Geological evolution of the Mississippi River into the Anthropocene

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Abstract
The Mississippi River maintains commercial and societal networks of the USA along its >3700 km length. It has accumulated a fluvial sedimentary succession over 80 million years. Through the last 11,700 years of the Holocene Epoch, the wild river shaped the landscape, models of which have become classic in geological studies of ancient river strata. Studies of the river were led by the need to develop infrastructure and to search for hydrocarbons, through which, these models have become quite sophisticated. However, whilst the models demonstrate how the wild river behaves, a monumental shift in fundamental controls on the entire fluvial system, broadly coinciding with the proposed mid-20th century onset of the Anthropocene Epoch, has generated new geological patterns that are becoming globally ubiquitous, and which the Mississippi River typifies. As such, whilst classic Holocene river models may be compared to human-modified systems such as the Lower Mississippi River (and others worldwide), locally the models may now only directly apply to its fossilized components preserved in the sub-surface. Such river models need adapting to better understand the present dynamics, and future evolution of these landscapes.

Keywords
Anthropocene, geology, Holocene, human-impact, Mississippi River, models, sediment

Introduction
Rivers are vitally important geomorphic features in both the natural world, and societally, including for resources and transport, while their paths can provide political barriers delineating national...
borders (Gibling, 2018; Large et al., 2018). Controversially and reductively treated as an economic asset, the Mississippi River, and its delta, was once estimated to have a value exceeding $330 billion (Batker et al., 2010), hence indicating the tight productive relationship humans have established with the river and its surrounding landscape, which humans have increasingly impacted (Chamberlain et al., 2018; Syvitski and Kettner, 2011; Törnqvist et al., 2020). Understanding human impact on, for example, flooding, navigation and loss of agricultural land, required an understanding of the river’s natural form and processes, as outlined by Fisk (1944). Such processes can include rates of river bend migration, important to design river-crossing infrastructure, and deposition-controlled changes of topography of channel and floodplain, that can influence navigability and flood risks through reduced levee heights.

Deposits formed by active rivers the size of the Mississippi can be many tens of meters thick, and hundreds of kilometers across (Colombera et al., 2013). In a meandering river, the thread of water constantly changes shape across a wide floodplain. Sediments guide the path of the river, and the river shapes the sediments (Allen, 1965; Leopold and Wolman, 1957), whilst vegetation helps to define the river’s morphology (Davies and Gibling, 2013). Aerial photographs revealed the classic sinuous river behavior and were used to draft the celebrated maps of Fisk (1944) made for the Mississippi River Commission (LeBlanc, 1996). Fisk went on to become Chief of the Geologic Research Section at Humble Oil and Refining Company (later becoming Exxon) (LeBlanc, 1996) helping to foster the relationship between prospecting for hydrocarbons and developing a classical geological model based on studying the Mississippi River.

In this paper, we review the importance of the Mississippi River in contributing to models of river and delta deposition; briefly describe the geological history of the river, notably during the Quaternary glacial intervals and subsequent development in the post-glacial Holocene as sea-levels rose; address some of the key changes to the river system during the last ~70 years of the Anthropocene, notably disruption associated with dam construction, flood control engineering, agricultural and industrial pollution, and the radical changes to biota; and finally consider what future changes may impact the river system.

**The Mississippi River as a model**

Fisk’s maps (later revised: e.g. Saucier, 1994, 1996), promulgated the Mississippi River as a global archetype of a meandering river in the minds of many earth scientists (Allen, 1965; Jordan and Pryor, 1992; Miall, 1978), and the Mississippi Delta has been equally closely studied (Bentley et al., 2016).

Geological investigations reach into deep history, looking beyond the flowing body of water and considering the strata left behind (e.g. Collinson, 1996; Miall, 1978). They underpin studies of yet more ancient river deposits, where the river itself has long disappeared (Davies and Gibling, 2013). The power of such models has become of economic importance, as over time, a river and its delta accumulate complex layers of porous and permeable sediment which, once deeply buried, may store oil and gas (e.g. Hubbard et al., 2011). Studies to better understand this phenomenon have been enormously important in helping to inform and enable fossil-fueled industrialization and agriculture, and consequently urban growth, and such studies continue to develop (Chamberlain et al., 2018; Nienhuis et al., 2020).

The present Mississippi River system, a veneer on an underlying sedimentary accumulation that reaches back ~100 million years (Blum and Pecha, 2014; Potter-McIntyre et al., 2018), is key to understanding current human impact and making future projections (Blum, 2019; Chamberlain et al., 2018; Rittenour et al., 2007). Before anthropogenic modification, the river system was a complex interconnected network of self-regulating dynamics. For example, coastal wetlands
provided habitats for wildlife and protection from storms (Costanza et al., 2014), whilst water and sediment that escaped the river during flood events fertilized and maintained the floodplains. As with any complex network, altering one component can trigger far-reaching secondary consequences, so as human demands on rivers have increased (Gibling, 2018), most acutely in the Anthropocene (post ~1950 CE), the form and function of rivers are being revolutionized as natural river mechanics interact with novel anthropogenic processes (e.g. Keown et al., 1986; Munoz et al., 2018; Syvitski and Milliman, 2007; Williams et al., 2014).

In the Mississippi and other rivers, anthropogenic impacts affect the entire geological framework, with geologically long-term consequences. Hydrocarbon extraction, which in the Lower Mississippi basin mainly takes place in the most downstream deltaic sectors, affects the landscape through groundwater extraction, accelerated soil drainage, sediment starvation, loading, and local ground subsidence, as in many large coastal deltas across the planet (Syvitski and Kettner, 2011). Meanwhile, burning the extracted hydrocarbons drives global climate change, which drives sea level rise and flooding that threatens human communities, so we seek to engineer and stabilize the river in response (Twilley et al., 2016). Industrial pollutants change river chemistry (Meade and Moody, 2010), and extensive damming upstream retains sediment so that the river can no longer effectively build new land downstream (Chamberlain et al., 2018). Additionally, vegetation has been changing along the river since the times of Cahokian indigenous settlement (~600–1350 CE; Brugam and Munoz, 2018), leading to widespread loss of sediment from its drainage basin, changes to the morphology of the river, and introduced biota crowding out native wildlife; all such processes have subsequently accelerated due to the industrialization of farming during the Anthropocene (Knox, 2001).

The river and its surrounding ecosystem have been strikingly, visibly transformed, resulting in both obvious and cryptic consequences for the Mississippi sedimentary system (Blum, 2019; Chamberlain et al., 2018; Coastal Protection and Restoration Authority of Louisiana (CPRA), 2017). Consequently, the classic geological models for river strata that the Mississippi helped to build are no longer applicable along much of the river itself and need be revised so that human impacts are incorporated, and the future river environment is better understood. As in the Holocene, the Mississippi River provides inspiration for the next generation of river science in the Anthropocene. We consider its primordial nature as context for its anthropogenic transformation now and into the future, showing how humans have become critical agents of sedimentary processes.

**Geological background**

The Mississippi basin contains a dense converging network that drains 45% of the area of the contiguous USA. The main stem of the Mississippi River, from Lake Itasca, Minnesota (~200 km south of the Canadian border) to the Gulf of Mexico, is a formal human selection from the thousands of possibilities of the tips of this branching network; if the Missouri River had been selected it would have added a further 1900 km to the length. The Mississippi river system began to form when the Western Interior Seaway ceased to exist toward the end of the Cretaceous (from 80 Ma or so onward). The tributaries of the Mississippi River flow from diverse landscapes affected by varied weather patterns, and contributions to total river discharge are highly variable, with mean annual low- and high-water discharge from 1961 to 2004, ranging between 0.6 and 2.0 km$^3$/day with peak discharge past New Orleans regulated at 3 km$^3$/day by flood diversion schemes (Nittrouer et al., 2008). The 2011 flood event surpassed such limits with discharges in excess of 5 km$^3$/day at Vicksburg, Mississippi (Heitmuller et al., 2017). With the water comes sediment that, where and when deposited, preserves the river’s history (e.g. Aslan and Autin, 1999). The river and its
The early Mississippi River. In Early Cretaceous time, 125–110 million years ago (Figure 1), North American rivers drained mainly northwards toward the Boreal Sea, though some rivers also flowed southwards from the Appalachian Mountains into the Gulf of Mexico via the Paleo-Tennessee River (Blum and Pecha, 2014). By Late Cretaceous times, from ~100 million years ago, large-scale sediment ultimately terminate in the seventh largest delta in the world, >14,000 km² in area (Couvillion et al., 2011), while including delta lobes accumulated over the last 12,000 years takes this to ~30,000 km² (Coleman et al., 1998).

Prior to anthropogenically-driven change, the Mississippi River underwent many transformations (Blum et al., 2017; Lumsden et al., 2016). Many such changes occurred in “deep time” (Figure 1) and frame the impact of subsequent anthropogenically-driven change, including the arrival of indigenous peoples, subsequent European colonization, and changes into the future.
tectonic changes altered much drainage westwards into an interior sea, the Western Interior Sea-
way, located in the approximate position of the present-day Rocky Mountains, global sea level then
being 100–200 m higher than today (Miller et al., 2011). As the Rocky Mountains began to rise
during the Laramide orogeny 80–55 million years ago (English and Johnston, 2004), this interior
sea disappeared and drainage patterns reconfigured, flowing into the Gulf of Mexico at least by the
Maastrichtian Age of the Cretaceous (72–66 million years ago) (Potter-McIntyre et al., 2018).

By the end of the Cretaceous (66 million years ago; Figure 1), southwards-draining river basins
were many times larger than in the Early Cretaceous (Blum and Pecha, 2014). The Paleo-Mississippi
River initially formed a small part of this, but then grew to dominance by capturing the drainage of
other paleo-rivers such as the Paleo-Platte, Paleo-Arkansas, Paleo-Tennessee, and the Paleo-Red
rivers between 60 and 30 million years ago (Blum et al., 2017). Sediment brought by this huge new
river caused the Gulf coastline to build out some 200 km southwards, turning the marine realm into
land, and forming the foundation of the modern Mississippi Delta (Bentley et al., 2016; Galloway
et al., 2000). Global temperatures over that time were generally cooling from greenhouse warmth
and overall mean surface and atmospheric CO₂ was decreasing (Davis, 2017; Foster et al., 2017).

By the Mid Miocene climate optimum (~15 million years ago) and mid Piacenzian warm interval
of the Pliocene (~3 million years ago), the global mean surface temperature was still ~2°C–3°C
warmer and sea-level up to 22 m higher than today (Miller et al., 2012). With a warmer world ahead
of us, Pliocene and Miocene conditions help us consider what the future Mississippi River may
look like.

Relief maps show relic meander loops of the Pliocene Mississippi River, high on the sides of the
modern Mississippi valley in a deposit known as the Upland Complex (Cox et al., 2014; Lumsden
et al., 2016). The detailed course of the Pliocene river is uncertain and the total width of the
Pliocene floodplains cannot be determined as only discontinuous remnants are preserved. However,
the extent of mapped Pliocene gravel deposits shows it broadly followed the line of the existing
river (Cupples and Van Arsdale, 2014). Morphological analysis recognizes paleochannel widths of
1.8–4.8 km and paleomeanders up to 9 km in radius (Cox et al., 2014). This contrasts with the mod-
ern Lower Mississippi River with average bankfull channel widths of 1.2 km and meander bend
radii of 2.9 km (Cox et al., 2014). The Pliocene deposits are thought to have once been more exten-
tive than those of the Holocene Mississippi River, the Pliocene river being estimated to have had
a catchment of 5–7 million km² (Cox et al., 2014), twice the current watershed. Its deposits were
subsequently removed in northern Minnesota and Ontario by repeated Pleistocene glaciations
(Cupples and Van Arsdale, 2014). Comparisons of the size of the paleochannels and meander loops
with those seen today has resulted in estimated average discharges of 7–8 km³ of water per day,
some five times today’s volume (Cox et al., 2014), with consequently much more sediment. Despite
the observation of meander loops, the Pliocene Mississippi River is interpreted as overall a braided
(i.e. many-stranded) system that flowed broadly southwards, leaving pebble-dominated deposits in
the Upland Complex (Cox et al., 2014; Lumsden et al., 2016). It remains unclear if the higher water
volume was due to a wetter Pliocene climate (Cox et al., 2014), and/or because the Mississippi
drainage basin extended into Canada, and so collected more water (Lumsden et al., 2016); but one
needs recall the difficulties in comparing a past inferred record with present measured values.

In the late Neogene and Quaternary (Figure 1), ecosystems were substantially reshaped as the
North American and South American plates slowly collided, leading to The Great American Biotic
Interchange (Woodburne, 2010) with large-scale and rapid exchanges of numerous species between
the newly conjoined continents (Stigall, 2019). Therefore, not only was the hydrology and climate
shifting into an ice age across the continent, but the entire biotic interplay was being
reconfigured.
A time of ice. In North America, the Laurentide ice sheet dominated the hydrodynamic landscape during the Quaternary Period (that began 2.6 million years ago; see Figure 1), reaching as far south as Chicago (Fulton and Prest, 1987). At the last glacial maximum, land ice around the world held enough water to cause a sea level fall of 130 m (Austermann et al., 2013; Wickert et al., 2013), and in North America, the massive Laurentide ice sheet depressed the crust by at least 300 m (Fulton and Prest, 1987).

As the ice sheet advanced and retreated across the landscape, it intercepted, rerouted, and permanently modified river networks across the continent (Broecker et al., 1989; Fildani et al., 2018; Fulton and Prest, 1987; Wickert et al., 2013). For instance, ice lobes on the northern Mississippi River periodically rerouted parts of the meltwater to the Arctic and Atlantic oceans rather than the Gulf of Mexico (Kennett and Shackleton, 1975; Rittenour et al., 2007), and ~20,000 years ago, the Upper Mississippi River was diverted by the Lake Michigan ice lobe (Curry, 1998).

During the Quaternary the Laurentide ice sheet waxed and waned over 50 times in response to repeated glacial/interglacial cycles every 40,000 years from 2.7 to 0.8 Ma ago, with subsequent glacial cycles being more intense and longer-lasting, with brief interglacials every 100,000 years (Cohen and Gibbard, 2011). These climatic switches drove changes in ice sheet geometry, in the depression of the crust by the weight of ice,¹ and in the amount of water entering the river system (Blum and Törnqvist, 2000; Fulton and Prest, 1987; Peltier, 2004). The dynamic Mississippi River continually adjusted its morphology to the resulting large variations in the volume and velocity of water and in the amount of sediment (Rittenour et al., 2007; Wickert et al., 2013), which is linked to the alternating glacial and interglacial phases because each altered the hydrological regime, hence changing meltwater routing and development of meltwater drainage basins. Approaching the coast, the low gradient of the Lower Mississippi River made it sensitive to fluctuations in sea level (Shen et al., 2012), which in turn affected the shape of the river, its floodplain and the delta (Rittenour et al., 2007).

The Last Glacial Maximum—20,000 years ago was followed from 17,000 to 7000 years ago by the Laurentide ice sheet melting as climate ameliorated, the greatest ice volume loss occurring 15,000–12,000 years ago (Aharon, 2003). While the ice sheets retreated, the Mississippi River swelled with glacial meltwater and carried much coarse sediment, and so behaved as a multi-threaded braided river (Rittenour et al., 2007). In subsequent times of less meltwater, the river system equilibrated to the new conditions and formed a single meandering channel (Knox, 1996; Rittenour et al., 2007; Saucier, 1996). The sedimentary deposits of such periodical mode switches in fluvial regime now form a complex accumulation in the Lower Mississippi Valley (Fig. 7 in Rittenour et al., 2007), and on the Mississippi Delta (Fisk, 1944; Saucier, 1996), with offshore equivalents in the deposits of the Gulf of Mexico (Fildani et al., 2018; Kennett and Shackleton, 1975).

Meltwater release rate varied greatly, and ice-dammed lakes periodically burst to cause catastrophic, far-reaching flood events (Teller et al., 2002). One such lake, Glacial Lake Agassiz, lying along the retreating Laurentide ice-margin, was for many thousands of years the largest lake in North America (Fildani et al., 2018). Lake Agassiz released many outburst floods, of up to tens of thousands of cubic kilometers of water, many down the Mississippi River into the Gulf of Mexico (Aharon, 2003; Teller et al., 2002). The last five major meltwater superfloods directed to the Gulf of Mexico occurred between 16,000 and 9000 years ago as the ice retreated (Aharon, 2003). Three of these superfloods at 13.4, 12.6, and 11.9 ka had discharge rates up to some eight times the scale of the modern river (Aharon, 2003). These floods could be sustained for decades or even centuries (Bentley et al., 2016) as the giant lakes drained. One superflood toward the end of the Younger Dryas (~11,900 years ago) swelled the flow to ~13 km³ a day for an estimated 1000 years (Aharon, 2003), comfortably exceeding the flood peaks of modern times. These superfloods impacted
marine biota, sea level, and oceanography (Bard et al., 1990). And, whether released eastwards or into the Gulf of Mexico, could even stop ocean circulation by creating a low-density “lid” of fresh meltwater on the ocean that did not readily mix with the denser seawater below (Aharon, 2003; Broecker et al., 1989; Teller et al., 2002). Consequences included severe regional climate changes due to the disruption of the Atlantic Ocean current system by weakening the Gulf Stream that would normally bring warmth to NW Europe (Broecker et al., 1989; Teller et al., 2002).

In the aftermath of the ice, the Mississippi drainage system was permanently changed to its present familiar form (Fildani et al., 2018). Dozens of inland lakes formed on the newly irregular topography, some of which remain, such as the Great Lakes. At the beginning of the Holocene, the river’s morphology shifted from a dominantly braided pattern to a dominantly meandering one (Rittenour et al., 2007).

The Holocene Mississippi River system. The river that established in the post-glacial Holocene Epoch (from 11,700 years ago) became the framework for the morphologies and processes that we recognize today. The river delta, meanwhile, continued to develop as sea-levels rose from about 17,000 years ago to about 7500 years ago, by which time global sea-levels had risen by ~120 m (Clark et al., 2016). By about 9000 years ago typical Holocene grassland and woodland had become established, stabilizing landscapes in a warming climate (Knox, 1996), setting the scene for the natural river and delta prior to human intervention. By this time, superfloods via the Mississippi River ceased as a shrinking Laurentide ice sheet stopped supplying meltwater surges to the south (Aharon, 2003).

River channel. In the Holocene, the Mississippi River flowed toward the Gulf of Mexico, free to meander across the floodplain under its natural dynamics and so continuously changing shape as material was eroded and redeposited around its bends (Allen, 1965). On a meander bend, the river currents are faster where they flow against the outer bank, eroding it, and slower on the inside of the bend, where deposition of sediment takes place (Allen, 1965; Leopold and Wolman, 1957). Through this process, the channel constantly shifts its course and remolds the landscape in doing so. The movement of a meander bend through time is recorded as scars in the landscape known as scroll-bar deposits (Figure 2a), which may be beautifully seen on aerial photographs (Ielpi and Ghinassi, 2014; Thompson, 1986) or on the maps of the Mississippi floodplain by Fisk (1944).

A meander bend, as it constantly adjusts its shape, can become highly sinuous, its upstream and downstream limbs coming ever closer around a thinning meander neck (Toonen et al., 2012). During a flood event, fast-flowing waters can break through the thin meander neck, forming a new, shorter, path for the river (Güneralp and Marston, 2012). The old meander loop becomes abandoned. Cut off from the main channel, the old meander loop forms a characteristically curved “oxbow” lake (Allen, 1965) (Figure 2b). It can take thousands of years for an oxbow lake to slowly infill with sediment (Munoz et al., 2018; Toonen et al., 2012), so sediment in ancient oxbow lakes can contain treasure troves of fossilized leaves and pollen, animal skeletons and other remains, which are vital to reconstructing paleoenvironments.

Sediment deposition. Clues to the river’s history and former ecosystems are in the composition and thickness of sediment layers, along with the animal bones, plant debris, chemical traces and relics of human culture caught up among them. Rivers often leave a particularly complicated sedimentary record because their deposits are laterally discontinuous and internally split into channel fill, levee, overbank and lake deposits, which in turn, have complexities relating to proximity to the active channel (Allen, 1965; Miall, 1985, 2006). During deposition, natural river landscapes are constantly shaped by the flowing river, with interruptions in deposition and active scouring resulting in hiatuses,
so that by the time the geographic processes become geological residue, much of the story is missing and requires additional means of reconstruction (Durkin et al., 2017).

In a river such as the Mississippi, different parts of the sedimentary system reflect the energy exerted on them during their formation. Sediment deposited in, or close to, the active river channel, is commonly sandy and/or pebbly, whereas sediment deposited farther from the channel is commonly mud-rich (Allen, 1965; Miall, 1985). In the Holocene Mississippi River, water was usually confined to the channel, but escaped during flood events to form temporary muddy pools and lakes on the floodplain, such as in crevasse splays (Figure 2c). In the Lower Mississippi River Valley, the floodplain can exceed 100 km across, with a flood-prone area of >90,000 km² (Galloway, 2004). In extreme flood events, swathes of mud, and silt can be deposited tens of kilometers away from the river (Day et al., 2016). Although each flood does not deposit much sediment, as many floods occur over time, the thin, muddy layers accumulate to form large volumes of sediment that literally build the surrounding landscape (Miall, 1985; Munoz et al., 2018; Toonen et al., 2020).

During the Holocene, the river can intermittently accumulate channel-related sand bodies surrounded by floodplain muds (Allen, 1965; Jordan and Pryor, 1992; Miall, 1985). Sandy sediment is more porous and permeable than muddy sediment and so such fluvial sand bodies came to be recognized as hosting excellent petroleum reservoirs (Fielding and Crane, 1987; Tye, 2004). Yet, the great complexity of fluvial deposits requires extensive research such that their complex patterns may be well enough understood for efficient extraction of hydrocarbons (Tye, 2004), that is, for optimal siting of production and injection wells (Fielding and Crane, 1987). In the last half-century, this has been one of the main stimuli for scientific study of river-laid strata, the discoveries from which have been able to improve efficiency of solid mineral mining, improve understanding
of groundwater movement, and better understand the variability of fluvial sediment properties improving the safety of engineering structures.

**Delta.** Where the sediment reaches the sea, the Mississippi Delta is found. It is considered as the classic example of a “birdfoot” delta (Collinson, 1996) in which fluvial depositional forces dominate over tidal or wave forces, allowing the elongate fingers of individual distributaries to build out tens of kilometers into the Gulf of Mexico (Fisk, 1961). The delta plain we see on land comprises >12,000 km² of wetlands and the delta depositional body extends for >30,000 km² underwater (Roberts, 1997). During the Holocene, an average of 400 million tons of sediment a year have built up to ~100 m thickness of delta-sediment (Roberts, 1997). As the sediment accumulated, the active lobe would subside under its own weight, the space so created being filled by more sediment to maintain the delta plain’s elevation. However, the delta is inherently dynamic and undertakes lobe switching (i.e. relocates the primary point of deposition) every 1000–1500 years, in a natural cycle (Bentley et al., 2014; Roberts, 1997). Delta lobe switching occurs when the dominant distributive channel is no longer the least resistant path to the sea, so it will become abandoned as a new shorter, steeper route to the gulf develops, to become the new dominant river mouth lobe. Such avulsions (i.e. a switch in course), can occur abruptly during a single flood event, or gradually over decades or centuries with repeated floods (Bentley et al., 2014; Roberts, 1997). The main flow of the river will now take an entirely new route to the sea, whilst the abandoned lobe, becomes starved of sediment and eroded by wave action whilst subsiding under its own mass (Bentley et al., 2016), meanwhile, the new delta lobe becomes established. Delta lobe switching has caused Mississippi River sediment to be distributed along ~300 km of coastline (Coleman, 1988; Roberts, 1997). The rate of growth of the delta depends on sediment supply. During major floods of the past, the river water had the power to move more sediment downstream than today, and so the delta could grow faster. By the Late Holocene, sediment deposited by the delta was steadily creating 6–8 km² of new land per year at the (now abandoned) Lafourche Delta lobe (Chamberlain et al., 2018). The oldest of the Holocene delta lobes dates back to 7500 years ago and was located in the far west of the delta complex (Roberts, 1997). The currently active Balize lobe, upon which New Orleans is located, is the most recent of many distinct mouth location, which initiated about a thousand years ago, and currently covers an area of ~10,000 km² within the eastern part of the complex (Roberts, 1997).

As Mississippi Delta sediment accumulated over tens of millions of years, heat and pressure turned organic material into oil and gas, which rose through the water-saturated sediments until reaching a porous and permeable sand unit capped with an impermeable layer such as clay, forming hydrocarbon reservoirs. The subsurface is complex, rendered yet more so because the masses of river-derived sand are encased in muds so soft and plastic that the sheer weight of overlying sediment makes the sedimentary deposits deform, causing subsidence, slumping, and underwater landslides (Maloney et al., 2020). During the Anthropocene, these landslides pose hazards to oil and gas infrastructure that has increasingly developed in areas prone to such slope instabilities (Chaytor et al., 2020). There are many oil and gas reservoirs around the Mississippi River, on the delta, just offshore and increasingly developed on the slope in excess of 200 km offshore. The Mississippi Delta was identified by Galloway (1975) as the prime model of a fluvial-dominated delta in a ternary diagram of delta types that also included wave- and tide-dominated systems. For geologists seeking hydrocarbons in similar settings worldwide, the Mississippi Delta provides a key model. It is the extraction of resources, such as hydrocarbons, that has contributed to the changes now transforming the Mississippi in the Anthropocene.
The anthropogenically influenced Mississippi system

Around the world, more sediment is now moved by humans than by natural processes (Cooper et al., 2018; Syvitski et al., 2020), so humans have therefore become a critical element of how river sedimentary systems function. Anthropogenic change to river systems has a long history, though the rate of change has accelerated since the Industrial Revolution (Gibling, 2018; Williams et al., 2014) and markedly so since the mid-20th century (Syvitski et al., 2020). Stresses on the Mississippi system have increased, and this section reviews the drivers and effects of some of the principal stresses. Historically, priority has been to maximize the system’s efficiency to help grow the economy through, for example, water and food supply, river transportation, mineral extraction, storm protection, and waste treatment (Batker et al., 2010). However, anthropogenic intervention over the last 70 years or so has crossed a tipping point into what might be termed an Anthropocene Delta social-ecological system state (see Renaud et al., 2013) and has fundamentally changed the Mississippi River to the extent that the very models of sedimentological processes that the Mississippi River helped develop are no longer applicable along much of its course.

Before large dams became widespread in the early 1950s, the sediment load and content of the Mississippi River is commonly considered to have been “natural,” though humans have been altering it since Cahokian times (Knox, 2006; Pompeani et al., 2019), with European impacts evident to some extent since the early 1800s (e.g. Kesel et al., 1992). The Mississippi system was initially locally influenced by indigenous North Americans through patchy deforestation and agriculture (e.g. Brugam and Munoz, 2018; Scharf, 2010; Smith, 2009), evident as shifts in nutrient inputs and biotic assemblages preserved in lake sediments. Such changes were greatly accelerated by early European settlers through deforestation, agriculture, mining, and urbanization, resulting in enhanced regional-scale nutrient loading and an increased diversity of pollutants (Gibling, 2018). By the mid-19th century, this river system was already significantly altered, with the start of drainage of wetlands and development of artificial levees, though it flowed more freely than today (Vörösmarty et al., 2004, Figure 2; Syvitski and Kettner, 2011, Figure 3). In the mid-19th century, sediment was being carried to both the Lafourche and Balize delta lobes. Whilst scientific measurements of sand and (mostly) mud volumes were not as accurate as today, they suggest that, at the start of the Anthropocene (~1950 CE), the river carried some 460 million metric tons of sediment annually to build the Mississippi Delta. From 1970 to 2013, this had fallen to about 130 million tons per year, largely due to the increase in dams (Bentley et al., 2016), causing a decline in delta growth (Maloney et al., 2018). Humans have been building levees since the 1700s (Blum, 2019), and engineers have encouraged extensive straightening of the main river channel through creating artificial meander cutoffs, so that cargo ships, water, and sediment have a shorter, more efficient route. Overall, the river channel is now much shorter, as some 243 km were removed from the Lower Mississippi River between 1929 and 1945, resulting in an expected increased gradient that has been associated with the development of mid-channel bars, but the anticipated increase in grain size is not seen (Smith and Winkley, 1996).

One obvious anthropogenic change is global warming-driven sea level rise, which is already particularly impactful for the Mississippi Delta as large areas of it are below, or only slightly above, sea level, and sinking (Glick et al., 2013; Hauer et al., 2016; Jankowski et al., 2017; Törnqvist et al., 2020; Turner et al., 2018). Sea level heights have varied throughout geological history, and the Mississippi Delta has experienced considerable sea-level rise in the past, for example during the late Pleistocene to early Holocene. Other anthropogenic activities such as mining, dam emplacement, increasing levee height, urban growth, land reclamation, dredging, farming, and hydrocarbon extraction are having a profound and novel impact on river and delta processes such as flooding, sediment distribution, and subsidence (Day Jw et al., 2007). They have established and
Figure 3. Schematic figure showing the various human interactions that can affect the function of the Mississippi River.
maintain change of unprecedented scale that now seems difficult to escape, driving a kind of landscape transformation new to geology, and that extends beyond the traditional models. Once again, the Mississippi River can provide the archetypal processes for a new fluvial sedimentary model: the anthropogenically influenced contemporary river (Figure 3).

The acceleration of anthropogenically-driven changes since the mid-20th century has been striking, even if we are only just beginning to grasp the nature, scale, and implications of this transformation. Key elements of a contemporary geological model of the Mississippi system may, though, be discerned, and include dams, river channel stability and floodplains, river contents, and the biota, as described below.

**Large-scale disruption (dams)**

Since 1900, dam construction has surged globally (Syvitski et al., 2005, 2020). There were few large dams within the Mississippi watershed in 1900 (Vörösmarty et al., 2004), while today there are more than 50,000 along the Mississippi River and its many tributaries (Syvitski and Milliman, 2007), built primarily to store water for hydroelectric energy, irrigation, and municipal water supply. However, dams only briefly stop the inexorable flow of water, and have only reduced water discharge slightly, from an estimated 580 km$^3$ of water per year pre-damming of the river system to 529 km$^3$ of water per year post-dam constructions (Vörösmarty et al., 2003).

Dams and their associated reservoirs have had a much greater impact on the river’s sediment load, trapping much of the sediment that would otherwise build up the floodplains downstream and ultimately construct the Mississippi Delta. Dam-trapped sediment is now rapidly building substantial Anthropocene deposits, and consequently the Mississippi Delta is now sediment-limited at about half the natural supply. In particular, large dams emplaced in the middle Missouri River in the early 1950s (Fort Randall, Gavins Point Dam, and Garrison Dam), reduced sediment input to the Mississippi River by about 75% by 1963 (Mize et al., 2018; Walling and Fang, 2003). Because of this, the Mississippi Delta’s growth is slowing (Chamberlain et al., 2018), and indeed its land area is shrinking as the delta subsides under its own mass. In 1956–2006, about 50 km$^2$ of delta plain was lost each year on average (Barras et al., 2008), accounting for about 80% of coastal land loss in the USA. The delta surface is also now on average about 0.6 m lower than at the start of the Anthropocene (Syvitski and Kettner, 2011), making it more vulnerable to submergence through sea-level rise. Remediation is not straightforward, as if the sediment load from these large dams was released, it would take approximately 100 years to take effect (Meade and Moody, 2010).

**Stability and floodplains**

Along the Lower Mississippi River between 1850 and 1927, more than a thousand levee breaks occurred that formed crevasse splay deposits (Figure 2), i.e. “natural safety valves”, which break through the levee and redirect water, and sediment out of the main channel, helping to prevent wider flooding (Davis, 1993). Historical crevasses in the levee were active for months, or years (Davis, 1993), with each resulting splay deposit being some 100–200 km$^2$ and up to 2 m thick (Day et al., 2016). Each of these deposits overlapped one another to form a continuous margin of sediment around the river (Blum, 2019), fulfilling a critical role in both forming and maintaining the surrounding landscape (Day et al., 2016). Natural crevasses and seasonal overbank flooding continue along unleveed floodplains of the Lower Mississippi River (Bentley and Magliolo, 2018). However, as individual crevasse events can devastate local communities (Davis, 1993), flood protection was built.
Construction of flood control levees began in 1718 after the French founded New Orleans (Colten, 2014), as initially small, disconnected, local efforts <1 m height. In the 1880s, the United States Government began to control and maintain the levees and, in response to large flood events, artificial levee height along the Lower Mississippi River was incrementally raised to 12 m by 1973 (Smith and Winkley, 1996). As a result, today’s Lower Mississippi River flows in a managed sinuous pattern set in concrete via revetments, walls, and artificial levees, and so can no longer freely meander. However, these tall flood protection levees mean that the Lower Mississippi River floodplain is now about 10% of its natural width (Hartfield, 2014, Figure 2). Sediment is no longer able to escape to the wider floodplain, which, together with the delta plain, is now almost totally disconnected from the river (Blum, 2019; Chamberlain et al., 2018). As a result, Louisiana’s extensive marshland, now lacking this freshwater supply, so is prone to saltwater intrusion and land subsidence (Nienhuis et al., 2020).

Today, floodwater is unable to naturally escape onto the floodplains (except during major floods exceeding the designed levee discharge levels), and so can attain higher flood heights and greater flow rates in the protected urban areas. Hence, positions of historic crevasses have been engineered into spillways that divert water and sediment from the Mississippi River (Davis, 1993; Day et al., 2012). For example, the Bonnet Carré Spillway near New Orleans, constructed in 1933, has since been opened 15 times, with flows of 3100–9000 m³ per second diverting freshwater and sediment directly into the saline Lake Pontchartrain (Day et al., 2012).

River sediment load and pollution

As the flux of sediment along the Mississippi River has decreased system-wide (see above), anthropogenically produced sediments and chemicals have increased. The array of human-generated materials evident in the river system has evolved to be uniquely diverse in geological time, these materials being carried and deposited together with the river sediment, having primary impacts on the sediment and secondary impacts on the biota.

A precursor to today’s anthropogenic pollution is the impact of mining of the Mississippi Valley Type lead-zinc ore deposits, first recognized along this river. Mine tailings along the riverbanks have been accumulating since lead mining started in the mid-1600s and became widespread in the mid-1800s in SW Wisconsin, NW Illinois and eastern Iowa (Heyl et al., 1959). In the 1840s, lead extraction peaked at about 27,000 metric tons per year and, as it declined, zinc became the main metal mined from the region, with 64,000 tons per year worked in the 1910s (Heyl et al., 1959); the last mine closed in 1979. The tailings from these workings still find their way into the river and accumulate in its sediment load therein. Despite starting as a localized point-source of contamination, bedload transportation ensures that it is dispersed down-river and although the concentrations may be diluted, the reach of the contamination within river-bottom sediments can be extensive and beyond direct remediation (unlike the original tailing sites). Lead and zinc have been shown to bioaccumulate in aquatic macro-invertebrates, with a direct relationship between sediment and water concentrations and the concentrations in organisms (Goodyear and McNeill, 1999), which may be a signature that could be observed in the fossil record of macro-invertebrates in the Mississippi River.

Anthropogenic materials that are increasingly common today includes an influx of microplastics, fly ash particles, glass microbeads, and novel chemicals (Zalasiewicz et al., 2019). Chemicals include persistent organic pollutants such as pesticides, pharmaceuticals, and triclosans (Kolpin et al., 2002). Quite how these materials travel through, and are successively buried and exhumed in, sedimentary deposits of the river system, eventually making their way to the sea, is still poorly understood (Wilkens et al., 2020). Many chemicals will not only dissolve in the water but also
clinging to sediment particles such as clays, whilst micro- and nano-sized plastics can be suspended in the water or adhere to soil particles (Keller et al., 2020). Chemicals can also transform and become locally concentrated en route, such as triclosans, which break down in the presence of water and UV light to form persistent, carcinogenic dioxins (Buth et al., 2010; Venkatesan et al., 2012) and can collect in lakes (Anger et al., 2013).

In the Mississippi River basin, agricultural pollution, especially from fertilizers and fertilizer-sourced microplastics (Mahon et al., 2017), is at a high level particularly where sourced from the Midwest farming states. The microplastic runoff problem is enhanced because the sewage sludge spread on to fields has not had microplastics removed, so these are inadvertently dispersed (Habib et al., 1998; Ng et al., 2018), while deterioration of plastic sheeting used around crops also contributes to microplastic run-off (Rillig, 2012). Farming pollutants, human sewage from urban areas, livestock wastes, and soil erosion all contribute to increased nitrogen, phosphorus and silicate entering the Mississippi River system. The ensuing nutrient enrichment feeds algal blooms that ultimately deplete river water oxygen content (Rabotyagov et al., 2014). A resulting “dead zone” extends westwards from the Mississippi Delta. Varying seasonally, it reached 22,700 km² (an area greater than that of Wales, UK) in summer 2017 and extended as far west as Texas (Rabalais and Turner, 2017).

**Biota of the river and floodplains**

The acceleration of international trade and recreational travel in the Anthropocene has facilitated rapid translocation of opportunistic organisms (neobiota) globally and between previously distinct ecosystems (Capinha et al., 2015; Seebens et al., 2017; van Kleunen et al., 2015). In the Mississippi River basin, the spatial and temporal patterns of anthropogenically-induced biotic introductions are shaping some of the most important, complex, and rapidly evolving characteristics of the region, and consequently the future paleontological record. Conversely, it is also important to note that species native to the Mississippi, such as the red swamp crayfish (*Procambarus clarkii*) have been introduced to other regions, becoming invasive in some ecologies (Oficialdegui et al., 2019).

Native species of the Mississippi River and Delta are being rapidly joined or replaced by a range of “neobiota”—non-native species ranging through microscopic organisms to macroscopic mollusks and fish. Many have become naturalized, forming self-sustaining populations (Blackburn et al., 2011) having originally been introduced intentionally, such as garlic mustard (*Alliaria petiolata*), first introduced to North America in the 1800s by European colonial settlers as a garden herb (Nuzzo, 1993). Others have been introduced unintentionally, such as the curly-leaf pondweed (*Potamogeton crispus*), accidentally translocated in shipments of fish for stocking (Stuckey, 1979) or on recreational boats (Cole et al., 2019).

Prolific, naturalized invaders in the Mississippi basin include the silver carp (*Hypophthalmichthys molitrix*), and bighead carp (*H. nobilis*). Native to Russia and China, these were imported into the USA in 1973 to control algal growth in fish farms. Silver carp escaped these hatcheries and now range through much of the Mississippi River system, across 20 states (Chick and Pegg, 2001). Bighead carp, released from Asian carp hatcheries when they closed in the 1970s, can grow larger than 45 kg and each day consume nearly 10 kg of plankton. Proliferating rapidly, they outcompete native fish species by stripping the water of the phytoplankton on which they depend (Egan, 2017). In some areas of the Mississippi basin, these carp invaders may now comprise more than 90% of the fish biomass (Egan, 2017), while the introduced northern snakehead (*Channa argus*) — a predator — also threatens native fish populations. Invasive mollusks, such as the zebra mussel (*Dreissena polymorpha*), are predicted to result in an extinction rate of 12% per decade for the 131 native
unionid mussel species in the Mississippi River (Ricciardi et al., 1998), while the invasive faucet snail (*Bithynia tentaculata*) also carries invasive parasites (Mastitsky et al., 2014).

Above the water, newly arrived plants such as the Eurasian water milfoil (*Myriophyllum spicatum*), native to much of Europe, Asia, and Africa, can form dense mats thick enough to make swimming or boating difficult (Jensen, 2010). The notorious water hyacinth (*Pontederia crassipes*) (Wolverton and McDonald, 1979) was introduced into Louisiana’s rivers from South America in 1884 (Julien, 2001) to become established throughout the Mississippi River and Delta. By forming floating “islands,” these taxa can impact the functioning of local ecologies as well as having high socioeconomic costs (Villamagna and Murphy, 2010). Water hyacinth proliferations in Louisiana (Swarzenski et al., 1991) are substantial enough to envisage their fossilization as future coal seams within the future Anthropocene record of the Mississippi. The riverbanks and floodplains, meanwhile, also harbor neobiota, such as the purple loosestrife (*Lythrum salicaria*) from Europe, and Eurasian common buckthorn (*Rhamnus cathartica*), which flourish today (Rasmussen, 1998).

Efforts to reduce the number of introductions include rigorous cleaning of both commercial and recreational vessels (Cole et al., 2019). However, neobiota continue to be introduced, flourish in their new habitats, and may ultimately leave a permanent fossil record of their presence. Indeed, large, structural changes to the Mississippi drainage network have opened new corridors for bi-directional species exchange, leading to irreversible and unpredictable alteration of its ecosystems on a decadal timescale. The artificial Chicago Area Waterway System (CAWS) now connects the Great Lakes with the Mississippi River, providing a non-stop navigation corridor between the Gulf of Mexico and Lake Erie, opening New York State’s door to trade with the middle of the continent. Chicago is built on the boundary between the Great Lakes watershed, which funnels water down the St. Lawrence River out into the North Atlantic, and the Mississippi basin channeling water southwards toward the Gulf of Mexico. In the mid-19th century, the divide was breached by a crude 2 meter-deep navigation channel. Its effects were felt immediately. In 1840, when the canal was under construction, Chicago had a population of 5000. In 1848, several years after the canal was completed, the population had boomed to 100,000, tripling again during the following decade (Egan, 2017). With the astounding economic benefits of the canal, though, came a stream of ecological trouble as two previously isolated aquatic ecosystems were united. Just in the past 20 years, the Great Lakes-St Lawrence River basin has accumulated over 180 non-native species (Pagnucco et al., 2015). Despite investment to prevent the spread of organisms between the Great Lakes and the Mississippi River system, taxa including zebra mussels and rusty crayfish (*Faxonius rusticus*) (Jacobs and Keller, 2017; Mills et al., 1993), have already crossed between the basins, with many more likely to follow (Rasmussen et al., 2011).

At the other end of the Mississippi River in Louisiana, many species face disruption as ecosystems shrink due to sediment starvation, subsidence and sea level rise, resulting in intrusion of saline waters. Since 1932, over 25% of deltac wetlands have become submerged (Couvillion et al., 2011). Louisiana’s distinct Bald Cypress—Tupelo Swamp forests are at particular risk from rising sea-levels, as key taxa within this habitat, such as the water tupolo (*Nyssa aquatica* L.), will be unable to regenerate if they become permanently inundated (Glick et al., 2013). Törnqvist et al. (2020) suggested that the submergence of the remaining ~15,000 km² of Louisiana’s marshland is likely unavoidable, and so much Bald Cypress—Tupelo Swamp habitat will likely convert to open water (Glick et al., 2013). Ecosystem transformation will spread across the whole delta as sea levels continue to rise, without concerted intervention to rewild or leave areas wild (Wilson, 2016). The delta’s environments continue to support, for example, significant interregional bird migration in eastern North America, and large wild mammals like black bears (Fritscher, 2017). A future for its ecosystems, and their interconnections more widely in North America, needs to be mapped out.
Future of the Mississippi River and its delta

Future challenges are arguably most pressing for inhabitants of coastal Louisiana. Land loss rates on the delta plain are approximately 45 km² per year (Couvillion et al., 2017), and threaten communities, energy infrastructure, the delta’s wetland ecosystem, fisheries, and commerce and navigation (Twilley et al., 2016). As deltaic land shrinks and global sea level rises, the population is moving inland (Hemmerling, 2018) in anticipation of further pressures (IPCC, 2018).

Reasons for the land loss are multi-faceted and many have been worsened by over-engineering (Blum, 2019; Syvitski et al., 2009). For example, construction of flood protection levees has kept river sediment from reaching the delta plain (Keown et al., 1986; Kesel, 1988), so naturally subsidizing land can no longer be replenished. Additionally, global sea level rise, subsidence, subsurface fluid withdrawal, reduced sediment supply, and anthropogenically-driven alteration of hydrology all contribute to Louisiana’s coastal land loss (Day et al., 2007; Nienhuis et al., 2020; Törnqvist et al., 2008). Subsidence in Louisiana’s wetlands is rapid at 9 ± 1 mm per year (Jankowski et al., 2017; Nienhuis et al., 2017), which is expected as a natural part of the delta lobe cycle (Yuill et al., 2009). However, continued hydrocarbon extraction, and the position of shipping canals in the marshes, has changed the hydrology of the modern delta, resulting in prolonged lower ground water level, which contributes to more rapid shallow subsidence than would be natural (Nienhuis et al., 2020; Turner and Mo, 2021).

However, land is being gained as well as lost. The Atchafalaya Delta lobe is growing (Couvillion et al., 2017), with an actively replenished sediment supply from the Atchafalaya River, contrasting with the other, sediment-starved, interdistributary bays (Twilley et al., 2016). The Atchafalaya Delta lobe has been developing since the 1500s (Fisk, 1952), and today covers an area of some 2800 km² (Roberts, 1997) (Figure 4). It was initiated because the Mississippi River began to naturally abandon the Balize Delta lobe as the distributive channel that flows to the Atchafalaya Delta lobe is steeper and shorter. The diverted flow began to rapidly shift to Atchafalaya Bay (Roberts, 1997), increasing to a volume where engineering intervention became needed to maintain the shipping routes into New Orleans. The Old River Control structure was completed in 1963 to manage flow into Atchafalaya Bay, to prevent the Atchafalaya Delta lobe becoming the primary outlet for the Mississippi River to the Gulf of Mexico (Blum, 2019). More recently, the entirely human-generated Wax Lake Delta initiated from an artificial channel cut in 1942 (Roberts, 1998), has since built out ~8 km into the sea, creating approximately 35 km² of new land (Allen et al., 2012) (Figure 4).

The land gain is temporary as the modern delta will continue to subside, from extraction of hydrocarbons and groundwater and sea level rise (Syvitski and Kettner, 2011) and transition into a collapsed social-ecological state (Renaud et al., 2013). The landscape, including New Orleans, without significant engineering intervention, may be submerged before the century’s end (Blum, 2019). In effect modern civilization along the river now faces the same predicaments as those of Cahokia, except that the tide of environmental change is this time caused by human actions. The resulting coastline vulnerability is spatially heterogenous (Jankowski et al., 2017), coastal Louisiana being at most risk of inundation (Hauer et al., 2016). The State of Louisiana Coastal Restoration Master Plan (CPRA, 2017) indicates a sea level rise of 78–140 cm by 2100. This region has 10,000–13,000 km² of land below 1 m in elevation (Blum and Roberts, 2012), likely to be submerged by 2100 with no action (Blum, 2019; CPRA, 2017). Submergence of the remaining ~15,000 km² of marshland is probably inevitable, with conversion of marsh into open water likely within 50 years (Törnqvist et al., 2020).

Along with many other large deltas around the world, the Mississippi Delta has become an expensive restoration project (Chamberlain et al., 2018), involving a $50 billion
coastal management plan to engineer river diversions to control the delivery of sediment to the delta plain (CPRA, 2017). However, hard engineering structures are expensive, and the delta already faces a crisis due to over-engineering (Blum, 2019). Therefore, soft engineering strategies, where engineers now look to mimic natural fluvial processes, have been suggested to mitigate land loss in coastal Louisiana (Day et al., 2018; Xu et al., 2019).

Sediment input is needed to mitigate against recent enhanced rates of delta land loss (Blum and Roberts, 2009). Substantial volumes of sediment are accumulating behind dams across the whole Mississippi basin (Blum, 2019). Large dams are difficult to alter, but smaller dams could be bypassed, and downstream increases in suspended sediment load should be observed within 1–2 decades (Kemp et al., 2016). Sand deposits left by the ancient river are also being explored for their potential in coastal restoration, with 530 Mt of potential deposits so far identified (Wang and Xu, 2018). But, even if that sediment was routed to the coastline, it might not remain there (Xu et al., 2019). If routed to forested wetlands, though, it could enhance sediment retention and create a sustainable ecosystem (Rutherford et al., 2018).

However, maximum rates of land growth from before human intervention, are 5–7 times lower than the recent anthropogenically-enhanced land loss (Chamberlain et al., 2018; Couvillion et al., 2017). Therefore, even if the entire basin were instantly returned to its natural state, net loss of land would likely continue as sea level rises. It seems unlikely that the Mississippi Delta can be sustained in a recognizable form into the future (Chamberlain et al., 2018).

As greenhouse gas levels rise and Earth’s climate warms, we are rapidly approaching a Pliocene-like climate (Salzmann et al., 2011). We already have Pliocene (if not Miocene: Westerhold et al., 2020) levels of atmospheric CO₂, and are waiting for Earth’s heat balance, ice sheet volume and global sea-level to come into equilibrium. The Pliocene Mississippi, despite being a time free of human interaction with the river, may therefore hold clues to how an Anthropocene Mississippi system might evolve, though even that state may be temporary if climate heats further to an Eocene-like greenhouse state (Burke et al., 2018). In either scenario, as the world warms and sea level rises,
much of the Mississippi Delta (and other sea-facing deltas in the world) will likely be drowned over the next century or two (Turner et al., 2018). A new delta will begin to form, perhaps somewhere near where Baton Rouge is now. Even that, though, in the next millennia will likely step farther backward upon the North American continent as sea level continues to rise, as the Earth slowly adjusts to its new heat balance.

The river, now shortened by losing its seaward portion, will be adjusting in other ways. Quite how its corset of concrete, brick and steel will develop will depend on how local populations adapt to losing the towns and cities of the delta. The displaced people will have to move inland and rebuild—and so add to the concrete, brick, and steel that holds the river tight. The abandoned infrastructure of New Orleans and its surrounding parishes, meanwhile, will either be degraded and eroded (those parts above the sea surface) or be in the early stages of burial and future fossilization (those parts at and beneath the newly extended shallow sea floor). Other scenarios might be envisaged, though, in which the technosphere (Haff, in Zalasiewicz et al., 2019) does not repair its physical fabric so effectively, if co-operation among its human components weakens. In such a situation human societies in the Mississippi basin may have to adopt different strategies to survive in this landscape, just as post-Cahokian cultures did several centuries previously.

The upstream Mississippi will warm as Earth enters its new, hotter climate state. There will be some physical and chemical effects, such as an increase in chemical weathering rates. The most visible consequences will likely include emerging new communities of plants and animals better adapted to the heat. Here, the array of non-native species may prove crucial, as some may be well placed to take advantage of this new warmer landscape. One might consider this a positive side-effect of the Anthropocene, it being better to have a functional local biosphere than the maladapted remnants of a former, cooler climate state. The Mississippi will then be a renewed river, in the new world of the Anthropocene.

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Note
1. Such inferences have been derived from a range of data, including isotopes in marine sediments, and describe large variations in global ice volume and sea level (Bintanja et al., 2005; Peltier, 2004).

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