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A bird's-eye view of reservoirs in the Mississippi Basin tips a need for large-scale coordination

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Abstract

Reservoirs are mostly managed at local scales as spatially independent units. A basin-scale perspective may increase awareness at a broader scope and generate insight not evident at local scales. We examined the array of reservoir attributes and fisheries in the Mississippi Basin to identify management opportunities. The basin is the third largest in the world and includes over 1,700 reservoirs >100 ha, the most of any river basin. Our bird's-eye view shows a piecemeal approach where reservoirs are mostly administered at the local level. Basin-wide or catchment coordination to holistically address problems that recur across the basin is mostly lacking. A basin-wide coordination arrangement could facilitate various facets of reservoir management. We reviewed governance arrangements in major river basins across the globe and concluded that the basin-wide administrative layer we encourage for the Mississippi Basin may already exist in some basins but may not be directly applicable everywhere.

KEYWORDS
catchment, dams, fisheries, governance, river basins, scale, spatial distribution

1 | INTRODUCTION

Fish managers seldom consider reservoirs at broad scales. Globally, reservoirs are usually regarded at the local scale as spatially independent, isolated units (Cowx, 2002; Hubert & Quist, 2010). Under this paradigm, traditional fish management approaches have focused on in-lake practices such as improving local habitats and conserving local fish assemblages. By focusing exclusively on local scales, managers forego advantages of thinking about reservoirs at broader scales (Peterson & Dunham, 2010). An alternative paradigm embracing larger scales may have the benefits of integrating patterns active across major river basins or sub-basins that influence numerous reservoirs alike (Bohn & Kershner, 2002).

Seemingly, hard-to-predict qualities at local scales (e.g. nutrient levels, Turner & Rabalais, 2004; species composition, Poff, 1997) influenced by an array of abiotic and biotic elements may become more predictable at larger scales where they are controlled mostly by climate, hydrology and physiography (Allan & Johnson, 1997). An implication of this perspective is that local reservoir conditions such as catchment land cover, water regimes, fish assemblages and fisheries are to a large degree under regional influence (Miranda, 2008). Such large-scale patterns are evident in the Mississippi Basin (Benke & Cushing, 2005). The dynamics of rivers in basins, and of reservoirs by association, are shaped by regional climate, geology, valley contours and catchment vegetation, as well as by large-scale human activities that alter land cover and hydrologic pathways (e.g. Koch, Guelda, & Bukaveckas, 2004; Oberdorff, Guégan, & Hugueny, 1995; Puckridge, Sheldon, Walker, & Boulton, 1998). Reservoir characteristics, storage objectives and operating policies shift across the Mississippi Basin with geographic longitude tracking a precipitation gradient (Nielsen, 2018). Analogously, the fish assemblages in these reservoirs change latitudinally following a temperature gradient (Griffiths, 2010; Griffiths, McGonigle, & Quinn, 2014). These large-scale patterns tend to produce heterogeneity in abiotic and biotic features among major catchments in the basin, homogeneity within catchments and environmental patterns that often recur across the entire Mississippi Basin (Caylor, Manfreda, & Rodriguez-Iturbe, 2005; Rodriguez-Iturbe & Rinaldo, 2001). Basins may be natural units for integrated reservoir resources planning, management and research because reservoir patterns are replicated across basins.

A basin-scale perspective may increase awareness of reservoir fisheries resources at a broader scope and generate insight not evident at the local level, thereby expanding the choice of management options to resolve environmental and fisheries problems. Our goal was to examine the array of reservoirs and their fisheries across the Mississippi Basin and its seven major catchments to identify management opportunities that may not be evident at the local scale. We begin with a review of broad characteristics of the Mississippi Basin and its catchments including physical attributes, human populations and fish fauna. We follow with an examination of the spatial distribution and properties of reservoirs in the basin according to major catchments. Next, we describe fisheries and their associated management issues concerning both fish and habitat. Because our review suggests an absence of basin-scale coordination, we consider the pros and cons of basin coordination with regard to facilitating reservoir fish management. Lastly, we review global basin coordination arrangements and debate whether the scheme suggested for the Mississippi Basin may be applicable to other major river basins. We relied on data assembled from various databases (referenced in Table 1), agency reports, book chapters and journal articles. The information we considered was limited by availability of large-scale records.

2 | CHARACTERISTICS OF THE MISSISSIPPI BASIN

The Mississippi Basin is one of the five largest in the world by area, stretching across nearly 3.3 million km^2 over all or part of 32 U.S. states and two Canadian provinces (Figure 1). It is the largest basin in the United States, covering about 41% of the contiguous states. Approximately one-quarter of the U.S. population resides within the Mississippi Basin. Indeed, its drainage is exceptionally vast, and its management concerns many.

The Mississippi Basin is typically subdivided into seven major catchments, including the Upper Mississippi, Missouri, Ohio, Tennessee, Arkansas/White, Red and Lower Mississippi (Figure 1). Each catchment has a distinct climate and physiography (Turner & Rabalais, 2004), as well as extent, discharge, land cover and population densities (Table 1). The diverse physiography of the Mississippi Basin includes the Appalachian, Ozark and Rocky mountains; the relatively flat midwestern prairies; and the alluvial floodplains of the major rivers, particularly the Lower Mississippi River. Plateaus across much of the basin are generally lower than 300 m above sea level, but the high plains in the Missouri and Arkansas catchments reach elevations of about 1,500 m. The area north of the Ohio and Missouri rivers that was glaciated during the Pleistocene is mostly flat to gently rolling and includes abundant natural lakes and wetlands. South of the Ohio and Missouri catchments the Mississippi Basin consists mostly of unglaciated low plateaus, except for the broad alluvial valley flanking the Mississippi River south of the confluence with the Ohio River. The southern and eastern portions of the Mississippi Basin receive the most annual precipitation, while the western portions receive the least (Betts, Ball, & Viterbo, 1999).

Much of the Mississippi Basin is largely an agricultural landscape that supports 92% of the U.S.'s agricultural exports and 78% of the world's grain and soybean exports (USNPS, 2020). Not surprisingly, cultivated land represents the largest share (35%) of area in the Mississippi Basin, followed by natural herbaceous cover (25%) and forest cover (21%). The cultivated class covers over 20% of each of the seven catchments and is especially prevalent in the Upper Mississippi catchment, which is almost 60% cultivated (Table 1). Herbaceous cover is dominant in the Missouri, Arkansas and Red catchments, covering 41%, 37% and 27% of area, respectively. Forests cover the most area in the Tennessee and Ohio catchments, representing 58% and 49%, respectively. Though wetlands make up only 4% of the total area in the Mississippi Basin, they are concentrated next to the Mississippi River and cover 19% of the Lower Mississippi catchment and 6% of the Upper Mississippi catchment.

Over 84 million people live within the Mississippi Basin. The Ohio and Upper Mississippi catchments include the largest populations, with the Ohio catchment having the largest density (Table 1). The value placed on fisheries and natural resources varies regionally as in certain regions fisheries play a larger role in society (Fremling et al., 1989; Schramm & Ickes, 2016). The Red catchment has the greatest percentage of licensed anglers in its population and the Tennessee the greatest concentration of licensed anglers relative to the size of the catchment. The Missouri, Lower Mississippi and Arkansas catchments draw the greatest percentage of non-resident license holders.

There are approximately 350 species of freshwater fishes in the Mississippi Basin representing 28 families (Brosse et al., 2013; Griffiths, 2010; Hocutt & Wiley, 1986). The fish assemblages of the northernmost catchments, Upper Mississippi and Missouri, have the largest representations of migratory species and low counts of riverine specialists and endemics relative to other catchments (Table 1). The fish assemblages of the central catchments including the Arkansas, Ohio and Tennessee have the largest species richness in the Mississippi Basin. These catchments have high percentages of

TABLE 1 Selected attributes of seven major catchments of the Mississippi Basin, including the Upper Mississippi (UM), Lower Mississippi (LM), Missouri (MO), Ohio (OH), Tennessee (TN), Arkansas/White (AR) and Red (RE) catchments distributed as per Figure 1

	Catchment						
Attribute	**UM**	**LM**	**MO**	**OH**	**TN**	**AR**	**RE**
Magnitude[a]							
Area (% of 3,288,285 km^2)	15	8	41	13	4	14	5
Annual discharge (km^3)	124	21	68	190	61	66	50
Discharge/km^2/day (m^3)	689	208	138	1,237	1588	387	786
Land cover (% by area)[b]							
Forest	20	24	9	49	58	20	23
Cultivated	59	34	32	37	23	30	24
Shrubland	1	6	12	1	3	6	16
Herbaceous	3	1	41	2	3	37	27
Wetlands	6	19	2	1	1	1	3
Developed	9	6	3	10	9	5	5
Population[c]							
Population size (millions)	24.3	7.8	12.6	24.4	5.0	7.9	2.3
Population density (humans/km^2)	49	28	9	58	47	17	13
Licensed anglers in population (%)	10	13	12	9	13	13	21
Licensed anglers/km^2	5.8	4.7	1.5	6.2	7.5	2.7	3.2
Licensed anglers/reservoir hectares	3.6	6.6	1.3	6.4	2.4	1.3	1.3
Non-resident licenses (%)	18	22	25	13	19	21	15
Fish fauna[d]							
Native species richness	164	167	152	222	199	179	157
Richness/1,000 km^2	0.3	0.6	0.1	0.5	1.9	0.4	0.9
Species of concern	4	4	6	7	17	6	11
Native endemic species	0	0	2	22	28	8	6
Diadromous species (%)	6	3	4	4	3	3	3
Potadromous species (%)	17	13	18	12	11	11	10
Resident species (%)	77	84	78	84	86	87	87
Riverine only species (%)	34	44	41	51	55	49	46
Riverine/lacustrine (%)	66	56	59	49	45	51	54
Reservoir scope (≥100 ha)[e]							
Number of reservoirs	471	101	453	278	56	206	138
Mean area (ha)	1,351	1,406	2,398	1,194	4,717	3,461	2,551
Area of basin impounded (%)	1.3	0.5	0.8	0.8	2.5	1.5	2.0
Total area impounded (km^2)	6,363	1,420	10,863	3,319	2,642	7,130	3,520
Total storage (km^3)	16.7	10.3	163.1	23.2	28.1	44.5	21.7
Mean depth (m)	2.7	4.1	6.4	5.6	12.3	5.7	4.6
Reservoir ownership (% by number)[e]							
Federal government	18	29	39	48	69	39	37
State and local government	57	52	20	36	2	44	47
Public utility	14	2	8	5	18	3	2
Private	11	17	33	11	11	14	14

(Continues)

TABLE 1 (Continued)

Attribute	Catchment UM	LM	MO	OH	TN	AR	RE
Reservoir primary use (% by number)[e]							
Flood control	9	22	22	34	59	28	36
Hydroelectric	27	4	8	6	37	16	0
Irrigation	1	2	44	0	2	12	8
Navigation	11	13	0	18	2	7	2
Recreation	49	50	19	28	0	10	22
Water supply	3	9	8	14	0	29	32
Targeted fishes (% of reservoirs with taxon as most targeted)[f]							
Black basses (Centrarchidae)	28	57	17	62	78	50	61
Catfishes (Ictaluridae)	22	7	8	19	0	19	6
Crappies (Centrarchidae)	18	34	16	9	13	15	9
Percids (Percidae)	14	0	28	5	0	9	20
Pikes (Esocidae)	1	0	2	3	0	1	0
Salmons (Salmonidae)	0	0	1	0	0	0	0
Sunfishes (Centrarchidae)	15	0	3	2	3	1	0
Temperate basses (Moronidae)	1	2	5	1	0	1	4
Trouts (Salmonidae)	0	0	20	0	6	5	0
Reservoir ageing[g]							
Mean age as of 2020 (years)	87	57	74	75	72	65	57
Functional age index	51	33	42	41	24	40	39
Fish habitat impairment (% of reservoirs)[h]							
Sedimentation	57	2	33	37	16	35	37
Limited connectivity to side waters	28	21	15	18	0	9	29
Mudflats/shallowness	26	26	19	15	3	2	33
Limited littoral structure	48	10	27	24	25	30	28
Type 1—large water fluctuations	4	8	25	6	9	7	19
Type 2—unnatural water regime	19	13	16	6	9	16	3
Point source pollution	0	0	1	0	0	1.5	3
Nonpoint pollution	43	5	25	13	0	11	8
Excessive nutrients	65	12	35	30	13	21	24
Algae blooms	18	5	9	6	6	3	12
Lack of nutrients	0	0	4	5	19	2	5
Eutrophication[i]							
Total nitrogen (μg/L)	1,368	1,040	1,591	847	512	851	1,393
Total phosphorus (μg/L)	94	177	206	77	78	85	162
Chlorophyll-*a* (μg/L)	49	48	36	24	20	22	37
Eutrophic or hypereutrophic (%)	79	68	76	48	32	64	73
Fisheries problems (% of reservoirs)[j]							
Low species richness	17	19	24	15	22	28	42
Low recruitment	12	13	18	11	17	19	29
Low fish abundance	14	18	21	15	22	23	29
Low fish size	19	13	21	14	9	20	25
Low angler satisfaction	18	15	20	17	9	20	24

(Continues)

TABLE 1 (Continued)

Attribute	Catchment UM	LM	MO	OH	TN	AR	RE
High invasive fish species	30	13	25	22	0	14	15
High fish kills	9	6	9	6	3	9	17

[a]Area retrieved from https://datagateway.nrcs.usda.gov/ and discharge from https://waterdata.usgs.gov/nwis/sw (21 January 2018).

[b]Land cover retrieved from datagateway.nrcs.usda.gov/ (23 January 2018).

[c]Population retrieved from https://www.census.gov/programs-surveys/decennial-census/decade.2010.html and licensed anglers from https://www.wsfrprograms.fws.gov/Subpages/NationalSurvey/National_Survey.htm (11 February 2018).

[d]Griffiths (2010).

[e]USACE (2018).

[f]Each value represents the percentage of reservoirs where the taxon is the principal target in the recreational fishery. Data from Krogman (2012).

[g]Mean age derived from year of impoundment retrieved from https://nid.sec.usace.army.mil/ords/f?p=105:1 (February 18, 2018) and functional age from Miranda and Krogman (2015).

[h]Each impairment represents a construct created from multiple survey responses scored in a 0–5 scale; values listed indicate the percentage of reservoirs with scores ≥3, representing moderate or higher impairment. Data from Krogman and Miranda (2016).

[i]Retrieved from https://www.epa.gov/national-aquatic-resource-surveys/data-national-aquatic-resource-surveys (9 September 2019).

[j]Each impairment represents a survey response scored in a 1–5 scale, with 3 = average; values listed indicate the percentage of reservoirs with scores ≤2 (low) or ≥4 (high). Data from Krogman (2012).

riverine specialists and endemic species, few of which migrate. The southernmost catchments, the Red and Lower Mississippi, fall in the middle in terms of their representations of migratory, riverine and resident species. However, unlike the Lower Mississippi, the Red also has several endemic species and the second greatest number of species of concern, after the Tennessee. Together, the assemblages of the Mississippi Basin compose a rich dynamic community of fishes representing 35% of North American freshwater species biodiversity.

3 | PROPERTIES OF LARGE RESERVOIRS IN THE MISSISSIPPI BASIN

The construction of dams in the Mississippi Basin accelerated in the early 20th century, peaked in the 1960s and curbed drastically afterwards (Figure 2). A secondary peak was evident during the 1930s when government programmes during the Great Depression emphasized infrastructure development to promote employment. The National Inventory of Dams (NID; USACE, 2018) catalogues over 1,700 large reservoirs (≥100 ha) within the Mississippi Basin. Altogether, these large reservoirs encompass over 35,000 km^2 (1.4 times the area of Lake Erie) and at normal levels store nearly 317 km^3 (0.7 times the volume of Lake Erie). It is estimated that the Mississippi Basin includes the largest number of reservoirs of any river basin in the world (International Rivers, 2019).

The Mississippi Basin encompasses 51% of the reservoirs ≥100 ha in the continental United States, but reservoir numbers and sizes vary broadly among catchments. The Upper Mississippi and Missouri catchments include the most reservoirs and the Tennessee the least (Table 1). By area and storage, the Missouri and Tennessee include the most water and the Lower Mississippi the smallest amount. These reservoirs impound 0.5% (Lower Mississippi) to 2.5% (Tennessee) of their respective catchments by area. The Tennessee catchment includes some of the deepest reservoirs, on average about 2–4 times deeper than reservoirs in other catchments. The shallowest reservoirs occur in the Upper Mississippi catchment.

Overall, about 75% of the dams of reservoirs ≥100 ha in the Mississippi Basin are owned by federal, state or local governments (Table 1). The private sector owns the rest. Although most reservoirs are multipurpose, flood control and recreation are the most prevalent primary purpose for dams listed by the NID (USACE, 2018). Nevertheless, distribution of primary uses varies greatly among catchments (Table 1).

4 | FISHERIES IN RESERVOIRS OF THE MISSISSIPPI BASIN

Reservoirs of the Mississippi Basin have historically supported commercial fisheries. Primary taxa targeted have included sturgeons (Acipenseridae), buffalo fish (*Ictiobus* spp., Catostomidae), paddlefish (*Polyodon spathula*, Polyodontidae) and catfishes (Ictaluridae) (Fremling et al., 1989; Schramm & Ickes, 2016). Commercial fishing decreased throughout the second half of the twentieth century due to a combination of circumstances including market and demographic changes, conflict with an expanding recreational fishing sector, the advent of commercial aquaculture, consumption advisories and harvest regulations (Klein et al., 2018). Presently, reservoirs in the basin support mostly recreational fisheries.

The spatial distribution of nine species groups targeted by anglers in the Mississippi Basin reveals the nature of reservoir recreational fisheries across the basin. In accordance with its status as the largest and most geographically diverse, the Missouri catchment has the greatest diversity of fisheries with all nine species groups targeted in the recreational fisheries (Table 1). The Missouri catchment

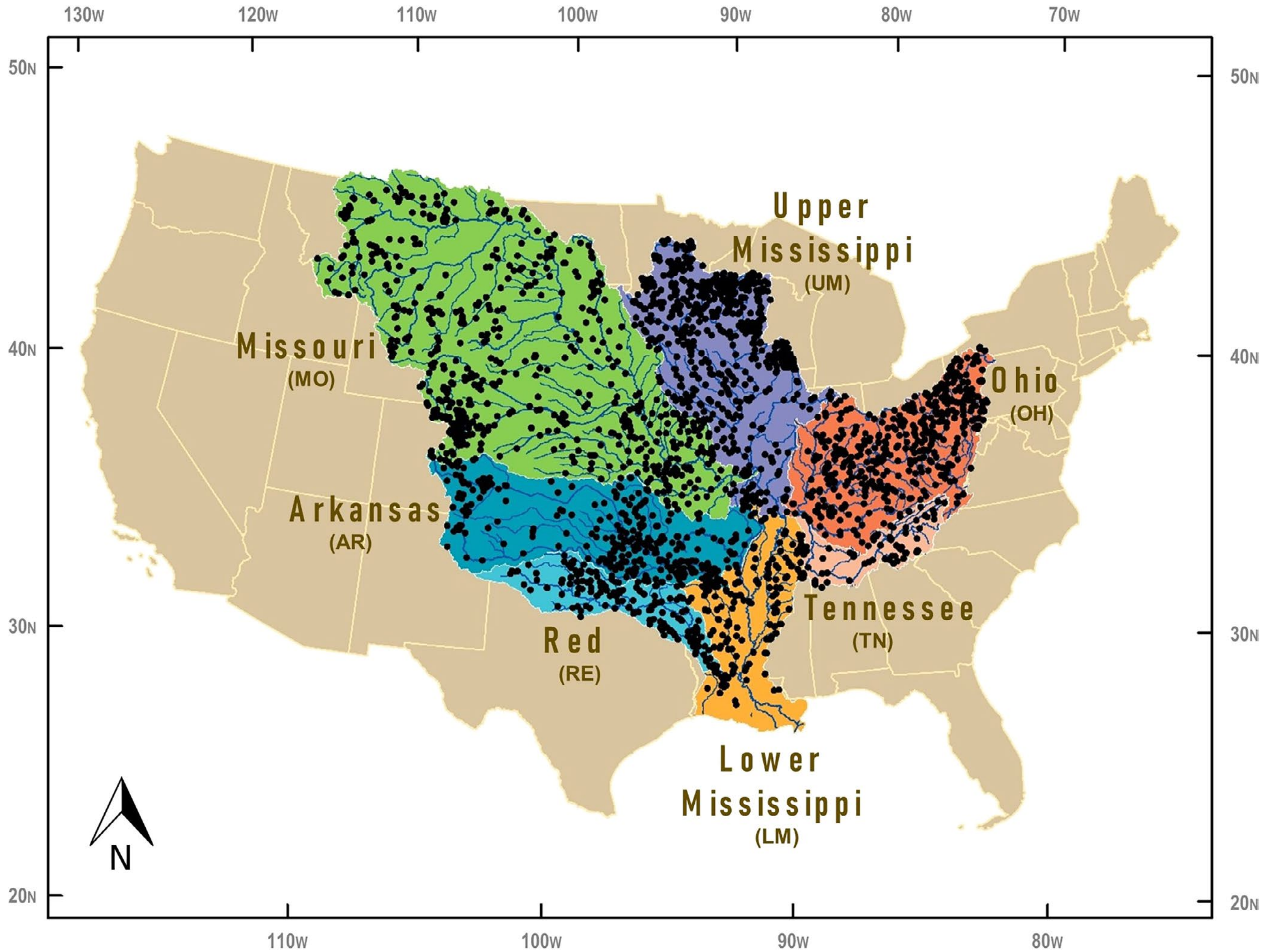

FIGURE 1 The Mississippi River Basin, its seven major catchments and the distribution of 1,703 reservoirs ≥100 ha. The United States was mapped with a Universal Transverse Mercator Projection

is characterized by some of the greatest representation of coldwater (e.g. trouts and salmons, Salmonidae) and coolwater taxa (Percidae and Esocidae), as well as temperate basses (*Morone* spp., Moronidae) but some of the lowest representations of black basses (*Micropterus* spp., Centrarchidae) that are dominant in other catchments (Figure 3a). In contrast, fisheries in the other six catchments were dominated by warmwater taxa, with a minority of coolwater taxa represented in the Upper Mississippi and Ohio catchments because of their northern distribution, and the Arkansas and Red catchments because their extension westward into the Great Plains and eastern slope of the Rocky Mountains. Often, these coolwater fisheries have been artificially facilitated by the new habitats created by reservoirs, although many fisheries must be maintained by periodic stocking. Limited coldwater fisheries have been possible in the Tennessee catchment because of suitable conditions in deep Appalachian reservoirs and coldwater hypolimnetic discharges in reservoir cascades. Warmwater fish represent over 90% of the fisheries in the Ohio and Tennessee catchments and 100% in the Lower Mississippi catchments. Black basses are dominant in these catchments, but crappies (*Pomoxis* spp., Centrarchidae) represent over a third of the most targeted taxa in the Lower Mississippi catchment.

A diversity of fisheries management problems afflicts reservoirs in the Mississippi Basin (Table 1). These problems are often innate to the artificial nature of reservoirs but are exacerbated by reservoir ageing (Pegg et al., 2015), development in the watershed, water storage management and invasive species, but prevalence varies among catchments. According to an online survey of fish managers (Krogman & Miranda, 2016), reservoirs in the western catchments, including the Red, Missouri and Arkansas, tend to have the most complications and the Tennessee and Lower Mississippi the least. The percentage of reservoirs rated as having low or below average species richness, recruitment, fish abundance and angler satisfaction were greatest in the western catchments (Figure 3b). Species richness and fish abundance were also a problem in the Tennessee catchment as some Appalachian reservoirs are deep and have low primary production inhibiting development and dynamics of fish assemblages. The northern catchments, including the Upper Mississippi, Missouri and Ohio, scored the largest percentages of reservoirs with high or above average invasive fish species. Conspicuous species include the exotic common carp (*Cyprinus carpio*, Cyprinidae) and the bigheaded carps (*Hypophthalmichthys* spp., Cyprinidae), but most of the invasive fish are North American species such as alewife (*Alosa pseudoharengus*,

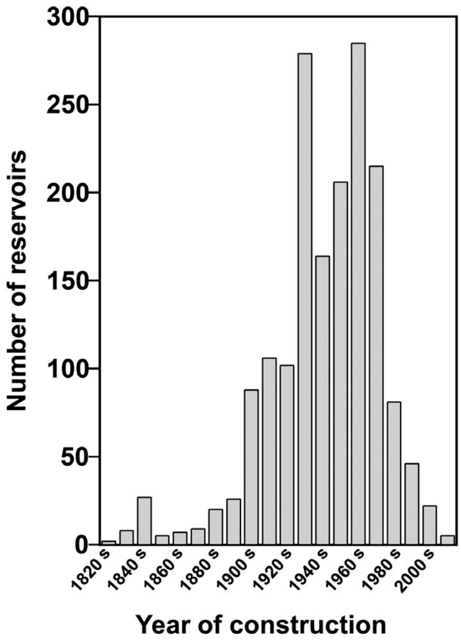

FIGURE 2 Year of construction of 1,703 reservoirs ≥100 ha in the Mississippi River Basin

Clupeidae), white perch (*Morone americana*, Moronidae), northern pike (*Esox Lucius*, Esocidae) and rainbow smelt (*Osmerus mordax*, Osmeridae) (USGS, 2019) that have been introduced or expanded their native range in the favourable conditions provided by reservoirs. Whereas the severity of these issues and effects on fish assemblages vary spatially depending on local conditions, they represent common themes that afflict management across the entire Mississippi Basin. Some of these management problems are likely to intensify as reservoirs continue to age and anticipated changes in climate reshape catchment use, water storage and species distribution (Miranda, Coppola, & Boxrucker, 2020).

As of 2020, the mean age of reservoirs in the Mississippi Basin was 74 years. On average, the oldest reservoirs occur in the Upper Mississippi catchment and the newest in the Lower Mississippi and Red catchments. However, the rate at which reservoirs age may not be best described by chronological age. The rate of ageing may depend on a diversity of attributes driven by climate and geography, catchment magnitude and composition, and reservoir hydrology and morphology. An index assembled as a multimetric scale by combining metrics expected to change directionally with reservoir senescence described functional age as an alternative to chronological age (Miranda & Krogman, 2015). The functional ages varied widely among catchments and corresponded to catchment differences in fish habitat impairments, eutrophication and fisheries problems.

Various fish habitat impairments are associated with reservoir senescence, but intensity and prevalence vary with regional conditions. Sedimentation is a major issue in reservoirs because of their characteristically large catchment area relative to natural lakes, which is accentuated in catchments with disturbed or unstable soils and most intensely manifested in shallow reservoirs (Juracek, 2015). Sedimentation is greatest in the Upper Mississippi catchment, which has the greatest fraction of cultivated drainages and the shallowest reservoirs, and lowest in the Tennessee catchment, which has the greatest fraction of forested landscapes and deepest reservoirs. Littoral mudflats, which reduce nearshore fish habitat and reservoir aesthetics, are an important impairment in the Red catchment and other catchments where shallow depth, high sedimentation and large water-level fluctuations converge. Sediment imports can also limit connectivity to side waters as aggradation of sediment above water level leads to embayment isolation and establishment of terrestrial vegetation on newly emerged lands. Such isolation is associated with land use, shallowness and water-level fluctuations and is most prevalent in the Red and Upper Mississippi catchments. Reservoir senescence is often linked to loss of structural habitat (Miranda & Krogman, 2015). The Upper Mississippi catchment that harbours the oldest reservoirs, by chronological and by functional age, included the largest fraction of reservoirs lacking structural habitat. However, the relationship between structural habitat and senescence is not strong (Miranda & Krogman, 2015) as structural habitat can be provided by submerged brush, aquatic vegetation, substrate and contour diversity, and other conditions that may or may not be related to reservoir ageing.

The flooding and dewatering of littoral areas associated with water-level fluctuations represents a major disturbance to reservoir ecosystems. Problems with water levels are particular to the reservoir's specific use and tend to be of two types. Type 1 water-level fluctuations represent those with large annual drawdowns or drawdowns that last several years. Type 1 distinctively afflicts reservoirs in the Missouri and Red catchments. Type 2 water-level fluctuations are those drawdowns that occur frequently and rapidly and are poorly timed relative to the needs of the biota or promote insufficient water retention time. Type 2 impacts reservoirs in the Missouri catchment, as well as the Upper Mississippi and Arkansas catchments.

Eutrophication is the process of nutrient enrichment that leads to algae blooms and deterioration of water quality, eventually causing changes to the reservoir environment (NRC, 2000) and biotic assemblages (Smith & Schindler, 2009). Eutrophication status is generally greatest in reservoirs of the Upper Mississippi, Missouri and Red catchments (Table 1). Water-quality changes associated with advanced trophic states (e.g. hypoxia, denser phytoplankton blooms, reduced water transparency and altered fish fauna) induce changes in fish food habits, spatial distribution and community composition. In extreme cases, hypereutrophication promotes dense, noxious phytoplankton blooms that can cause regular fish kills or lead to undesirable shifts in fish assemblage composition (Bachman et al., 1996; Kautz, 1982). Reservoirs in the Tennessee catchment have the lowest nutrients with 62% classified as oligotrophic or mesotrophic. Studies have shown that mesotrophic reservoirs, which represent most reservoirs only in the Ohio and Tennessee catchments, tend to produce the most desirable fisheries (Maceina et al., 1996).

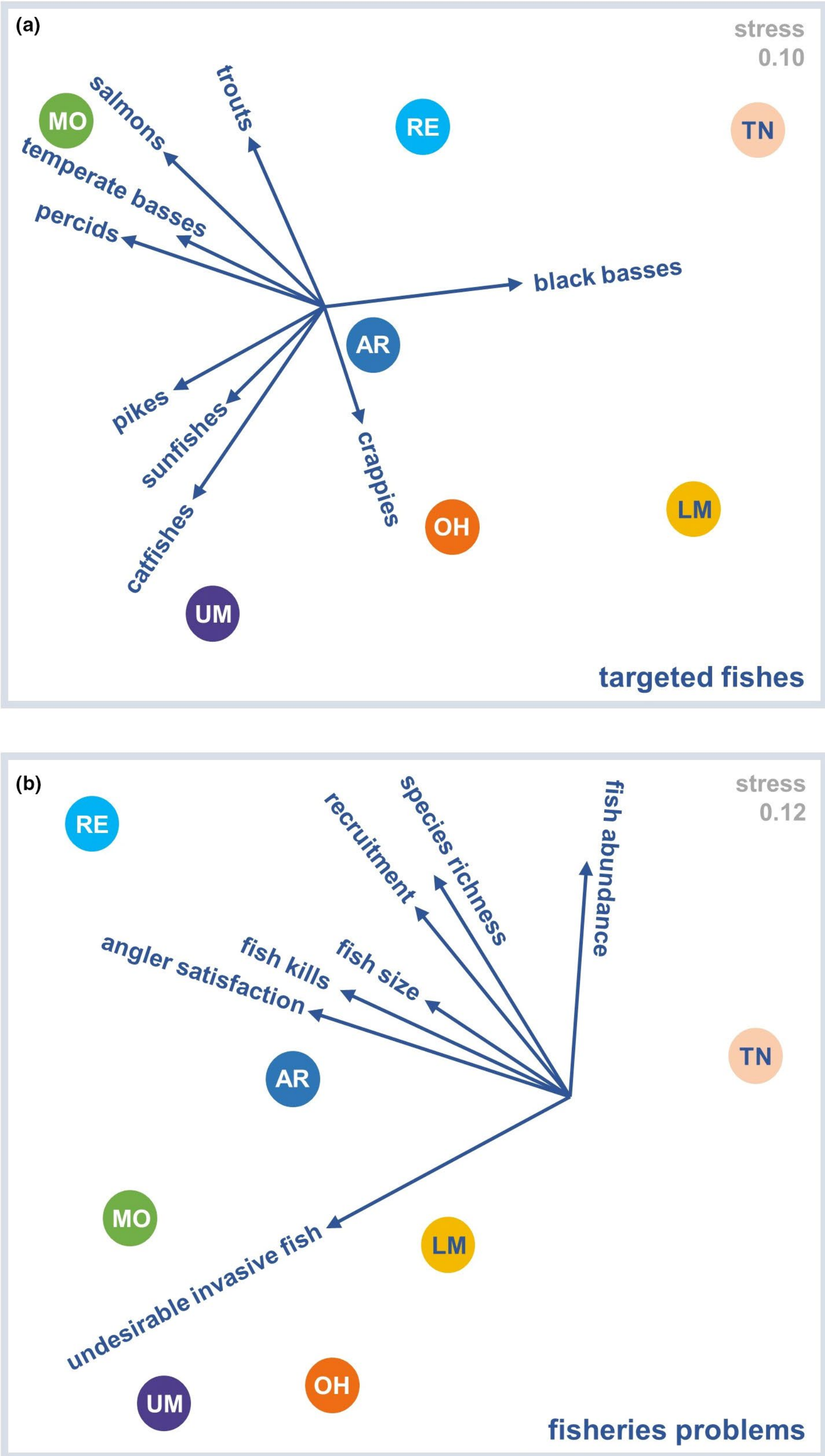

FIGURE 3 Two-dimensional ordinations of the selected attributes (Table 1) for targeted fishes (a) and fisheries problems (b). We conducted the ordinations with non-metric multidimensional scaling applied with PRIMER-E, version 7 (Clarke & Gorley, 2015) to a distance matrix constructed with a Euclidean coefficient

5 | LARGE-SCALE COORDINATION CONSPICUOUSLY ABSENT

The Mississippi Basin supports a broad assortment of reservoirs and fisheries over a vast area encompassing multiple state jurisdictions organized as a federalist system, where governance is divided between two sets of governments: one national and the other sub-national. Climate, geomorphology, land cover, land use and zoogeography interact with distribution of human populations, and their water control needs to influence catchment-specific aspects such as reservoir morphology, water regimes, sedimentation and eutrophication. Differences within and among catchments shape the local fish assemblages and fisheries. The reservoirs are mostly managed at the local level (e.g. reservoir scale, regional scale within a state jurisdiction). Our review suggested a lack of basin-wide coordination and mostly absent catchment cooperation to facilitate integrated reservoir management and to address issues that recur across the Mississippi Basin. The current piecemeal approach is likely the product of the federalist state organization of the United States.

Organizational fragmentation and inadequate communication among agencies are often a major obstacle to effective management (Nichols et al., 2016). In the Mississippi Basin, there are hundreds of state and local government agencies, often matched by federal agencies involved in managing water, watersheds, agriculture development, waterfowl, fish and others, sometimes with contradictory goals, which is inevitable in a government structure that is designed to represent a diversity of stakeholders. For example, fisheries management goals may conflict with the water storage schedule established by a river authority, or with the regulatory decisions of an environmental quality agency about land-based production facilities. Within this organizational structure, monitoring and management typically defaults to small-scale assessments that target specific local problems and support local-scale interventions and may miss opportunities to manage stressors acting at large scales (Sachedina, 2010). Without large-scale coordination, local assessments may not produce data that can be adequately aggregated to discern large-scale long-term needs, nor management activity effective beyond parochial complications (Carter & Currie-Alder, 2006). The concept of a river basin as governance unit has existed for centuries (Molle, 2009) but basin-scale coordination remains a major gap, which if filled may expand our understanding of patterns and processes at adequate spatial scales, and to quantify how human activities affect them (Schmeller et al., 2015).

5.1 | Large-scale coordination pros

A basin-scale view of reservoirs can reveal an alternative set of resource issues and opportunities, apart from those relevant at local scales, and possibly an alternative set of conservation strategies not so evident at local scales, but obvious at broader scales. At the single reservoir scale, frequent complications include abnormal water levels, unsuitable water quality, lack of habitat complexity, inadequate fish assemblage composition and too little or too much fish harvest (Figure 4), although emphases vary among basins or among catchments within a basin. These reservoir-scale problems commonly occupy most reservoir fishery managers. At the catchment scale, a wider dimension of issues and concepts emerges, with properties that influence multiple reservoirs in a catchment. These include aspects such as climate, land use, longitudinal and lateral connectivity, migratory and invasive species, and outreach to public with distinct regional values. Thinking at an even broader basin scale, yet another layer of concepts gains relevancy, including coordination to make management and research more robust by pooling activities under a common vision and planned implementation. Coordination at the catchment and basin scales offers opportunities for developing comprehensive plans, synchronizing data collection, collaborating in geographically allocated management experiments and representing the interests of the broader basin to legislative bodies at the national level.

A limited number of governmental administrative and regulatory programmes have expanded their missions to include large-scale environmental management programmes. The Tennessee Valley Authority was established to coordinate development and natural resource exploitation within the Tennessee catchment, but its mission has grown to include improvement of ecosystem functions and socioeconomic integrity (Teclaff, 1996). The U.S. Army Corps of Engineers centres on managing flood control and navigation over the Mississippi Basin, but their mission has expanded to include management of environmental problems that necessitate large-scale coordinated responses such as migratory species, invasive species and optimal water storage in reservoir systems. The U.S. Environmental Protection Agency manages state reporting for Section 305b of the Clean Water Act to produce large-scale biennial inventories; this programme is limited only to waters with a significant nexus to navigation, and nonpoint discharges from agricultural areas are generally exempted from oversight. Akin to Section 305b reporting, there is an opportunity to coordinate fisheries data collection and reporting in the Mississippi Basin to provide annual glimpses. The Sportfish Restoration Program administered by the U.S. Fish and Wildlife Service funds fishery monitoring, management and research, yet the opportunity to coordinate these activities has not been capitalized. Additionally, the Mississippi Interstate Cooperative Resource Association (MICRA) is an organization of state natural resource agencies with fisheries management jurisdiction in the Mississippi Basin. It provides coordination and communication among management entities but is limited to interjurisdictional fishery resources. Without coordination beyond that provided by MICRA for interjurisdictional fisheries, isolated assessments within the Mississippi Basin may not necessarily align to produce data that can be aggregated to meet basin-wide assessment and policy needs.

Throughout the Mississippi Basin, there are various stakeholder groups that operate within catchments (e.g. Upper Mississippi River Conservation Committee, Missouri River Watershed Coalition, Ohio River Foundation). Often, stakeholder groups such as these can more effectively implement change than federal or state organizations because they can rally the regional public (Hearne, 2007) and cross jurisdictional boundaries. By bringing these stakeholder groups under a common umbrella, a basin-wide management organization can incorporate local values. Collaboration between the stakeholders of large-scale initiatives, including property owners, local communities, and government and non-government organizations, is required to enable adaptation of large-scale basin plans to local preferences, reconciliation of numerous plans or scaling up of local actions (Guerrero, Mcallister, & Wilson, 2015; Wyborn & Bixler, 2013).

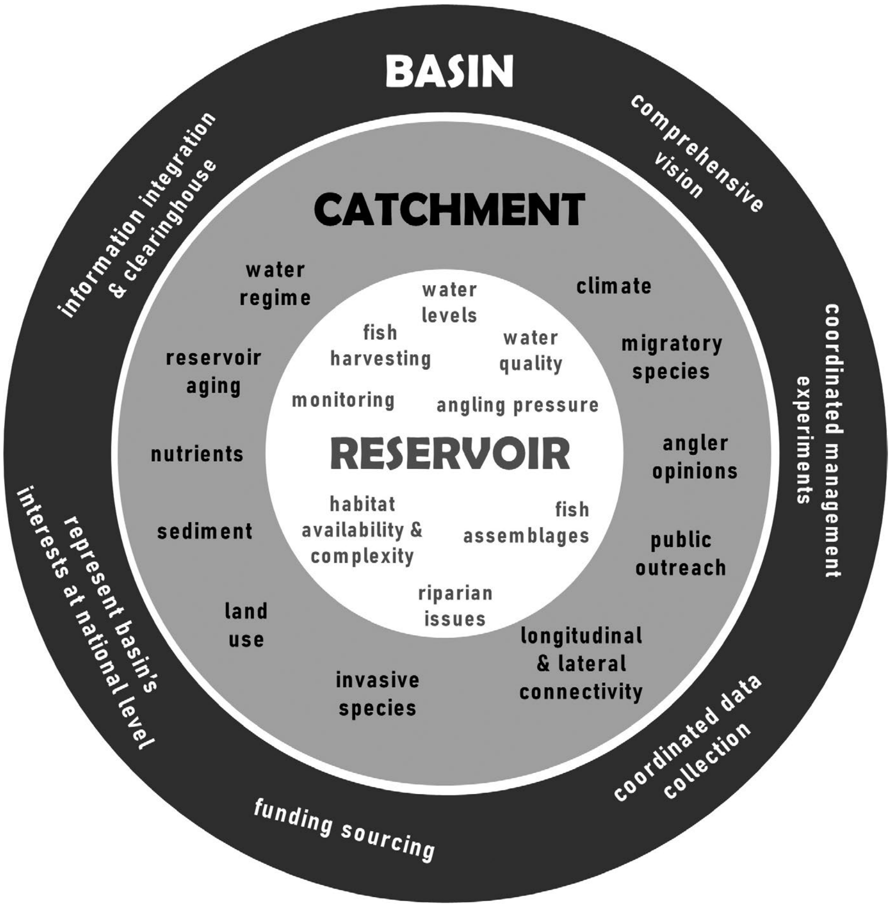

FIGURE 4 A continuum of interdependent scales ranging from the basin, to the catchment, and to the reservoir. Each scale reveals an alternative set of resource issues (examples given). Some issues associated with adjacent scales could be construed at both scales

5.2 | Large-scale coordination cons

Though there are many benefits to basin-wide reservoir management coordination, there are also obstacles. Enforcing policies across multiple jurisdictions (e.g. states, provinces) becomes an issue as each jurisdiction has different objectives with regard to not only its fisheries, but other factors that influence its reservoirs. A jurisdiction that relies heavily on agriculture production may not be very receptive to a proposed plan to improve its fisheries if it resulted in an increased cost to farmers. Jurisdictions also set aside varying amounts of funds for reservoir fisheries management, so a jurisdiction may deem that a proposed project is too expensive for them to implement. In addition, many jurisdictions may only be partially in the basin, so they may not want to manage that part of their region differently when in their eyes, it is not any different than the rest. The slow rate of return likely accompanying basin-level management actions may also soften political and agency support for large-scale management in favour of fine-scale actions with immediate returns. Moreover, a basin-wide fisheries management organization in many cases may only make recommendations and not actively enforce policies, which could result in the organization being ignored and becoming largely ineffective (Hearne, 2007). Yet, if authorized by laws or agreements, a basin-wide fisheries management organization could be given mechanisms to compel cooperation. For example, relevant national or international funds could be withheld from jurisdictions that do not comply.

5.3 | Large-scale coordination model

Perhaps large-scale coordination in the Mississippi Basin could be achieved with an arrangement like the North American Waterfowl Management Plan (NAWMP, 2012). The waterfowl plan, active for over 30 years, is managed by a committee that provides leadership and oversight for activities undertaken in support of the plan. The committee provides a forum for discussion of major issues and makes recommendations to regional conservation agencies. The plan provides the framework needed for a large-scale conservation scope, but its implementation occurs at the regional level. A basin-wide reservoir coordination arrangement could facilitate (a) tracking significance and distribution of existing and emerging threats to reservoirs in the Mississippi Basin; (b) developing strategy for addressing the most common management problems; (c) increasing the robustness of management experiments through improved replication across the basin over catchments strata; (d) pooling resources, experience and knowledge to avoid unnecessary duplication and maximize the value of conservation investments; and (e) representing the interests of this huge resource to ensure adequate support from federal agencies and congress. Such an arrangement could help steer reservoir fisheries management through a likely turbulent 21st century as reservoirs age beyond their useful life and climate shifts render status-quo management ineffective.

6 | GLOBAL APPLICABILITY

Globally, reservoir fisheries are administered under diverse styles of basin-wide organizations, ranging from polycentric to monocentric. The Mississippi Basin has a polycentric administration that relies on a decentralized, adaptive, homegrown approach emphasizing suitably sized managerial subunits within the basin, local knowledge and locally agreed standards (Lankford & Hepworth, 2010). Conversely, a monocentric administration would have a centralized organization overseeing the entire basin with an apex authority that coordinates collection of data and resource allocation over a hierarchy of sub-basins (Molle, 2009), and seeks to manage basin-wide fisheries with broad-scale standards and procedures. Successful basin management of water resources (Lankford & Hepworth, 2010) and their fisheries (Welcomme, 2016) require a sensible balance between polycentrism and monocentrism, as a monocentric basin-wide vision may be needed for polycentric local management to function. This principle is implemented by the North American Waterfowl Management Plan and may apply to reservoir fisheries. In some basins, depending on governmental organization and history, there may be a clear case for a well-financed regulatory authority deploying centrally planned monitoring and management activities. In others, because of national or other jurisdictional divisions, a central control might not be feasible at this moment in history or must be comparatively smaller and/or weaker.

Besides the Mississippi, other river basins with large numbers of reservoirs include in descending order (Lehner et al., 2011) the Yangtze (China), Danube (central Europe), Paraná (east-central South America), Ganges (southern Asia) and Murray-Darling (south-eastern Australia). These basins are administered under a mix of polycentrism and monocentrism, partially determined by existing governmental partitions and economic development status. The Danube Basin is the most international basin in the globe, shared by 19 countries, and its management has in recent decades achieved monocentric coordination under the auspices of the International Commission for the Protection of the Danube River (Sommerwerk et al., 2010). The focus of the commission has been on environmental issues; fisheries management remains mostly polycentric under the control of regional authorities. In contrast, fisheries in reservoirs of the Yangtze Basin are under the control of the Yangtze River Fisheries Administration within the Chinese Ministry of Agriculture. While fisheries in the Yangtze Basin have distinct apex supervision, management effectiveness is diminished by inadequate provincial infrastructure, resources and participation (Chen, Duan, Liu, & Shi, 2004; Zhou, 2006), resulting in ineffectual monocentrism due to weak polycentrism. Like the Yangtze, responsibility for management of the Murray-Darling Basin is centralized within the Australian government that has adopted a comprehensive plan to deal with environmental challenges and water allocation (Ross & Connell, 2016). Fisheries management in reservoirs of the Murray-Darling Basin is a balance of monocentrism and polycentrism, with some programmes and policies widely standardized but others left to the discretion of the four states in the basin (Lintermans, 2004). In the Ganges Basin, lack of cooperation among three nations has curbed monocentric activities, and lack of funds within each nation has produced a soft polycentric approach to management (Shahjahan & Harvey, 2012). Like the Ganges, the Paraná Basin encompasses three countries, although Brazil occupies about 75% of the basin. Perception of the risk of multilateral cooperation has prevented joint international action to create basin organizations (Calcagno, Yamashiki, & Mugetti, 2002). Reservoir fisheries management is mostly under the control of centralized government agencies with limited staff and budgets to conduct monitoring, develop management strategy and enforce laws (Metcalfe, Collins, Menone, & Tundisi, 2020). In the Ganges and Paraná basins, there has been scant river basin planning or formation of monocentric coordinating bodies, and polycentrism to accommodate local scales and the diversity of stakeholders and interests is restricted by lack of capitalization.

The monocentric governance layer we encourage for the Mississippi Basin may already exist in some basins but may not be applicable everywhere. The Mississippi Basin has a robust polycentric infrastructure and is well positioned to receive and accept a basin-wide framework through judicious delivery of funding incentives. The same is true for the Danube Basin where the legal framework provided by the European Union Water Framework Directive can facilitate transboundary innovation in administration. The basin-wide framework we propose for the Mississippi Basin may have already been implemented in the Murray-Darling Basin (Ross & Connell, 2016); however, pushback from state governments and other obstacles remains a risk for continued reform in the basin. As for the other major basins considered, a balance between monocentrism and polycentrism may be decades away as local infrastructure is developed, and international differences are resolved. It should be easier in smaller basins and those under one or few government partitions. Moreover, for reasons described in this paper, establishment of efficient river basin management is a process that can take decades. Therefore, long-term support is key. Central governments or external organizations wishing to promote integrated reservoir fisheries management on a river basin scale may need to be prepared to sustain their commitments to reform.

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CONFLICT OF INTEREST

The authors have no conflict of interests.

DATA AVAILABILITY STATEMENT

All data used in this article were derived from public domain resources.

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