processes (all provide resources)	Improved rights to own and control land and natural resources within the LRI	Ensure **improved rights to owning and controlling** land and natural resources in the LRI Build **resilient LRI communities**
	1.5 By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters	Hydrological, geomorphic and ecological processes (all contribute to resilience)	Build resilience to impacts of shocks and disasters related to the LRI	
SDG 2	2.3 By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment	Hydrological processes (determine productivity through water availability)	Ensure equal access to land in the LRI Increase agricultural productivity in the LRI	Ensure **better access** to land in the LRI Increase agricultural **productivity** in the LRI Increase **resilience** of production systems through improved adaptation capacity
	2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality	Hydrological processes (determine resilience)	Build resilient food production/agricultural systems in the LRI Strengthen capacity for adaptation to social and environmental changes	
SDG 3	3.9 By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination	Hydrological, geomorphic and ecological processes (all interact with water quality)	Reduce water and soil pollution in the LRI	Reduce water and soil **pollution** in the LRI

Table 1 (continued)

SDG	Target	Related LRI process	Stage 1 (per target)	Stage 2 (per SDG)
SDG 6	6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all	Hydrological processes (determine water availability)	Ensure equitable access to water and related ecosystem services in the LRI	Ensure **access** for all to water and aquatic ecosystem services in the LRI Increase **water-use efficiency** in the LRI Strengthen **resilience** of aquatic ecosystems
	6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally	Hydrological, geomorphic and ecological processes (all interact with water quality)	Reduce water pollution in the LRI	
	6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity	Hydrological processes (influenced by efficiency)	Increase water-use efficiency Build resilience against water scarcity in the LRI	
	6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes	Hydrological, geomorphic and ecological processes (all underpin ecosystems)	Ecosystem protection and restoration Build resilience of ecosystems in the LRI	
	6.B Support and strengthen the participation of local communities in improving water and sanitation management	Hydrological, geomorphic and ecological processes (all influenced by management)	Community engagement in managing the LRI	
SDG 7	7.2 By 2030, increase substantially the share of renewable energy in the global energy mix	Hydrological processes (determine potential)	Improve share of renewable energy accessible within the LRI	Improve **infrastructure and technology** in the LRI to help provide more renewable energy
	7.B By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programmes of support	Hydrological and geomorphic processes (determine potential)	Upgrade and improve infrastructure and technology in the LRI	

Table 1 (continued)

SDG	Target	Related LRI process	Stage 1 (per target)	Stage 2 (per SDG)
SDG 9	9.1 Develop quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all	Hydrological, geomorphic and ecological processes (all interact with infrastructure)	Build resilient infrastructure Ensure equitable access for all to reliable and sustainable infrastructure in the LRI	Improve infrastructure **resilience** in the LRI Ensure **access** to all to reliable infrastructure Improve **resource efficiency** in industry
	9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities	Hydrological, geomorphic and ecological processes (all interact with infrastructure)	Upgrade and improve infrastructure and technology Increase resource efficiency and promote clean technology in the LRI	
SDG 11	11.1 By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums	Hydrologic and geomorphic processes (determine safety and sustainability)	Ensure access for all to decent housing and upgrade slums in the LRI	**Ensure access** for all to housing, public and green spaces in the LRI Protect **cultural and natural heritage** associated with the LRI Build **resilience** to water-related disasters
	11.4 Strengthen efforts to protect and safeguard the world's cultural and natural heritage	Hydrological, geomorphic and ecological processes (all linked to natural heritage)	Protect cultural and natural heritage in the LRI	
	11.5 By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations	Hydrological, geomorphic and ecological processes (all contribute to resilience)	Increase resilience against natural disasters associated with the LRI	
	11.7 By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities	Hydrological, geomorphic and ecological processes (all underpin green spaces)	Ensure access for all to public and green spaces in the LRI	

Table 1 (continued)

SDG	Target	Related LRI process	Stage 1 (per target)	Stage 2 (per SDG)
SDG 12	12.2 By 2030, achieve the sustainable management and efficient use of natural resources	Hydrological, geomorphic and ecological processes (all interact with natural resource provision)	Natural resource management in the LRI	Protect **natural resources** provided by the LRI Reduce **pollution** in the LRI
	12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment	Hydrological, geomorphic and ecological processes (all interact with water quality)	Reduce waste and pollution entering the LRI	
SDG 13	13.1 Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries	Hydrological, geomorphic and ecological processes (all contribute to resilience)	Increase resilience against natural disasters associated with the LRI	Increase **resilience** against natural disasters associated with the LRI
SDG 15	15.1 By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements	Hydrological, geomorphic and ecological processes (all underpin ecosystems)	Conserve and restore ecosystems in the LRI	**Conserve and protect** ecosystems in the LRI **Reduce land degradation** in the LRI **Protect** biodiversity and habitats in the LRI
	15.2 By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally	Hydrological, geomorphic and ecological processes (all underpin ecosystems)	Protect forests in the LRI	
	15.3 By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world	Hydrological, geomorphic and ecological processes (all underpin ecosystems)	Reduce land degradation in the LRI	
	15.5 Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species	Hydrological, geomorphic and ecological processes (all underpin ecosystems)	Protect biodiversity and natural habitats in the LRI	
	15.8 By 2020, introduce measures to prevent the introduction and significantly reduce the impact of invasive alien species on land and water ecosystems and control or eradicate the priority species	Hydrological, geomorphic and ecological processes (all underpin ecosystems)	Reduce invasive species in the LRI	

In addition, the outcomes of stage 1 and 2 of the content analysis are also illustrated approach that maintains a practical level of methodological complexity. In this section, the challenges to meeting the overarching sustainable development priorities in the LRI, derived in stage three of the content analysis, are explored using examples from across the world.

Access and control to LRI resources and ecosystem services

Resources and ecosystem services provided by the LRI are directly linked to multiple SDGs (Fig. 1). However, due to the geomorphic context of LRIs (i.e. longitudinal landscape features constrained by valleys), access to and control of these resources and services are often highly unequal, both in terms of the river itself and the surrounding land.

First, with regards to the river (water) itself, decision-making and management around water rights allocation are complex and highly dependent on national and local legislation (Costa 2015; Richter et al. 2020; Wang et al. 2009). However, there are several common examples of processes that directly impact access and control of people to river resources and services, e.g. water abstraction rights, access to river water for cultural/religious purposes, and fishing rights. The best known example of a development-related activity that affects control and access is the construction of valley-spanning river dams. Construction of a large dam puts management of river flows across entire regions in the hands of governing bodies (Richter et al. 2010). Because of its global relevance, the impact of river dams on achieving (or not achieving) multiple SDGs is discussed in more detail as a case study (Sect. 4.2). Additionally, other human actions and interventions can indirectly compromise the access and control of resources (e.g. water and fish) for people living within the LRI, such as water pollution and over-abstraction of river water (Richter et al. 2020). Due to the contribution of factors operating through direct and indirect pathways, there have been increased efforts to manage river systems holistically through river catchment management approaches and transboundary river boards (Falkenmark 2004; Rinaldi et al. 2016; Smith 2020). Nevertheless, it remains challenging to manage river (water) use without compromising the needs of downstream users. To address this challenge, some rivers have been granted legal rights to increase the capacity to manage a river and its functions in its entirety (De Vries-Stotijn et al. 2019; O'Donnell and Talbot-Jones 2018).

Second, the land within the LRI is often subject to privatisation by multiple actors, restricting access and control to ecosystem services related to agriculture, industry, housing and recreation (Dudley 2017; Klimach et al. 2019). Location within the LRI and proximity to the river is a highly desired commodity across the world, so control and access to the LRI and its services is often unequal. For example, farmers near water sources (e.g. rivers or reservoirs) often get better access to water that those further downstream along rivers or near irrigation canal systems (Saldías et al. 2013). Similarly, the high prices for desirable and safe riverfront properties limit the possibilities of low-income households to access the riverside (Nicholls and Crompton 2017). Conversely, proximity to the river does not always guarantee access to associated resources and services, especially if its safe use has been compromised by pollution, e.g. clean drinking water in riverside slums (Price et al. 2019).

Social and environmental resilience of the LRI

Resilience is generally defined as the capacity to recover from a disturbance after incurring losses (Lake 2013). Within the context of the LRI, resilience can be defined as the capacity of people, organisms, and ecosystems to persist and recover in the face of natural and human-induced variations in hydrological, geomorphic and ecological processes (Fuller et al. 2019; Van Looy et al. 2019). Due to its spatial connectivity and interactions between numerous processes and ecosystems, the LRI has the capacity of offering high levels of resilience against climatic and environmental extremes (Funk et al. 2019). For example, the spatial connectivity of rivers with the surrounding land (e.g. overbank flooding and groundwater flows) helps replenish soil moisture and aquifers which increases the drought resilience of human and ecological communities in the LRI (Dott et al. 2016; Jacobson 2019). Similarly, overland flooding helps deliver new plant propagules that underpin ecologically resilient ecosystems (Braatne et al. 2007) and floodplains and riparian vegetation act as physical barriers against damaging floods (Everard and Quinn 2015; WWF 2016).

However, due to this spatial connectivity and elongate shape of LRIs, they are also more sensitive to human-induced changes as compared to many terrestrial ecosystems (i.e. disturbances propagate across the landscape more easily) (Dudgeon et al. 2006). As a result, human activity significantly impacts the social and environmental resilience of the LRI. As floodplain soils present fertile land for agriculture with easy access to irrigation possibilities, floodplains are increasingly drained and disconnected from river systems (Entwistle et al. 2019; Tomscha et al. 2017), causing degradation of ecologically important wetlands and important buffer zones against climate extremes (Kingsford et al. 2016). For example, severe degradation of floodplain functionality has occurred across the UK since 1990, corresponding with an increase in intensive agriculture cover in the floodplain from 39% in 1990 to 64% between 2007 and 2015 (Entwistle et al. 2019). In addition, multiple examples exist of river systems that have experienced morphological changes from sinuous channels and active gravel

Fig. 2 Illustration of all selected SDG targets that call for action in the LRI specifically related to hydrological, geomorphic, and/or ecological processes

beds to straighter channels with lower geomorphic activity (Grabowski et al. 2014). These changes can be caused by the presence of flow regulating infrastructure and resulting changes in sediment transport and channel incision (Brandt 2000), agricultural embankments (Fuller et al. 2019), or a compounding effect of several factors (Surian and Rinaldi 2003). These human-induced alterations to river form and surface water connectivity with floodplains can make the LRI more sensitive to extreme events. For example, on the River Tray (UK), reaches with limited human impact experience less erosion and ecological habitat loss as opposed to those with embankments (Fuller et al. 2019). Furthermore, while human activity can generate higher levels of resilience locally by creating reservoirs and irrigation canals (e.g. resilience against droughts), these interventions often result in lower degrees of resilience across the entire LRI by reducing streamflow and flow variability (Wohl 2019), impacting all zones of the LRI (Grabowski et al. n.d.). In addition, other human interventions such as deforestation and urbanisation can strongly decrease the capacity of the LRI to store water, leading to water stress. For example, an assessment of drought-resilience in the sub-catchments of the Mahanadi river (India) indicates that areas with the highest tree cover and lowest population density experience the lowest risk of experiencing environmentally damaging droughts (Rajput and Sinha 2020).

Finally, the above examples are related to impacts and changes caused by direct human activity (e.g. water abstraction, deforestation). However, the resilience of the LRI is also affected by indirect processes. One such example is the introduction of invasive species in river systems (Gallardo et al. 2016), which can have far-reaching impacts on river ecology (e.g. disruption of aquatic biodiversity due to water hyacinth (Villamagna and Murphy 2010)) and geomorphology (e.g. increased riverbank erosion due to Himalayan Balsam (Greenwood and Kuhn 2014)).

Sustainable natural resource use within the LRI

The LRI provides a wide range of natural resources. Apart from water provision, the hydrological, geomorphic, and ecological processes within the LRI support habitats for fish and other economically relevant fauna (Dudgeon et al. 2006), allow forests to grow through regulating groundwater levels (Koopman et al. 2018), and deliver nutrients (Kuemmerlen et al. 2019), construction materials (e.g. aggregates) (Peduzzi 2014) and valuable minerals such as gold to downstream river channels and floodplain soils (Zwane et al. 2006). Despite the potential of the LRI to provide resources that can support the attainment and achievement of multiple SDGs (by providing income and sustaining livelihoods), these resources are often extracted at unsustainable rates (i.e. a resource extracted faster than the natural replenishing rate of the resource), causing negative feedback mechanisms to other SDGs (UNESCO-UN Water 2020).

Water is of course a primary resource within the LRI. Around 30% of human-consumed water comes from aquatic ecosystems (rivers, lakes and wetlands) (UNESCO-UN Water 2020). Water abstraction from rivers and connected aquifers often results in impacts far beyond the point of abstraction (De Graaf et al. 2014). For example, abstraction in the lower Yangtze River (China) has led to reduced flows and salt intrusions in its estuary (Zhang et al. 2012). These processes can have impacts on water quality (e.g. pollution of groundwater) and ecology (e.g. invertebrate drift) (Wooster et al. 2016).

Other resources within the LRI are also removed at unsustainable rates. Overfishing is common in rivers and reservoirs across the world, which threatens local communities that depend on these ecosystems for their livelihoods (Allan et al. 2005). Another example is the mining of minerals and aggregates in rivers, which can cause a wide range of environmental and social impacts within the LRI (Koehnken 2018). Because of the timely and complex nature of aggregate mining (Bendixen et al. 2019), this example is further discussed in detail as a case-study (Sect. 5.3). Aside from specific resources provided by the LRI, there are other resources extracted from the LRI that are not unique to the LRI itself (e.g. timber). However, the removal of these resources can have an impact on the accessibility and availability of other resources. For example, research in the Amazon has shown that deforestation of floodplain forests is linked with declining fish catch (França Barrosa et al. 2020). These findings stress the importance of a systemic approach to sustainably managing resources and ecosystem services across the LRI.

Sustainable development challenges in the LRI

Numerous examples were provided in the previous section to support action on the three identified priorities for sustainable development in the LRI: access and control, social and environmental resilience, and sustainable resource use. However, interactions and feedback mechanisms between hydrological, geomorphic, and ecological processes within the LRI complicate the identification of solutions (Grabowski et al. 2022). These process interactions generate both positive and negative impacts towards the achievement of the three identified priorities for sustainable development in the LRI (and thus on multiple SDGs), requiring coordinated assessment and planning of the impacts of development measures.

In what follows, three examples are used to illustrate how human–environment interactions within a particular (local) area of the LRI results in hydrological, geomorphic, and ecological impacts across the *entire* LRI (Fig. 3). The aim of presenting these case-studies is to emphasize the importance of understanding place-specific challenges towards sustainable development. First, urbanisation is presented as a human influence occurring on the land surface that affects the LRI, locally and downstream. Then, dams are introduced as an example of human influence within valleys that propagate impacts upstream and downstream in river networks and laterally into the outer zones of the LRI. Finally aggregate mining is an example of a human influence on river channels and the floodplain that can cause severe local and downstream environmental and human impacts. The hydrological, geomorphic and ecological processes and interactions that generate impacts are described in detail in Grabowski

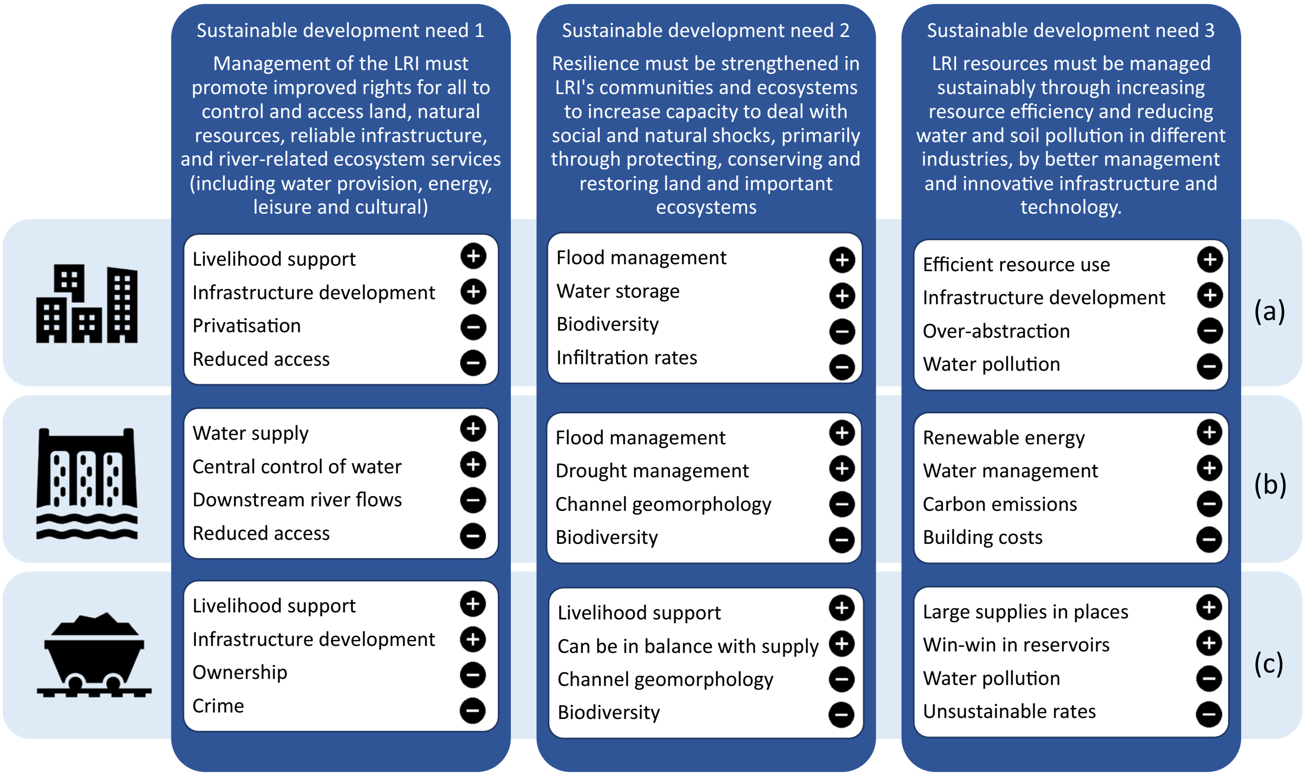

Fig. 3 Three examples of human–environment interactions within a particular (local) area of the LRI that result in potential hydrological, geomorphic, and ecological impacts across the *entire* LRI: **a** urbanisation (land), **b** river dams (land-river), and **c** aggregate mining (river). For each process, examples of positive (+) and negative (−) impacts on the LRI are provided

et al. (2022) for all three examples. Here, we connect these processes and impacts to the three SDG themes identified in the content analysis: access and control, social and environmental resilience, and sustainable resources.

Urbanisation in floodplains and the wider catchment

Most of the world's cities have developed in close proximity to freshwater resources (e.g. rivers, lakes, aquifers). As a result, many LRIs, and especially floodplains, are characterised by high urbanisation rates (Monk et al. 2019). For example, the spatial extent of rivers and floodplains around the city of Kumasi (Ghana) decreased by 83% between 1985 and 2003 (from 38km^2 to 6km^2) (Amoateng et al. 2018). Urban areas therefore play a pivotal role in supporting sustainable development across the LRI.

(i) Access and control to LRI resources and ecosystem services

Despite facilitating access to water through water supply networks, urban areas also create and enforce unequal access and control to LRI resources and ecosystem services. More specifically, urbanization impacts access and control of these resources and ecosystem services in two main ways: (i) increasing private ownership, and (ii) the creation of (physical) barriers.

First, while rivers cannot be generally owned by people, the land surrounding them can, which is especially the case in urban areas. Socio-economic inequalities in ownership are very pronounced in urban areas, which often means that low-income households have less control over where they live and how they have access to the river and its services. For example, low-income households often live in the most flood-prone areas and experience less investment in flood protection than wealthier areas (Braun and Aßheuer 2011; Liao et al. 2019; Porio 2011). As a result, management strategies within the LRI such as urban flood protection can enforce existing inequalities in access and control to LRI resources and ecosystem services (Douglas et al. 2008; Liao et al. 2019), by, for example, evicting low-income households for the purpose of managing floods in wealthier areas (e.g. to enhance water retention, widen surface water channels, and develop urban green space) (Batubara et al. 2018).

Second, the way cities and urban centres are developed often limit how people can make use of river resources and services. Major roads or high embankments often line riverbanks within urban areas, creating a physical and social barrier to the river. Although these issues are increasingly recognized along with the human and environmental benefits of having access to urban rivers (Ahern 2013; Eden and Tunstall 2006; Kondolf and Pinto 2017), urban planning often limits control and flexibility in how the land and river can be used.

(ii) **Social and environmental resilience of the LRI**

From a hydrological, geomorphic, and ecological perspective, urbanisation is a highly disturbing process. In an attempt to optimise human use of river systems, urban rivers and the land surrounding them are strongly modified (Amoateng et al. 2018; Batubara et al. 2018; Vietz et al. 2016). Rivers are straightened, culverted, and dredged, and the land surface levelled and drained to facilitate transport, building of houses, and to remove water (and waste) out of cities (Vollmer and Grêt-Regamey 2013). These changes to landforms and resulting changes to LRI processes (e.g. reduced infiltration, disconnectivity, channel incision) (Paul and Meyer 2001) increase the need for additional infrastructure to protect cities against flooding (e.g. embankments and levees). However, the construction of urban infrastructure in the LRI often leads to unintended feedback mechanisms. In general, embankments lead to narrower channels, lower infiltration rates, and higher river flows. As a result, higher river levels have been observed in urbanised areas (Putro et al. 2016), which increases flood risk and associated economic, environmental, and social damages (Dawson et al. 2008). These feedback mechanisms decrease the resilience of the LRI against socio-environmental shocks.

Furthermore, these effects are likely to exacerbate in the future due to continuing urbanisation and climatic changes (e.g. extreme events) (IPCC 2014). In an attempt to rebuild some socio-environmental resilience in several cities, more space is being (re) created for water within the LRI, e.g. within regulatory frameworks such as ‘making space for water’ in the UK (Ellis and Lundy 2016; Johnson et al. 2007) or ‘room for the river’ in the Netherlands (Rijke et al. 2012). These efforts are also increasingly combined to create multiple benefits using blue-green infrastructure (Ashley et al. 2013; Lawson et al. 2014) and to be socially integrating (O’Donnell et al. 2017; van Herk et al. 2011).

(iii) **Sustainable natural resource use within the LRI**

Finally, urbanisation also puts enormous pressure on water and other natural resources provided by the LRI, which can result in far-reaching environmental and socio-economic impacts.

The most important LRI resource for urbanisation is water, whereby access to water is a primary driver allowing urban centres to develop (Smith 2020). Therefore, water abstraction from rivers and connected groundwater tables is strongly linked with urbanisation. Aside from impacts such as salt intrusion (Zhang et al. 2012), continued abstraction in urban areas may result in unsustainable feedback mechanisms. In many cities, groundwater has been extracted for centuries, which has significantly lowered the groundwater table. This process has allowed the construction of urban infrastructure by reducing the amount of water in the ground (e.g. subway systems and underground parking) (Yoshikoshi et al. 2009). However, when industrial activity reduces and less water is abstracted, groundwater levels can recover and threaten this underground infrastructure. This is for example the case for London, where groundwater needs to be managed by continuing abstraction to maintain the subway system (Environment Agency 2018).

In addition, over-abstraction of groundwater has also led to land subsidence. For example, local rates of up to 28 cm/year of land subsidence have been observed in Jakarta (Indonesia) between 1982 and 2010, which in many locations is attributable directly to groundwater abstraction and is causing increased flood risk (Abidin et al. 2011).

Furthermore, the characteristics of urban landscapes can also result in unsustainable use of resources. For example, runoff from urban surfaces (i.e. streets, roofs and overflows from sewage systems) introduces harmful substances, such as heavy metals and excess carbon, into river water and aquatic ecosystems, with negative consequences on resource availability and use (de Miguel et al. 2005; Rossi et al. 2013; Selbig et al. 2013; Walling et al. 2003). Finally, urbanisation also influences the rate of extraction of other resources from the LRI, such as timber and aggregates (Sect. 5.2).

The above examples, especially contradictory cases (e.g. water abstraction as need vs. hazard), illustrate that to achieve greater sustainability in natural (water) resource management, a whole systems approach is required that considers the impact of urbanisation on hydrology, water quality, geomorphology and ecology of the LRI, locally and downstream.

Valley-spanning dams

Valley-spanning dams are a prime example of controls on river flows, which can both support and compromise progress on the three overarching sustainable development priorities, through direct and indirect hydrological, geomorphic, and ecological processes.

(i) **Access and control to LRI resources and ecosystem services**

Dams and reservoirs generate important ecosystem services, e.g. stable water supply and water for irrigation, downstream flood protection, opportunities for recreation and fishery, and the generation of renewable energy (McCartney et al. 2019). Given that dams are the primary reason why only around 37% of the world's rivers longer than 1,000 km remain free-flowing over their entire length (Grill et al. 2019), the global benefits dams provide in terms of resources and services is significant.

However, it is well established that valley-spanning dams also strongly limit access and control to these same resources and services. First, dams displace people and communities. The World Commission on Dams estimate that around 40 to 80 million people worldwide have been displaced due to dams and reservoirs (Richter et al. 2010). Second, the construction of a physical barrier, in combination with changes in water flow and transfer of matter (e.g. sediment and nutrients), disrupt control over and access to ecosystem services up- and downstream of dams (e.g. reduced access to water, fish and means of transport) (Toro 1997), which to date has affected an estimated 470 million people (Richter et al. 2010).

Additionally, central control of water flows can reduce access to water and other ecosystem services provided by the LRI. This is the case along the hydraulic and geomorphic active zones (e.g. reduced flows in the river), but also in the surface-water connected and soil moisture zones (e.g. reduced groundwater recharge) (Grabowski et al. 2022). At local scales, social inequities exist between dam beneficiaries. Water from reservoirs or produced energy is not necessarily accessible for the people living in close proximity to the dam, whose direct access has been impacted (Richter et al. 2010). Over larger spatial scales, central control of water flows can cause conflicts between the controlling actors and downstream regions. Dam-related political tensions are especially critical for transboundary river systems (UNEP and GEF 2016). For example, the Mekong River Commission (MRC) was established in 1995 between Thailand, Vietnam, Laos and Cambodia to provide a platform to build consensus between the different countries to manage the river system. Yet, Laos ignored the MRC and started to build two dams, putting future cooperation at risk (Middleton and Allouche 2016; Smith 2020). Dams are also known to have been used in the context of war as a repressive measure (Gleick 2019).

(ii) **Social and environmental resilience of the LRI**

Due to the more stable water supplies associated with reservoirs and the more regular flows throughout the year, resilience to the effects of droughts to people living in the LRI is often impacted positively with the construction of valley-spanning dams (Billington et al. 2005). Similarly, flow regulation also provides a form of flood management downstream by reducing peak flows, therefore increasing the resilience of the LRI to absorb extreme flood events (Glenn et al. 2008).

However, dams and reservoirs and their up- and downstream impacts are also the main causes of the loss of river connectivity (Grill et al. 2019). River disconnectivity can result in legacy effects that persist long after the initial disturbance caused by dam construction (Gregory 2006; Grill et al. 2015; Pandit and Grumbine 2012; Richter et al. 2010). Dams disrupt the downstream flow of water and sediment, causing erosion and river incision that impacts ecosystem services, such as biodiversity (Wohl 2019). Consequently, the resilience of river systems to absorb climatic extremes is often strongly impacted by the presence of valley-spanning dams, because they prevent the natural response and adjustment of river systems and facilitate a change in land use downstream. The most extreme example is the devastating impact of high water releases from dams following intense rainfall (Grant et al. 2013). Dams create a perception of safety against disasters from natural hazards, such as floods, which leads to increased development in downstream floodplains. Therefore, when extreme weather events fill reservoirs to or beyond operational capacity, emergency dam releases, or worse dam failures, can have socially and environmentally devastating consequences (Davila et al. 2020).

(iii) **Sustainable natural resource use within the LRI**

As discussed earlier, dams and associated reservoirs generate new ecosystem services and more stable resource supplies (Beck et al. 2012). However, an assessment by Ansar et al. (2014) suggests that large hydropower dams in most countries are too costly and take too long to build to compensate for the negative consequences discussed above. Similarly, studies have also showed that the carbon emissions from hydroelectric reservoirs (due to decomposition of organic material deposited in the reservoir) are substantial, increasing greenhouse gas emissions, from a power supply championed for its low-carbon credentials (Barros et al. 2011; Li and Zhang 2014).

Aggregate mining in rivers

At an estimated 50 billion tons per year, aggregates are the most mined material in the world (Peduzzi 2014). This demand for aggregates is driven by urbanization, as most aggregate is used in the construction industry to produce concrete and asphalt (Peduzzi 2014; Torres et al. 2017). However, sand suitable for construction is not as easy to find as one might expect. While sands cover extensive areas of the world (e.g. oceans and deserts), they are often located far from construction sites and have characteristics that make them unsuitable for construction (i.e. rounded grain shaped). Therefore, sand is commonly mined from rivers and floodplains, which provide the right type of sand close to areas of demand (Koehnken 2018).

(i) **Access and control to LRI resources and ecosystem services**

With urban populations increasing by 65 million people annually, the demand for aggregate, which has doubled in the last decade, will continue to increase (Peduzzi 2014; Torres et al. 2017). Therefore, aggregates are an essential part of modern society, and mining has the capacity to be a reliable source of income for local communities (ACET 2017). Especially in the Global South, many households depend on aggregate income to support their households through artisanal and small-scale riverine sand mining operations (ACET 2017; Peduzzi 2014).

However, in many countries across the world, there is a lack of policies and regulations around aggregate mining in rivers to ensure sustainable extraction. Thus, illegal mining thrives, causing significant social and environmental impacts, a crisis identified as a "looming tragedy of the commons" (Torres et al. 2017). Furthermore, the lack of regulations has led to the emergence of "sand mafias" that control the extraction and trade in aggregates (Bendixen et al. 2019). Especially in India, currently with the third-largest construction industry in the world, the problem of aggregate mining-related crime is increasing in recent years, whereby access and distribution of the resource is increasingly managed by criminal networks (Mahadevan 2019).

(ii) **Social and environmental resilience of the LRI**

Depending on the scale, type and frequency of aggregate mining in rivers, the extraction of aggregates from a river can cause a cascade of geomorphic and ecological impacts, particularly if upstream sediment supply is insufficient to replenish what has been removed. Impacts can range from local disturbance of the riverbed to impacts that resonate far beyond the place and time of extraction, including loss of land and the livelihoods it supports (due to riverbank erosion) and degradation of water quality and ecological habitats (due to increased water turbidity) (Bendixen et al. 2019; Farahani and Bayazidi 2018). Given that the annual consumption of aggregate is twice the estimated annual sediment load carried by rivers worldwide (Peduzzi 2014), aggregate mining is likely to cause significant disruptions to hydrological, geomorphic and ecological processes, which undermine the social and environmental resilience of the LRI (see Sect. 4.2) (Torres et al. 2017).

The lower Mekong is one of the most studied river systems in terms of sand mining impacts (Hackney et al. 2020; Jordan et al. 2019; Manh et al. 2015). Results highlight that sediment supply from the upper reaches is insufficient to compensate for the loss of extracted material in the lower reaches, leading to riverbank instability and large-scale erosion of land. Similar impacts have been observed in other rivers, including the Ouémé, Benin (Lalèyè et al. 2019), the White Volta, Ghana (Musah 2009), the Njelele, South Africa (Gondo et al. 2019), the Tatao, Iran (Farahani and Bayazidi 2018), the Muda, Malaysia (Teo et al. 2017) and the Balason, India (Wiejaczka et al. 2018).

(iii) **Sustainable natural resource use within the LRI**

The geomorphic impacts caused by aggregate mining (e.g. erosion) can reduce water and food security. Within rivers, erosion leads to increased turbidity levels (i.e. higher sediment concentrations in the water) which affect water quality and results in higher water treatment costs. High turbidity levels also degrade aquatic ecosystems and threatens the livelihoods that depend on related ecosystem services (Pitchaiah 2017). Along the banks of rivers and floodplains, soil erosion can disrupt the productivity of food sources (e.g. erosion of cropland) (Koehnken 2018; Torres et al. 2017). Furthermore, aggregate mining in the Mekong Delta is even found to contribute to increased salt intrusion during the dry season, leading to drinking water pollution and salinization of cropland (Torres et al. 2017).

Conclusion

The LRI is an essential zone for sustainable development due to the environmental processes that support social and economic activity. However the complex interactions and feedbacks between hydrological, geomorphic, and ecological processes and human activity causes unanticipated consequences that may be distant in space or delayed in time (Grabowski et al. 2022). Thus, high-level assessment of SDG targets done at a coarse spatial scale do not capture these processes and interactions and the associated impacts on people and sustainable development. Therefore, this study proposed a contextualisation of the SDG framework into place-based themes to help achieve sustainable development in the LRI.

Key priorities for sustainable development were identified through a normative content analysis of the SDG targets. The multiple explicit linkages between the SDG targets and the LRI clearly illustrate that the LRI has the potential to be a hotspot for sustainable development, but that explicit action is needed to (i) improve access to and control of its resources and ecosystem services, (ii) increase its resilience against natural and social disasters, and (iii) more efficiently use its natural resources. However, through case-studies, it was also demonstrated that interactions and feedback mechanisms between hydrological, geomorphic, and ecological processes within the LRI cause positive and negative impacts on people and the environment. While urbanisation, dam construction, and aggregate mining all occur (locally) within specific zones of the LRI, their high-level impacts compromise sustainable development across the entire LRI and beyond. Starting from the place-based priorities and challenges for sustainable development in the LRI, this study can be used as a practical framework to assess context-specific impacts, which will help achieve the SDGs without compromising the functions and services of the LRI.

Acknowledgements This work was supported by funding from the UK National Environment Research Council (NE/S01232X/1), the National Natural Science Foundation of China (No. 41911530080) and the Indian Department of Biotechology (BT/IN/TaSE/69/AA/2018-19).

Data availability Data sharing is not applicable to this article as no new data were created or analysed in this study.

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