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SPECIAL FEATURE: ORIGINAL ARTICLE

Synergies and Trade-offs between Sustainable Development Goals and Targets

The land–river interface: a conceptual framework of environmental process interactions to support sustainable development

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Abstract

Rivers and their surrounding lands are focal points of human development in the landscape. However, activities associated with development can greatly affect river processes, causing significant and often unintended environmental and human impacts. Despite the profound and varied environmental impacts that development-related alterations cause through hydrological, geomorphic, and ecological processes, they are not widely acknowledged outside of river management and affect resource availability and hazard exposure to people. In this paper, we propose a novel, interdisciplinary conceptual framework of river–land process interactions to support sustainable management and development. We introduce the term 'land–river interface' (LRI) to describe areas of the landscape in which river processes affect land, vegetation, and/or fauna, including humans, directly or indirectly. The multiple links between LRI processes and factors at the river basin, valley, and river channel (i.e. reach) scale are synthesized and a conceptual zonation of the LRI based on the process is proposed to serve as a framework to understand the impacts of human activity. Three examples of development-related activities (urbanization, dams and aggregate mining) illustrate how alteration to the form and functioning of river basins, valleys, and channels cause a range of impacts to be propagated throughout the landscape, often spatially or temporally distant from the activity. The diversity and severity of these impacts on the environment and people underscore the need to incorporate river processes, as represented in the LRI concept, into broader environmental management to better anticipate and mitigate negative impacts and maximize positive outcomes to deliver the benefits of sustainable development across society.

Keywords Fluvial geomorphology · Urbanization · Dams · Sand mining · Integrated water resource management

Introduction

Rivers, floodplains, and the inland wetlands associated with them are intimately tied to human civilization and development. They are among the most biodiverse ecosystems on land (Dudgeon et al. 2006) and have long provided humans with the building blocks for civilisation: timber, reed and peat for construction and fuel (Baka and Bailis 2014); fishing, hunting and foraging grounds; and ideal locations of agriculture (Lewin 2010). Rivers and the land that surrounds them continue to be focal points for development (e.g. hydropower, navigation, water abstraction, and land for intensive agriculture and urban development). While these human actions have undeniable direct social and economic benefits, the highly connected and responsive nature of river systems means that development impacts can propagate

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through the landscape to affect the environment and people in a variety of ways.

Regardless of where development activities occur in the landscape, they can impact the environment and people more widely through their influence on river processes. Changes to land cover (e.g. deforestation, urbanization), land use (e.g. agricultural intensification), surface topography (e.g. flood levees, embankments, channel planform), and water storage and regulation (e.g. valley-spanning dams and reservoirs) affect the flow of water (i.e. surface and ground water) and sediment (e.g. silt, sand, gravel) through a catchment and river network (Downs et al. 2013; Wohl and Beckman 2014; Marcinkowski et al. 2017; Wohl 2019). By altering these hydrological and geomorphic processes, and associated ecological communities, development activities change how a river behaves, which affects risk exposure (e.g. overbank flooding, bank and bed erosion) and resource availability (e.g. freshwater supply). These impacts from development-related activities are evident irrespective of whether development is distributed within the catchment or localized within the valley or river channel. Changes to land cover in a catchment (e.g. urbanization), regardless of proximity to river channels, can increase peak river discharges, degrade aquatic ecosystems and fisheries resources, cause incision that increases bank erosion, and expose communities in floodplains to increased flood and erosion hazards (Du et al. 2015; Roy et al. 2016; Booth et al. 2016; Vietz et al. 2016; Walsh et al. 2016). Modifications to valleys, such as dams that impact the land and river directly, cause significant changes to water levels, discharges, sediment flow, and channel form that profoundly affects ecological and human communities along with the river network and further into the terrestrial environment (Richter et al. 2010; Beck et al. 2012; Kondolf et al. 2018; Park et al. 2020; Ibisate et al. 2013; Aguiar et al. 2016; Bejarano et al. 2018). Finally, localized activity, like the extraction of aggregates from rivers and floodplains for construction, have much wider impacts than might be assumed. Sand and gravel extraction from river channels cause incision, bank erosion and river widening, and the lowering of water tables which affect communities and vegetation, locally, downstream, upstream, and laterally into the landscape (Scott et al. 1999; Torres et al. 2017; Koehnken 2018; Koehnken et al. 2020; Schwartz et al. 2021). While some of these impacts are well known and considered in sustainable development (e.g. hydrological and geomorphic effects of dams), there remains insufficient recognition of the multiple processes by which development activities can propagate impacts through the river network and back into the landscape to effect the environment and people.

River systems must be considered more comprehensively in environmental impact assessment and integrated land–water resource planning to minimize significant unintended impacts on the environment and people from development. However, the large number and diversity of impacts propagated by rivers, which can be realized distant from the development activity and delayed over time through a wide range of processes (hydrological, geomorphic, and ecological), make it challenging to identify clear causal links to predict impacts or identify root causes when they have occurred. A new interdisciplinary, process-based conceptual framework is needed to integrate scientific understanding from existing hydrological, geomorphic, and ecological frameworks and models, which have successfully informed the management of specific river-related issues (e.g. water resources, sediment transport, biodiversity and nature conservation) (e.g. Poff et al. 1997; Habersack 2000; Thorp et al. 2006; Bracken et al. 2013, 2015; McCluney et al. 2014; Gurnell et al. 2015). Along with the framework, a new, inclusive vocabulary is required to facilitate the identification of process-impact relationships and the communication of these to technical specialists and environmental managers across a range of disciplines, plus stakeholders and the wider public. While numerous terms exist to describe rivers and the surrounding land, they are challenging to use in an interdisciplinary, process-based conceptual framework, because (i) the processes that create or influence them are not apparent to non-specialists, (ii) those processes may no longer be operating due to development activity (e.g. floodplains are not 'flood'-plains when they are disconnected from rivers by levees or embankments), and (iii) the areas of a landscape affected by some river processes may not relate to any specific landform. By describing and delineating rivers and the land that surrounds them based on processes, we can better understand how impacts to the environment and people can arise via multiple river-related pathways.

In this paper, we propose a novel, interdisciplinary conceptual framework for environmental impact assessment and integrated land–water resource planning that describes how development activity propagates through spatio-temporal river-land interactions to impact the environment and people. First, we propose the term 'land–river interface' to describe areas of the landscape in which river processes affect land, vegetation, and people, directly and indirectly. We summarize the river basin, valley, and reach scale drivers of river-related hydrological, geomorphic and ecological processes, and explain how rivers affect the surrounding landscape and, in doing so, develop a conceptual zonation of the land–river interface. Then, through an interdisciplinary literature review structured around three examples of development-related activities (urbanization, dams and aggregate mining), we develop the causal linkages between development and the significant environmental and social-economic consequences in the LRI via river processes. Finally, we argue that society will be better able to coordinate the management of land and water resources, minimize unintended and often detrimental consequences, and plan synergistic solutions to support sustainable development using an interdisciplinary conceptual process-based framework of river–land interactions.

The land–river interface: where rivers affect people and the environment

An interdisciplinary, process-based, conceptual framework must use terminology that accurately describes the concepts and minimizes potential misinterpretation between disciplines. At the outset of this paper, we propose the term ‘land–river interface’ (LRI) to describe the portion of the landscape in which the land, vegetation, and/or fauna, including humans, are affected by processes, directly or indirectly, influenced by rivers. While there are arguably countless ways that rivers influence people and the environment (e.g. chemical fluxes, carbon transport dynamics, and cultural and spiritual), here we focus on three broad types of river processes (i) the flow of water over and through the land surface (i.e. hydrological processes); (ii) the reshaping of land through erosion and deposition (i.e. geomorphological processes); and (iii) the growth, interaction, and activity of river-dependent biological organisms (i.e. ecological processes).

We recognize that numerous terms are already used to describe rivers and the surrounding land (Fig. 1). However, none encompass all areas of the landscape affected by or dependent on rivers nor effectively communicate the processes by which the effects are occurring. Commonly-used terms identify topographical features or ecological habitats (e.g. floodplain or riparian zone), but the underlying processes that form, maintain, or influence them may only be evident to disciplinary specialists or may no longer be operating in a development-impacted river system. Furthermore, some terms that identify an area of the landscape affected by a river process (e.g. erodible corridor, Piégay et al. 2005) are not widely used outside of their discipline, typically emphasize a single process, and /or do not align well with topographic features (e.g. an erodible corridor may only exist across a limited lateral spatial extent of a floodplain or valley but can include edges of terraces and hillslopes). The novelty of our usage of the term ‘LRI’ is that it defines areas of the landscape that are directly and indirectly affected by several river processes, whether or not they are aligned with topographical features or habitats.

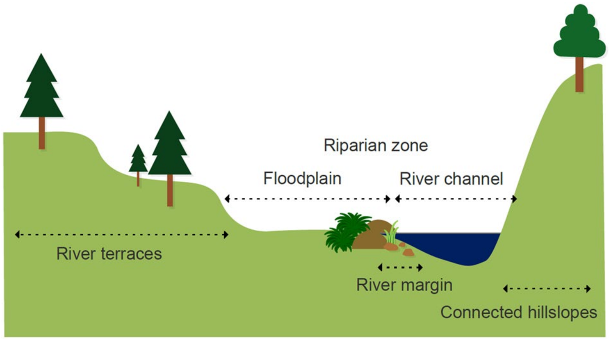


Fig. 1 Illustrative cross-section of a river channel and its valley, annotated with selected commonly-used descriptive terms

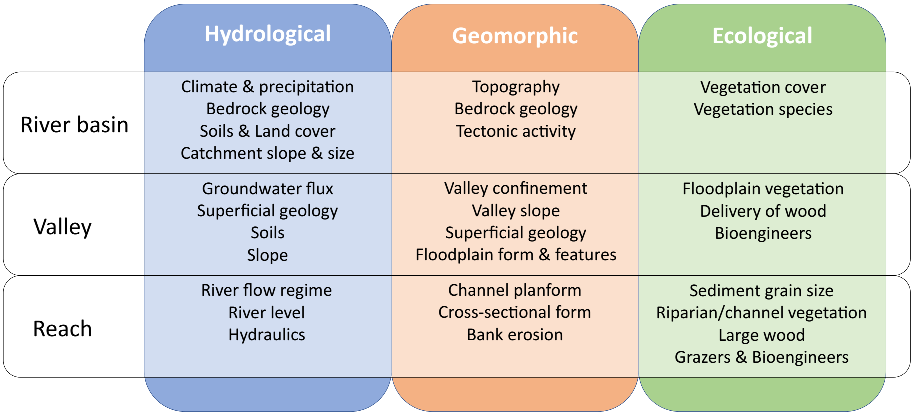
Whilst terms like the LRI have appeared previously in the scientific literature (e.g. ‘land–water interface’, ‘land–freshwater interface’, ‘river–land interface’, and ‘river–riparian interface’), they neither encompass the same range of processes that we propose nor explicitly consider two-way interactions between aquatic and terrestrial environments. Some previous terms have been used within a single discipline to describe ecological habitat gradients (ecotones) or mosaics (Jaiswal and Pandey 2019; Swanson and Bohlman 2021), the influence of riparian vegetation and channel morphology on river water quality and aquatic ecology (Karr and Schlosser 1978), and the input of resources from rivers to the land surface (Richardson et al. 2010; Tonkin et al. 2016; Terui et al. 2017). By formally defining the LRI and delineating it based on river processes that influence the landscape, our intention is to facilitate the interdisciplinary identification and explanation of the causal linkages between development activity and its environmental impacts.

The scientific understanding of the processes affecting the LRI, in their respective disciplines, are supported by strong foundations in the literature. This paper first draws together and summarizes these underlying scientific concepts to explain how processes operating in the LRI are influenced by factors operating at multiple spatial and temporal scales. That understanding is translated to propose a conceptual delineation of the LRI based on the dominant processes by which rivers influence the surrounding landscape to aid the interpretation of causal links between development-related activities and impacts on the environment and people in the LRI.

River-related processes affecting the land–river interface

Rivers and floodplains are an expression of hydrological, geomorphic and ecological processes within the natural and anthropogenic context of the landscape (Brierly and Fryirs 2005; Kondolf and Podolak 2014; Habersack et al. 2014; Wohl 2016; Gurnell et al. 2016). Factors operating at a hierarchy of spatial and temporal scales influence these processes (Fig. 2), such that perturbations or alterations acting spatially distant from a river channel can greatly affect the LRI, often with substantial time lags. Thus, to fully appreciate how development activity impacts through river processes to affect the environment

Fig. 2 Natural factors that influence fluvial processes, organized by spatial scale (river basin, valley and reach) and theme (hydrological, geomorphic, and ecological)



	Hydrological	Geomorphic	Ecological
River basin	Climate & precipitation Bedrock geology Soils & Land cover Catchment slope & size	Topography Bedrock geology Tectonic activity	Vegetation cover Vegetation species
Valley	Groundwater flux Superficial geology Soils Slope	Valley confinement Valley slope Superficial geology Floodplain form & features	Floodplain vegetation Delivery of wood Bioengineers
Reach	River flow regime River level Hydraulics	Channel planform Cross-sectional form Bank erosion	Sediment grain size Riparian/channel vegetation Large wood Grazers & Bioengineers

and people in the LRI, we must first summarize briefly the key processes and the factors (i.e. drivers) that influence them in the river basin, valley and reach scale, focusing on hydrology, geomorphology, and ecology.

Hydrological processes and drivers

The movement of water over and through the land surface is the primary control of LRI processes. Several natural factors at the regional and river basin scale determine the amount of water that a river carries (i.e. discharge, $m^3 s^{-1}$) and its variations over time (i.e. flow regime, floods, droughts), including climate, topography, geology, soils and vegetation cover (Shaw 2011). Understanding the contribution of those factors to the flow regime is the essential first step to conceptualizing how development activities affect the environment and people in the LRI to facilitate sustainable development. Some factors do not change significantly over management-relevant timescales (i.e. years-decades), such as river basin topography, geology, and soil type. However, they affect strongly the partitioning of flows between surface and groundwater pathways at the river basin scale to influence the timing and magnitude of river discharge (McDonnell 2013; Chiverton et al. 2015; Rust et al. 2021), moderating or accentuating the impact of other factors that are changing more rapidly, such as climate, vegetation cover, and soil hydraulic properties (Van Vliet et al. 2013; Rust et al. 2014; Cheng et al. 2017). The flow regime controls many geomorphic and ecological processes in the LRI, as it dictates the timing, magnitude and frequency of high and low discharges that (i) generate overbank flooding, (ii) drive erosion and deposition in the channel and valley (Fryirs and Brierley 2013), and (iii) maintain water levels in the river and surrounding aquifer during droughts (Bravard et al. 1997; Stella et al. 2013; Gurnell et al. 2015).

Geomorphic processes and drivers

River geomorphic processes are the engines that create landforms in the LRI (e.g. terraces, floodplains, river-associated wetlands), which support human settlement, agriculture and a diversity of plant and animal species (Everard and Quinn 2015). Equally, though, they represent hazards to people and property (e.g. landslides and riverbed and bank erosion) (Janes et al. 2017). Geomorphic processes in the LRI are driven primarily by channel discharge, so are influenced by the hydrological drivers described above, but are also affected by factors in the river basin, valley and reach that control the availability of sediment (i.e. supply), how easily it can be transported to the channel (i.e. connectivity), and local deposition and erosion (Fig. 3). Upland areas with steep terrain are sediment generation zones, in which

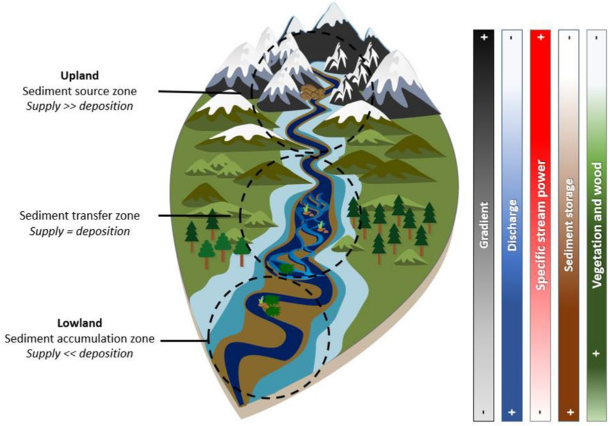


Fig. 3 Catchment patterns in geomorphic drivers (gradient, discharge, stream power and sediment storage) that affect the land–river interface. The covariation in these drivers generates regions where local supply exceeds local deposition and sediment is transported downstream (sediment source zone), local supply is equal to local deposition and sediment flux from upstream is passed downstream unhindered (sediment transfer zone), and local deposition exceeds local supply thus sediment from upstream is deposited (based on Fryirs and Brierley 2013, pp. 10 and 33)

more sediment is delivered to a channel (via landslides, bank erosion, etc.) than can deposit locally (Fryirs and Brierley 2013). As little as 10% of a large catchment may be responsible for most of the sediment carried by the river, the majority of which may be transported during less than 1% of the year (Wohl et al. 2015). As the landscape becomes flatter, stream power decreases, less coarse sediment is delivered to the channel, sediment inputs become finer in grain size, and the geomorphic action of the river begins to create floodplains and terraces (Fryirs and Brierley 2013). High discharges (especially the maximum discharge that the channel can contain, i.e. bankfull) induce geomorphic adjustment of the river. Bank erosion, sediment erosion, and sediment deposition within the channel alters the planform (e.g. shape, sinuosity) and longitudinal profile (e.g. riffles and pools), which over time create a mosaic of active and relic features in the floodplain (e.g. abandoned channels, backwaters). In this sediment accumulation zone (Fig. 3), overbank flooding deposits fine sediment on the floodplain (e.g. sand, silts and clays), creating topographic variations (natural levees and backswamps) and adding inputs of carbon, nutrients and plant propagules. Geology and vegetation are crucial factors that influence the input and storage of sediment and large wood in river systems, which affect channel planform, lateral mobility, floodplain form, and riverbed levels (Wohl 2019; Wilkes et al. 2019).

Ecological processes and drivers

Ecological processes, related to vegetation and animals, are the final 'natural' driver of the LRI. Vegetation responds to and alters hydrological and geomorphic processes at river basin, valley, and reach scales. For example, at the river basin scale, vegetation cover affects temperature, evapotranspiration, and precipitation and influences the partitioning of overland and subsurface flow pathways to affect the river flow regime (Tabacchi et al. 2000; McDonnell 2013). Terrestrial vegetation affects sediment supply and connectivity by influencing soil erosion, mass wasting, and bank erosion (Morgan and Rickson 1995; Simon et al. 2006; Kim et al. 2017). In channel, vegetation and fallen trees and branches (i.e. large wood) play critical roles in altering hydraulic forces, inducing sediment deposition and erosion, stabilizing river banks, and altering channel form (Corenblit et al. 2007; Gurnell 2013, 2014; Wohl 2014). Thus, changes to the vegetation community within the LRI (e.g. invasive species and human-induced land cover change) can drive a cascade of hydrological and geomorphic impacts (Wohl 2015). Animals, large and small, have important effects on the form and functioning of the LRI. The effects operate through direct modification of soil, sediment and water flows pathways and storage and indirect effects through herbivory and predation (Rice 2021). While large ecosystem engineers, such as beavers and hippopotamus are well known for their impact on river hydrology, sediment transport and floodplain habitat creation and maintenance (McCarthy et al. 1998; Brazier et al. 2021), the indirect effects of grazing animals may be equally important for sustainable development in the LRI. Research has shown that intense grazing pressure on riparian vegetation can shift its community composition and structure, which in addition to the hydrological and terrestrial ecology implications, can also affect river form and geomorphic activity because of the lack of vegetation to stabilize banks, bars, and islands (Beschta and Ripple 2006, 2008). The increase in grazing pressure may be caused by direct human action, such as increased stocking, or through indirect ecological pathways, such as the extirpation or exclusion of a predator of native grazers.

Zones of the land–river interface

We propose a conceptual delineation of the LRI into broad zones based on river-related processes to support improved holistic management of the LRI that reduces the impacts of development on the environment and people. The delineation builds on and links existing conceptual models in hydrology, fluvial geomorphology, and ecology that generalize process interactions and the influence of topography and local environmental conditions to identify spatial patterns or zonation (Ward et al. 2002; Bornette et al. 2008; Gurnell et al. 2015).

We identify four zones within the LRI to describe the direct and indirect effects of river processes on the environment and people (Fig. 4): hydraulic active zone, geomorphic active zone, surface water connected zone, and soil moisture zone. In the hydraulic active zone, rivers have their most obvious impacts on land, vegetation and people within their channels, where flowing water exerts strong hydrodynamic forces. In the geomorphic active zone, the erosion of land and deposition of sediment extends the river's influence to the riverbank and portions of the valley in which the land surface characteristics (i.e. topography, surficial geology, soil texture) are affected by river geomorphic processes. In the surface water-connected zone, overbank flooding inundates the land surface. Flooding temporarily expands the area of the aquatic environment, creating seasonal washlands and wetlands in the floodplain and allowing the dispersal and displacement of aquatic and terrestrial organisms (e.g. seeds and living wood or riparian trees, floodplain fish). Finally, in the soil moisture zone, rivers can influence the surrounding landscape due to their influence on groundwater and soil water availability. Where the geology is conducive to the formation of aquifers, the directionality of flow can vary over time and space. While typically water flows from the land to the river, river water can flow downward and outward in a 'losing' reach or during dry periods to maintain

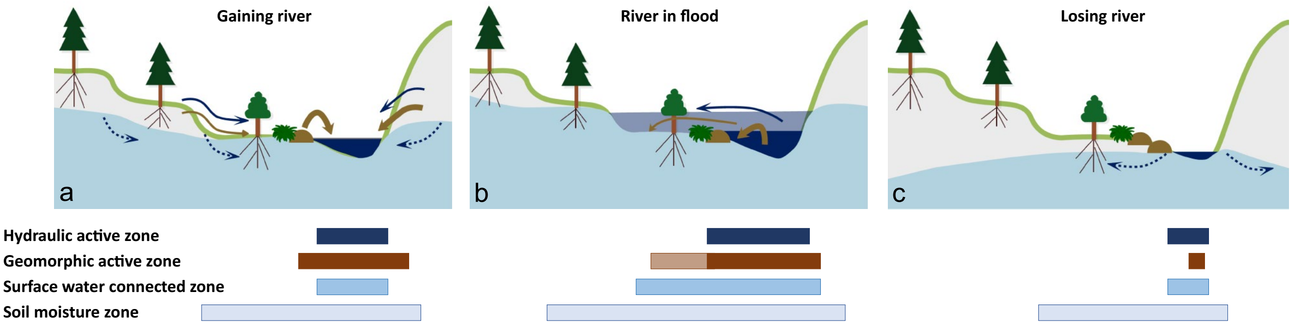


Fig. 4 The land–river interface is defined by the influence of river processes on the landscape. The LRI has four zones (hydraulic active, geomorphic active, surface water connected and soil moisture), which vary in size and location based on factors, such as climate, valley form, geology and surface topography. These locations and widths are illustrated here in a (**a**) 'gaining' river, (**b**) a river in flood, and (**c**) a 'losing' river

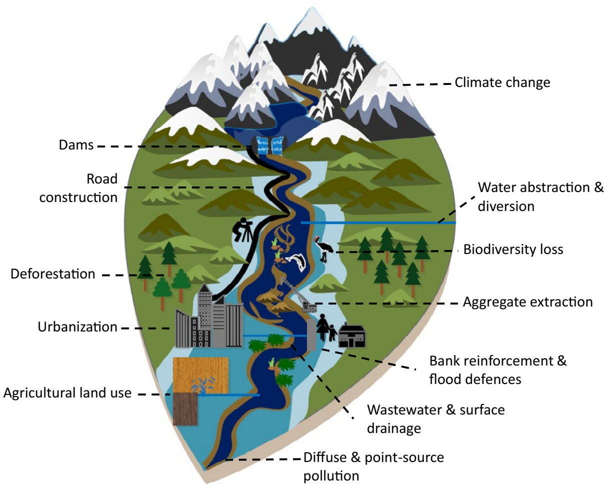


Fig. 5 Numerous human activities affect the land, water, and people within the LRI, but their impacts may be spatially distant or delayed in time

groundwater levels in the surrounding landscape, which has important effects on soil moisture for crops and natural vegetation (Fig. 4c).

The zones of the LRI are not exclusive; they overlap and influence one another (Fig. 4). The presence, size, and location of each zone are dependent on numerous factors, such as climate, valley form, geology, and surface topography, and, thus, vary between and along with river systems (Fig. 5). The LRI zone in the confined valley of a headwater mountainous stream will be narrower than in the wide alluvial floodplains further down the catchment. Equally, the location and width of LRI zones will change over time due to hydrological, geomorphic, and ecological processes. However, through an understanding of the river-related processes and the hierarchy of drivers that affect them, the zones help us to evaluate how a specific location within the LRI may be affected directly or indirectly by development activity.

How does development impact the environment and people in the LRI?

A barrier to greater acceptance and incorporation of river science into assessment and management in support of sustainable development is the paucity of evidence to determine causal linkages between multiple pressures, processes, and impacts. Development is not consistent with the scientific method of changing one variable at a time. The river basin, valley, and reach scale drivers of river-related hydrological, geomorphic, and ecological processes in the LRI are affected by the full suite of human activities related to development, including climate change, deforestation, intensive agriculture, water abstraction and diversion, and pollution (Fig. 5). Thus, the mechanisms and timescales by which river processes propagate the impacts of development on the environment and people only become apparent through a comprehensive and interdisciplinary review. By amassing and interpreting scientific evidence on the hydrological, geomorphic, and ecological impacts of three common development-related activities (urbanization, valley-spanning dams, and aggregate extraction), which occur at different locations and scales in the landscape, we identify these causal linkages and provide a more complete foundation on which to assess, predict, and avoid development impacts in the LRI.

Urbanization

Between 2018 and 2050, an estimated additional 2.5 billion people will be living in urban areas, with the greatest growth predicted in Asia and Africa (United Nations 2019). Urbanization is occurring within the LRI and more widely in river basins and, thus, causes significant direct and indirect changes to the LRI.

Impacts of urbanization on river processes in the LRI

Urbanization within the LRI has direct impacts on local river-floodplain form and processes (Fig. 6). Where the urban fabric encroaches onto floodplains and in proximity to rivers, engineered interventions are required to minimize risk to people and property and maximize the use of space for buildings, roads, and parks. Riverbanks are reinforced and flood defenses built, disconnecting the river from the landscape. The impacts are a reduction in the lateral extent of channel mobility (i.e. erodible corridor, Piégay et al. 2005) and local flood storage, often referred to as 'freedom space' (Biron et al. 2014; Buffin-Bélanger et al. 2015). High reinforced embankments and levees increase the channel capacity (i.e. deeper bankfull channel). While local risks are reduced, the greater discharges that the river carries increases river depth and bed shear stress (Vietz et al. 2016), resulting in the loss of sediment-associated river habitats and incision of the riverbed. Local incision can perpetuate upstream, in a process called knickpoint retreat or knickpoint migration, thus extending the impacts to river systems upstream. The likelihood of knickpoint formation is dependent on the material properties of the bed and the river hydraulics (Bressan et al. 2014; Papanicolaou et al. 2019). While this phenomenon is widely reported from past land cover change and there is coverage in the press about river-related infrastructure failure in cities (e.g. bridge pier scour), more research is needed to document the occurrence and severity of incision in urbanizing areas.

Even when the urbanization does not directly impact the floodplain or river channel, the connected nature of river systems means that its indirect impacts can perpetuate over long distances (Booth et al. 2016; Vietz et al. 2016; Walsh et al. 2016). Urbanization in the river basin affects the landscape in a multitude of ways. Impervious surfaces and surface water drainage networks accentuate overland flow pathways and increase the flashiness of river systems, causing short return period peak discharges to increase in magnitude with urbanization. Early work on small catchments found that the 2-year flood discharge, i.e. the annual maximum daily discharge with a 50% change of recurrence, increases in magnitude by 2–5 times with urbanization (Hollis 1975). Similarly, increases in flood frequency in the rapidly urbanizing subcatchments of the Pearl Delta region of China (1990–2010) had a significant positive linear to changes in built-up land (positive) and a negative linear relationship to changes in forested land (Du et al. 2015). The degree of hydrological impact is determined by the proportion of impervious surfaces connected to streams via stormwater drainage systems [i.e. effective imperviousness (Vietz et al. 2016)] and the factors that naturally affect flow regimes, like climate and geology (Booth et al. 2016). Recent modelling work by Russell et al. (2020) provides evidence that this change in flow regime is sufficient to explain the widespread problems of channel incision and widening (2–3 times to 15 times wider; Chin 2006). The higher discharges and water levels increase the capacity of the river to transport the coarse sediment that composes the riverbed and banks (Russell et al. 2020).

Impacts of urbanization on people in the LRI

While the positive economic and social aspects of urbanization cannot be overlooked, the impact of urbanization in terms of environmental processes (hydrology, geomorphology and ecology) can cause feedbacks that increase risk and exacerbate existing social-economic inequalities. Urbanization can drive encroachment of both formal and informal settlements into the LRI, decreasing the extent of rivers and floodplains and increasing the river-related risks of (particularly) low-income earners in urban areas, further magnifying socio-economic inequality (e.g. Amoateng et al. 2018). More generally, rapid urbanization alters fundamentally the form of the LRI and the connectivity between the land and river, which negatively impacts access, use, and perceptions of rivers by people (Dempsey et al. 2018).

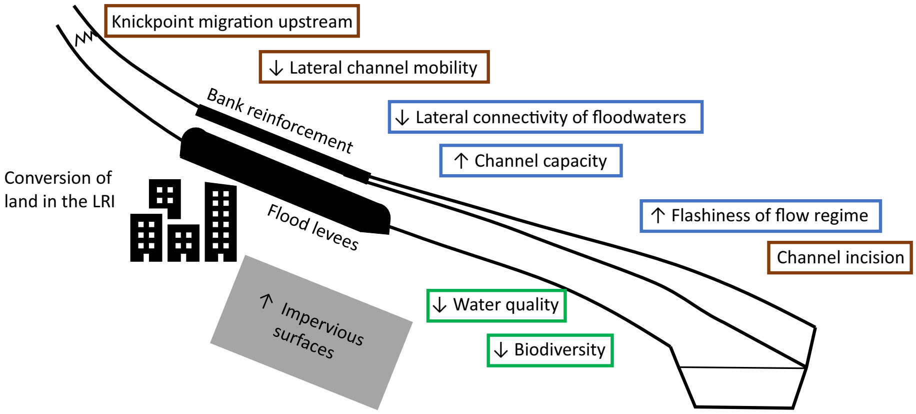


Fig. 6 Urbanization alters the land and rivers causing hydrological (blue), geomorphic (brown), and ecological (green) impacts on the land–river interface

Urbanization impacts on hydrological or geomorphic processes can affect people downstream in the LRI. For example, upstream development can increase sediment loads, alter flow regimes, and narrow the river channel, leading to increased downstream urban flood frequency. If the response is the construction of local flood defences, rather than addressing the upstream causes of altered river processes, local LRI inhabitants of the surface water connected zone, often in low-income settlements, may be evicted (e.g. Batubara et al. 2018). Furthermore, channel incision and narrowing, commonly reported as downstream impacts of urbanization (Vietz et al. 2016), have been shown to undermine river-related engineering infrastructure (i.e. scouring of bridge piers) and, through the lowering of the water table, the survival and succession of vegetation in the soil moisture zone. However, direct causal relationships between these geomorphic changes and socio-economic descriptors are difficult to define due to the confounding effects of dam construction, aggregate mining, and other human activity (e.g. channel realignment, flood levees), plus the interactions and dependencies with other factors, such as water quality, river ecology and fish stocks (Roy et al. 2016; Walsh et al. 2016).

Dams

Humans have been altering the flow of rivers through the construction of dams and other impoundment structures for millennia. Dams are constructed for many purposes, such as flood risk reduction, water storage and supply for consumption and irrigation, enabling navigation, and power generation (Beck et al. 2012). They come in many forms depending on the landscape setting and their purpose. In general, there are two main types: (i) channel-spanning and (ii) valley-spanning. Channel-spanning dams are relatively small structures placed across the channel itself, primarily for providing power to mills and surface water abstraction points (Csiki and Rhoads 2010). They have small storage reservoirs, limited mechanisms to control discharge, and often overtop at high discharges. Terminology varies, for instance channel-spanning dams may be referred to as weirs or 'run-of river', 'low head', or 'overflow' dams, though these latter terms are less precise and are also used for other types of dams. Valley-spanning dams create large reservoirs, from which downstream discharge is controlled. They are typically built for hydropower, flood control, and water supply. Diversion schemes for hydropower and irrigation may use either a channel- or valley-spanning dam to maintain levels and redirect flow through pipes or canals. While there are important impacts of channel-spanning dams (Csiki and Rhoads 2010), this section will focus on valley-spanning dams because of their increasing number (Zarfl et al. 2015) and the greater impact they have on the LRI. Valley-spanning dams are also illustrative of development activities that directly affect both the land and river in the LRI (i.e. valley scale).

Impacts of dams on river processes in the LRI

Valley-spanning dams alter the form and functioning of river systems greatly with significant impacts felt throughout the LRI (Fig. 7). The physical barrier that a dam presents, and its control of downstream discharge, causes significant changes to water levels, flow regimes, sediment regimes, and channel form that can affect ecological communities and people, upstream and downstream of the dam (Richter et al. 2010; Beck et al. 2012).

Upstream of a dam, the LRI is transformed due to the inundation of the valley as the reservoir fills. This hydrological impact of dams is the most obvious and widely reported, as it materializes over a relatively short time period (i.e. over a period of months to several years). The flowing river

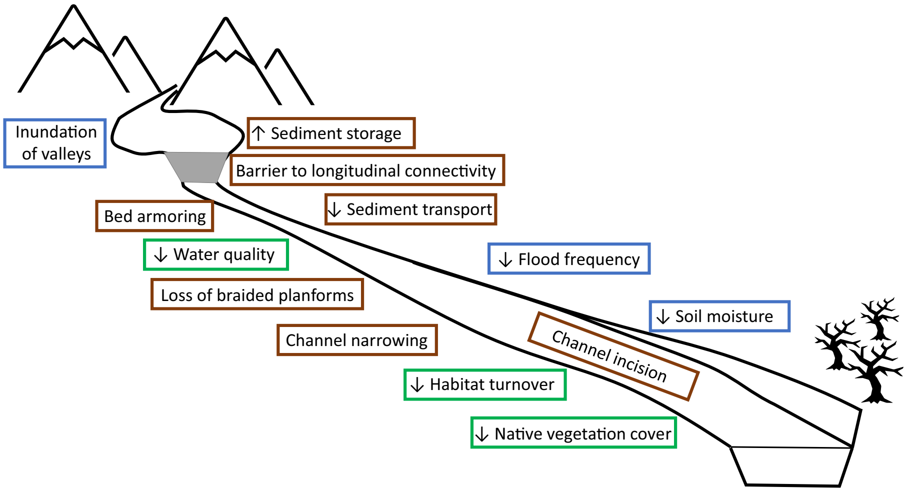


Fig. 7 Valley-spanning dams alter flow regimes and disrupt sediment transport causing hydrological (blue), geomorphic (brown), and ecological (green) impacts on the land–river interface

is replaced by a lake, which changes fundamentally the aquatic and riparian ecological communities. As dams are often placed in the upper catchment (i.e. headwaters), which is a geomorphic area of net sediment erosion and transport downstream, the reservoirs act as a sink for the coarse and fine sediment delivered to the river upstream (Petts and Gurnell 2005). The trap efficiency of the dam depends on the size and shape of the reservoir, the amount and grain size of sediment being transported by the river, and the flow regime. A new, large dam will trap virtually all sediment (Fig. 8). Over time, though, a sediment wedge forms at the upstream end, which builds and extends (i.e. progrades) downstream towards the dam, akin to delta formation (Csiki and Rhoads 2010; Juracek 2015). As reservoir volumes are reduced, water flow and turbulence may keep fine sediment in suspension long enough, or it is resuspended from the bed (i.e. bottom set) in turbidity currents, to be transported over the dam spillway. Once coarse sediment aggrades to the level of the dam spillway, it can pass unhindered downstream. While the trapping capability of mega-dams is obvious, even low-head, valley-spanning dams can trap considerable sediment and fundamentally alter the landscape form and river functioning long after the structures have degraded or been removed (Walter and Merritts 2008).

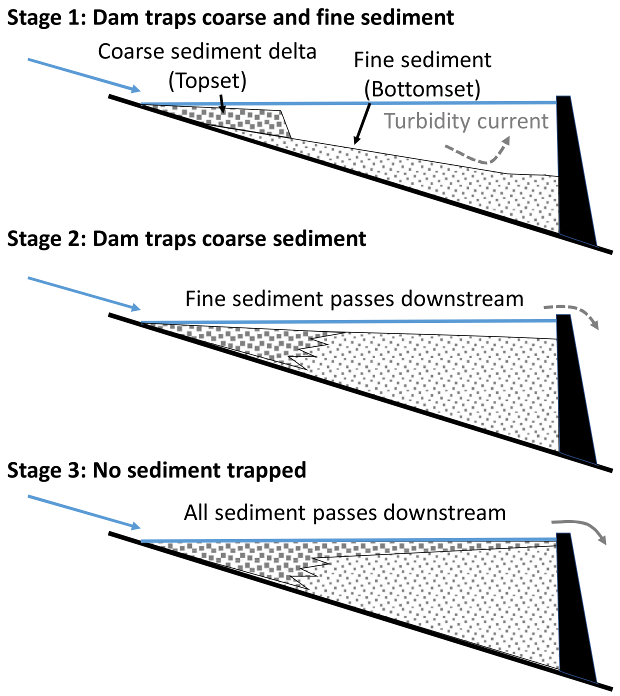


Fig. 8 The impacts of a dam on sediment transport are dependent on reservoir size, sediment regime, and dam stage. (1) Sediment is trapped continuously in a deltaic deposit, though turbidity currents may resuspend fine sediment. (2) A channel and floodplain form in the reservoir, only coarse material is trapped. (3) Coarse sediment accumulated on the dam crest. No impediment to sediment transport (modified from Csiki and Rhoads 2010; Juracek 2015)

Dams have significant downstream impacts that, through geomorphic processes, can extend over great distances and operate over long timescales. These impacts are determined by the changes to the flow and sediment regimes caused by the dam within the geological context of the river reach (Brandt 2000; Grant et al. 2013). In general, flood control and water supply dams will reduce the frequency and magnitude of peak annual discharge, which is a key driver of geomorphic change (Fig. 9a) (Richter and Thomas 2007). Due to the seasonal nature of rainfall, this storage and/or diversion of water shifts the seasonality of discharges, reducing average daily discharges in wet periods but increasing baseflow in dry periods (Fig. 9b). If the dam produces electricity through short duration releases (i.e. hydropeaking), this can also cause unnaturally high discharges for a period of hours (Fig. 9c). Short duration, high discharge dam releases, though, can form part of the naturalization of flow regimes to reduce negative downstream impacts on channel geomorphology and ecology (Poff et al. 1997).

The trapping of bedload sediment by the dam results in artificially lowered sediment loads downstream (i.e. sediment starvation). This loss of sediment input combined with the reduction in peak flows typically causes a narrowing of river channels below dams. This effect is most pronounced in multithread river reaches, such as high-energy braided rivers (Nelson et al. 2013; Vercruysse and Grabowski 2021). Bed incision or armoring may accompany channel narrowing; the clear water discharged by a dam has excess energy (not expended during sediment transport) which is exerted on the riverbed and banks, scouring away the fine sediment fractions and/or the erodible bedrock. Channel bed aggradation or channel widening can also occur if sediment is generated during the construction phase or channel banks are less resistant to erosion than the riverbed, respectively (Brandt 2000; Petts and Gurnell 2005; Grant et al. 2013). Impacts on channel cross-section form and bed level can extend for 10s of kilometers or more downstream (Vercruysse and Grabowski 2021). Researchers predict that the impact of dams in the Mekong River, the 10th longest river in the world, will decrease floodplain sedimentation by 40% and delta sedimentation by 90%, leading to concerns about increased subsidence and saltwater intrusion (Van Manh et al. 2015; Kondolf et al. 2018).

The downstream hydrological and geomorphic impacts of dams affect natural riparian and floodplain vegetation. The decrease in annual peak flows reduces the geomorphic activity of the river, decreasing channel migration and adjustment, topographic change, and habitat turnover, which results in a loss of physical habitat and natural vegetation diversity over time in the channel, riparian zone and floodplain. This effect is most pronounced in active rivers in drier climates (Ibisate et al. 2013; Aguiar et al. 2016; Bejarano et al. 2018). Changes to the channel dimensions and bed

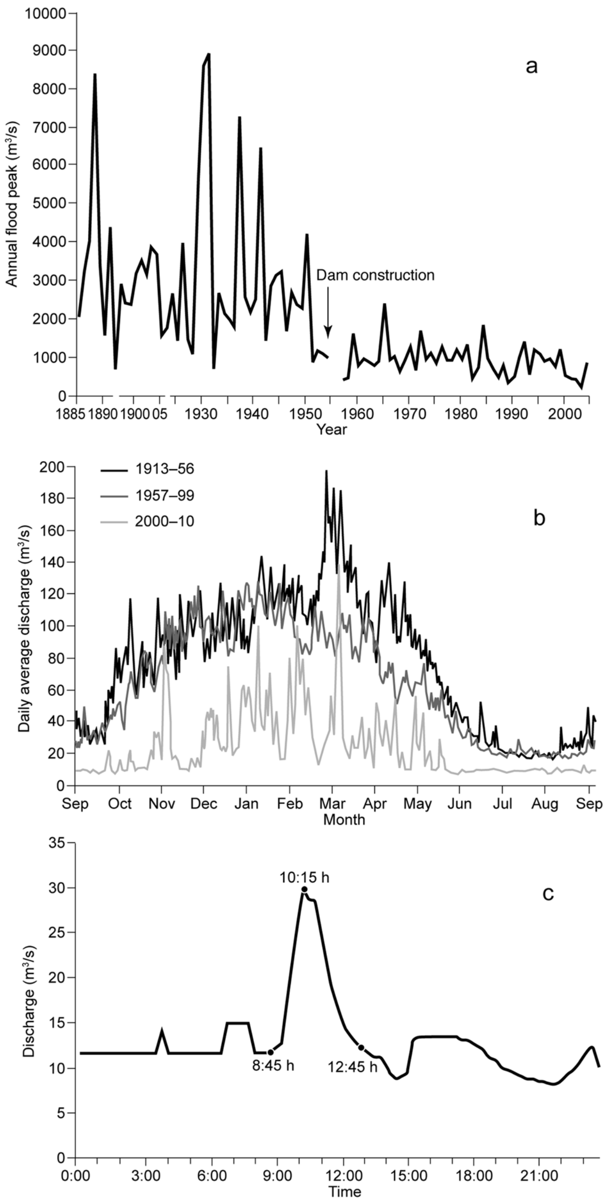


Fig. 9 **a** The impact of dam construction on annual flood peak in the Savanah River, Georgia, USA (Richter and Thomas 2007). Dam construction between 1959 and 2004 on the Aragon River, Spain, **b** altered seasonal patterns in daily discharge and **c** daily discharge due to releases from hydropower dams (Ibisate et al. 2013). The multi-panel figure was modified from the original and reproduced with permission from Grabowski et al. (2014)

level also affect vegetation communities through impacts on groundwater levels, soil moisture and flooding. A reduction or cessation of overbank flooding limits the spatial extent of the recruitment of plant propagules that are transported by river flows (i.e. hydrochory) (Braatne et al. 2007). Less overbank flooding and lowered water levels in the channel cause a decrease in soil moisture that affects plant survival in the soil moisture zone of the LRI (Dott et al. 2016). In combination, these impacts result in a decrease in the cover of floodplain specialist plant species, which can facilitate the establishment and spread of invasive and non-native species (Braatne et al. 2007; Dott et al. 2016). Modelling work has shown that channel incision of only 1 m can lower groundwater levels and soil moisture up to 100 m away from the channel with impacts felt all year but most pronounced during dry spells (Loheide and Booth 2011).

Impacts of dams on people in the LRI

Dams can bring substantial benefits to development. Through their direct interaction with water flow, they provide flood protection, renewable energy and water supply, and help to reduce river-related risks to property, agriculture and infrastructure. Consequently, dams enable the expansion of settlements and the establishment of intensive farming in the geomorphic active and surface water-connected zones of the LRI. However, there are numerous negative impacts of dams. Upstream of the dam, the displacement of people, loss of farmland, inundation of cultural and historical sites, and disconnection of communities has an almost immediate social impact (Beck et al. 2012). Downstream of the dam, social and economic impacts may be equally significant but often take longer to materialize, depending on the river processes involved (Richter et al. 2010). Resources affected by biological and ecological processes, such as fisheries, will respond quickly to the changes in water quality (e.g. temperature, dissolved oxygen) and the flow regime downstream of the dam, compounded by changes in channel dimensions, bed substrate and connectivity with the floodplain (Richter et al. 2010; Beck et al. 2012; Liermann et al. 2012). Next, changes to the flow regime will impact natural vegetation communities and the resources they provide (e.g. timber, fuel, food) and traditional agricultural practices, like flood-recession farming (Richter et al. 2010). These vegetation and land cover changes have knock-on effects on other ecosystem services, such as pollination (Santos et al. 2018). The densification of human settlements in the floodplain exposes a greater number of people to the residual risk of flooding (large but infrequent flood events do still occur). Geomorphic impacts often take the longest to emerge. For example, incision downstream of dams in China created terraces that have been opportunistically used for settlements and agriculture for migrating populations (Guo et al. 2015). However, these landforms are unstable and have been prone to subsidence and mass wasting by the river, exposing people to significant natural hazards. Similarly, though much more distant from the dams themselves, the predicted subsidence of deltas, such as the Mekong, due to decreased sediment loads downstream of the dams, threatens millions of people living in towns and cities in the delta and, additionally, those who depend on its agricultural and fisheries products (Kondolf et al. 2018).

Aggregate mining

Sand and gravel are the most mined minerals in the world by volume, with an estimated 32–50 billion tons extracted annually (Peduzzi 2014; Koehnken 2018). Commonly known as aggregate, they are the main component of concrete and asphalt and are required for land reclamation and the building of road embankments and levees. Extraction of aggregates from floodplains and river channels is common practice, as: (i) rivers are found throughout the landscape passing conveniently near development areas, (ii) river sediment is less rounded than sediment from coastal areas or deserts, and thus better suited for engineering purposes, and (iii) the river has already done the work of grading the sediment, making it easier to process. With rapid population growth and urbanization in many countries, the potential scale of aggregate extraction from rivers and its environmental and social impacts are becoming apparent (Torres et al. 2017; Koehnken 2018; Koehnken et al. 2020; Schwartz et al. 2021). In this section, we summarize how the altering of river form and processes by aggregate mining impacts the environment and people in the LRI.

Impacts of aggregate mining on river processes in the LRI

Aggregate mining changes the form of the LRI locally and interrupts sediment transport downstream (Fig. 10). In combination, these changes can propagate impacts downstream, upstream and laterally. Exactly how this operates in a river is difficult to predict, but is related to the type of mining, volumes of sediment extracted, the sediment load of the river, and the local reach context (e.g. superficial and bedrock geology).

Aggregate mining can occur in three distinct locations: the floodplain (LRI surface water connected zone), exposed bars during low flow (LRI geomorphic active zone), and the active channel (LRI hydraulic active zone) (Singh et al. 2016). Floodplain mining has a pronounced impact on the topography of the LRI, with the creation of pits in former courses of the river. However, downstream consequences due to the loss of sediment in the system (akin to the sediment starvation effect of dams) are reduced or delayed because the floodplain is a longer-term store. Yet, if floodplain mining occurs near the active channel or, more generally, in the erodible corridor, bank erosion or channel avulsions can connect them to the river creating locally widened reaches (Kondolf 1994). In-stream pit mining and bar skimming at low water levels have a more pronounced impact on local reach dimensions, creating substantially wider channels until upstream inputs of sediment replenish bars. Depending on the energy of the river system and sediment loads, these local impacts may persist for years or decades (Dépret et al. 2021; Vercruysse and Grabowski 2021). The local impacts of in-channel aggregate extraction are more challenging to observe and ascribe specifically to mining. The method is typically practiced on large sand bed rivers by numerous actors operating at a variety of scales. In rivers like the Mekong, in-channel mining for sand occurs over most of its length, and any impacts on river levels or channel is complicated by the effects of dam and river stabilization and engineering (Bravard et al. 2013). However, recent research confirms that in-channel mining has a pronounced impact on local riverbed levels, which is sufficient to trigger bank erosion and river widening (Hackney et al. 2020).

The impacts of aggregate mining propagate along the river channel and laterally into other zones of the LRI primarily through its impacts on river form, bed level, and water level. Channel incision is the most reported impact of aggregate mining. Studies have documented drops in the level of riverbeds, ranging from 0.2 m (Scott et al. 1999) to 30 m (Huang et al. 2014), with numerous examples of 2–5 m of incision recorded from rivers in temperate regions (Kondolf 1994; Rinaldi and Simon 1998; Surian and Rinaldi 2002). However, in many of these studies, other confounding interventions were implicated, such as upstream sediment controls, dams, channelization and the construction of flood levees and bridges. In the most extreme cases of incision (average—8 m; maximum—30 m), a highly erodible geology and a large flood event (typhoons) are implicated (Huang et al. 2014). Channel narrowing or widening can occur depending on the type of mining (explained above) and the relative erodibility of the riverbanks (i.e. surficial geology) vs. the riverbed and underlying geology (Surian and Rinaldi 2002; Hackney et al. 2020; Koehnken et al. 2020). Similarly, propagation of incision upstream (knickpoint retreat) depends on the severity of the local impact, the flow regime and the relative erodibility of the bank and bed. Knickpoint retreat has been observed to extend up to 10s of kilometers upstream of the main river and into tributaries (Kondolf 1997).

Changes to channel geomorphology and bed levels can strongly affect plant communities in all zones of the LRI, as introduced previously when discussing dam impacts. In a controlled field study, Scott et al. (1999) documented significant impacts of aggregate mining on groundwater levels and the riparian forest following bar skimming and pit mining within the active channel of an ephemeral river. The lowering of the riverbed by 0.5–2 m caused a similar drop in water levels, which placed the mature cottonwood forest (*Populus deltoides* subsp. *monilifera*) under water stress. Over the next three years, the scientists observed extensive tree mortality (88% mortality). More widespread impacts associated with incision have also been reported. Stella et al. (2013) found

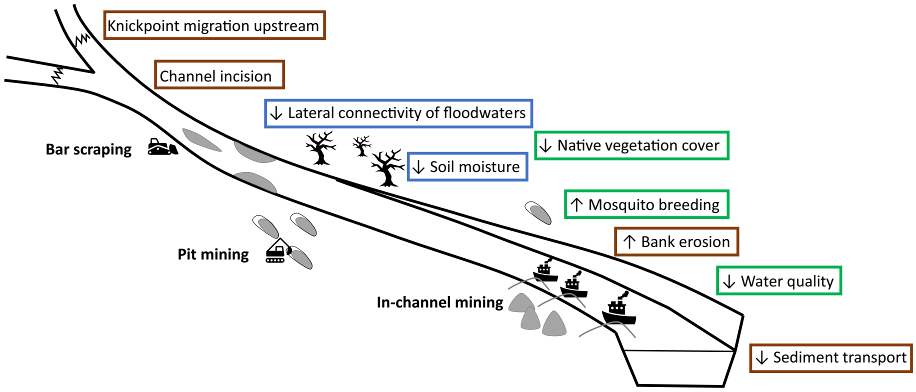


Fig. 10 Mining of sand and gravel (i.e. aggregate) causes hydrological (blue), geomorphic (brown), and ecological (green) impacts in the land–river interface

that basal growth rates of a riparian tree species (*Populus nigra*) declined over time at sites that experienced channel incision caused by aggregate mining at other locations. In both examples, it is the lowering of the water table and decreases in soil moisture that places the vegetation under stress in periods of droughts. Interactions, though, are complex and often site-specific; a recent review noted examples where channel narrowing and stabilization led to increases in riparian forest cover and higher diversities due to the presence of pioneer species (Koehnken et al. 2020).

Impacts of aggregate mining on people in the LRI

The impacts of environmental changes on people due to aggregate mining are similar to those observed for urbanization and dams. The removal of aggregate from the river system starves downstream river sections of sediment, which leads to geomorphic changes (e.g. channel incision or widening). Along the Mekong River, riverbank erosion causes damage to homes (Ahmed et al. 2020), and is predicted to increase in frequency and scale with continued in-channel mining (Hackney et al. 2020). Along with dams, aggregate mining is a significant contributing factor to the decreased sediment loads being delivered to the delta which is threatened by subsidence and sea-level rise from climate change imperiling the lives and livelihoods of millions of people (Kondolf et al. 2018; Park et al. 2020). There are local impacts of sand mining on human health and safety. Pit mines in the floodplain or active channel retain water and can create ideal suitable habitats for water-born vectors or disease, e.g. malaria. Still water collecting in sand mining pits along the Rudan River (Iran) was identified as the most common habitat for larval *Anopheles* sp., the genus of mosquito that transmits malaria (Soleimani-Ahmadi et al. 2013). More generally, there are many examples of direct and indirect negative consequences of poorly regulated (or unregulated) and often illicit mining from the LRI on people, in terms of health, violence, criminality and socio-political tension (Torres et al. 2017; Schwartz et al. 2021).

Discussion

The concept of the LRI integrates our scientific understanding of environmental processes to explain how the impacts of human activities propagate through the landscape via rivers. In this discussion, we (i) revisit the lessons learned from the examples of development impacts that (ii) underscore the reasoning behind the LRI concept, and (iii) explain how the LRI concept is compatible with integrated approaches to environmental assessment, management, and sustainable development.

The case studies highlighted three development-related activities (urbanization, valley-spanning dams, and aggregate mining), which occur at different locations and scales in the landscape. They emphasise four main points about river processes and their effects on the landscape. First, the environmental impacts of development may be local, but, crucially, they often extend far downstream and even upstream in the river network. These long-distance impacts are caused by alterations to the connectivity and flux of water and sediment in the river system and are often slow to materialize. For example, while upstream environmental impacts are quickly observed in the reservoir of a newly constructed dam, the significant changes to riverbed level and channel form caused by urbanization and aggregate mining, which propagate upstream to impact infrastructure stability and the alluvial water table, can travel up river networks over years to decades. Therefore, we must consider the possibility of long-distance impacts of development, which may, counterintuitively, be manifest upstream. Second, the impacts of development can extend far beyond the river channel into the terrestrial environment. Direct alterations to channel and valley form will alter flood inundation extent and frequency, affecting the flux and timing of water, sediment, carbon and ecological organisms in the landscape. However, it is the indirect pathway, via geomorphic processes, that is more challenging to predict and manage. Channel incision, which has been reported for all three examples of development activities, disconnects the river from the surface-water connected zone and, as the alluvial water table drops, narrows the soil-moisture zone, affecting natural vegetation, agriculture, and the accessibility of freshwater and groundwater for communities. Third, feedbacks between hydrological, geomorphic, and ecological processes will drive other impacts. For example, the loss of riparian forests due to the lowering of the water table with channel incision will make local geomorphic change more likely (due to decreased stability of the riverbanks) and affect form and river dynamics further downstream (due to the reduction in the delivery of large wood and changes in sediment supply and transport). Finally, humans in the LRI are being severely impacted by environmental changes induced by development. In some cases, the impact is a direct result of the hydrological, geomorphic or ecological change propagated by the river. In others, it is the reduction in the dynamism of the river that creates a sense of security to exploit new opportunities (e.g. utilising the surface water-connected zone for agriculture and settlement), which makes them susceptible to extreme events. In essence, development activity creates a false perception that the river has been tamed and no longer poses a threat to human lives or livelihood.

The catalogue of impacts on the environment and people reported from urbanization, dam construction, and aggregate mining highlights the pressing need for increased awareness of hydrological, geomorphic, and ecological processes in river systems in wider environmental assessment and management. In proposing the LRI concept, we acknowledged that numerous terms already exist to describe rivers and the surrounding landscape (Fig. 2). While the linkages between these landforms and river processes are well established in the scientific literature, there are surprising differences in interpretation. Even the most basic terms, like channel and floodplain, are used variably within scientific domains and more widely in management. For example, both the terms 'channel' and 'floodplain' are applied to the coarse sediment bed of a high-energy braided river that typically has multiple active and inactive sub-channels at low discharge. However, the term 'floodplain' does not convey the correct understanding of processes in this instance, as there is significant geomorphic activity in terms of bedload transport, erosion and deposition. In the LRI concept, the processes operating are evident in the overlap of hydraulic active, geomorphic active, surface water and groundwater connected zones. Similarly, in naturally functioning, low-energy rivers, the distinction between channel and floodplain can be difficult to discern, especially when there are numerous side channels and a variety of aquatic and wetland habitats with different degrees of connectivity to the main river. The dichotomy of river vs land, or even river vs. floodplain, overlooks the importance of other aquatic and wetland habitats and the processes that maintain them. In the LRI concept, the hydraulic and geomorphic processes in the river help to differentiate it from the surface water and soil moisture zones in the wider landscape. Thus, in proposing the LRI, our goal is to make a process-based understanding of river systems and their impacts on the land surface more widely accessible to policy makers, environmental and land managers, engineers, and stakeholder and community groups.

As the LRI and its zones are a synthesis of existing scientific knowledge on natural processes but applied to a constrained spatial extent to highlight how rivers impact the land surface, the concept slots easily into existing integrated environmental management approaches. Watershed, catchment and integrated water management approaches already aim to take a holistic view of the water in the landscape and its importance for the natural environment and people. When these approaches incorporate river-based and geomorphic frameworks (Brierly and Fryirs 2005; Kondolf et al. 2006; Fryirs and Brierley 2016; Gurnell et al. 2016), many of the processes outlined in the LRI concept are considered, but their aim is to understand the controls on river and floodplain processes and form. The LRI concept takes it one step further by explaining how river processes and geomorphic changes affect the wider landscape. Furthermore, a key addition to the LRI concept is the soil moisture zone, which emphasizes, yet further, a river's connections to the terrestrial environment. Alluvial groundwater levels and soil moisture are important for the sustainability of agriculture, forestry, and natural ecosystems, especially in arid climates and in the context of increasing frequency and severity of droughts. These dependencies strengthen the relevance of the LRI to other integrated resource management approaches, such as integrated water resource management and the water-food-energy nexus, which also consider interconnections between the land and water and the interdependencies in the resources they provide (McGrane et al. 2019; Salmoral et al. 2020).

In this paper, we have demonstrated several important ways by which river processes respond to development activity to profoundly impact the functioning of terrestrial ecosystems and the health, wellbeing and economic activity of communities that live alongside rivers (Richter et al. 2010; Beck et al. 2012; Kondolf et al. 2018; Park et al. 2020). We have also made the case for the LRI as a concept that helps to explain these process interactions and impacts, making them more widely accessible, so that the unintended and detrimental impacts of management and development can be minimized and synergistic benefits maximised. These ambitions align with the principles of sustainable development. In a companion article in this special issue, Vercruysse et al. (Inreview) develop further the connection between the LRI and the United Nations Sustainable Development Goals. Through a content analysis of the SDG framework, the authors reduce the complexity of the 17 SDGs and 169 targets to identify three broad management priorities (equitable access to resources, resilience to natural and social shocks, and resource efficiency) that would support the attainment of SDGs directly affected by river processes in the LRI. Then, they explain how key development activities (urbanization, dams, and aggregate mining; the same examples used in this paper) impact the priorities for sustainable development in the LRI. Future research should apply the LRI concept to specific case study catchments to evaluate how it can assist in the identification and appraisal of development and management options. We also encourage consideration of additional human dimensions to the LRI, be it the governance and institutional structure affecting management from the top-down, the social-economic factors affecting activities on the ground from the bottom-up, or the wider social and cultural factors that influence how, as a society, we view, interact with, and value the LRI (Azhoni et al. 2018). Finally, we recognize that no new concept is entirely complete when it is first proposed. There are numerous ways in which additional zones could be added to the LRI based on natural processes, such as a laterally extended ecological zone that considers fluvial inputs of resources and food web linkages (Richardson et al. 2010; Tonkin et al. 2016; Terui et al. 2017), or a biochemical zone related to the hyporheic zone and surface–groundwater interactions (Magliozzi et al. 2018; Lewandowski et al. 2019). We welcome further synthesis and development of the LRI concept to support an integrated environment and sustainable development.

Conclusion

Sustainable development must minimize unintended and detrimental environmental and social consequences. To do this, a deep understanding of natural processes and the mechanisms by which they are affected by human activities is needed. By identifying and describing a new geographical unit, the land–river interface, our aim is to highlight the important feedbacks and interactions between hydrological, geomorphic and ecological processes that drive these dynamic and responsive regions of our landscapes. Rivers and the surrounding land are central to development, but activities related to development (urbanization, dams and aggregate mining) generate significant impacts on the environment and people through river processes. These impacts may be direct or indirect, local or distant, upstream or downstream, in a channel or on land. They can be felt immediately or years to decades later. Only by taking a holistic perspective on land and water resources will we be best able to anticipate and mitigate potential negative impacts and maximize positive outcomes to deliver the benefits of sustainable development across society.

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