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As the world's second most consumed resource, sand is being depleted at an alarming rate. China accounted for nearly half of the world's sand consumption in 2012. Here we present a material flow analysis of sand from 1995 to 2020 that shows China's overall sand supply surged by approximately 400% over the study period, yet the proportion of natural sand dropped from ~80% to ~21% due to the increasing use of manufactured sand. From 2010 to 2020, China's natural sand supply nearly halved due to the strict policies on natural sand mining and the promotion of manufactured sand. This shift demonstrates a possibility for mitigating impacts on natural sand resources during industrialization and urbanization.

Construction of infrastructure is accelerating the depletion of natural sand reserves at an alarming rate[1,2]. In 2015, global sand extraction surpassed 13 billion tonnes per year (Gt yr^{-1}), notably outpacing its natural replenishment rates[3]. Projections suggest that, by 2030, the demand for sand could more than double, reaching between ~20 and 49 Gt yr^{-1}. This surge is largely attributed to population growth and rapid urbanization, particularly in developing countries[4]. Beyond the issue of resource scarcity, unrestricted sand mining poses serious environmental threats, such as riverbank erosion[5], loss of biodiversity[6] and deterioration of water quality[7]. It also leads to illegal labour practices and 'sand mafias'[8].

Previous research has acknowledged the extensive and severe natural sand depletion, as well as its far-reaching consequences[4,9,10]. However, there is still a lack of detailed understanding about the complete life cycle of sand, which includes its extraction, production, usage and disposal. Conducting a thorough material flow analysis (MFA) of sand would illuminate how sand is utilized at each stage of its life cycle and could identify effective strategies for managing sand resources. This is crucial not only for sustainable sand management but also for responding to recent appeals from the United Nations[3,7].

Here, we make an attempt to close this knowledge gap by introducing a dynamic MFA framework to quantify China's sand flow throughout its entire life cycle from 1995 to 2020. This study concentrates on China because it is the largest developing country and accounts for almost half of the world's sand consumption in 2012 (ref. 7). Facing diminishing sand reserves, China's central and local governments have implemented conservation strategies. These include establishing regulations for sand mining management[11], developing the River Chief System[12] and enhancing the National Construction Sand Standard[13]. In this context, we specifically examine the changes in China's sand supply and consumption patterns, as they can assist policymakers in seeking strategies to curb natural sand depletion and related environmental challenges.

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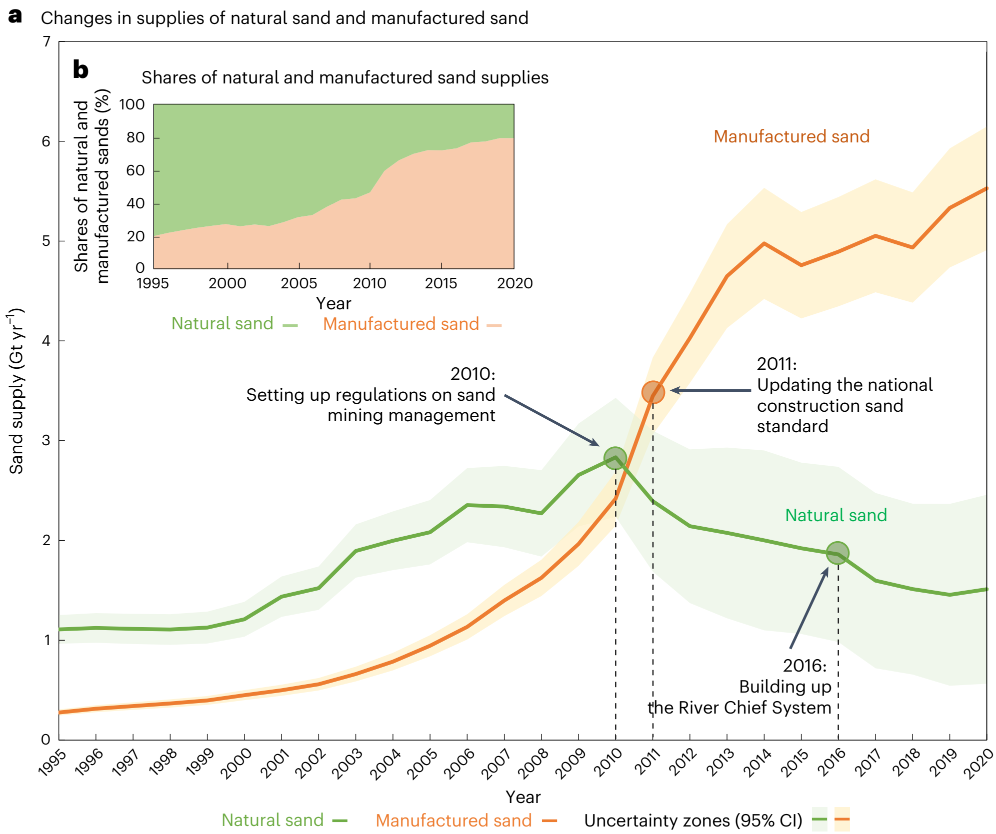

Fig. 1 | Historical trends of China's natural sand and manufactured sand supplies. a, Changes in supplies of natural sand and manufactured sand. **b**, Shares of natural and manufactured sand supplies. The orange and green dots in **a** represent the times when specific sand management policies were enacted. The solid lines are presented as the deterministic results, and the shaded areas indicate the 95% confidence interval (CI) of the estimates. The detailed introduction of China's sand management measures is presented in Methods, and the additional results are presented in Supplementary Information 2.

Our MFA framework is specifically designed to trace national sand flows through five main processes (mining, fabrication, manufacturing, use and waste management), which include over 40 types of sand flow (for example, extraction, production, consumption, losses and trade flows) and their accumulation in 14 final applications (in-use stocks)[14]. Due to the naturally occurring diversity of sand types, this study specifically focuses on 'construction sand', a type that has been extensively studied in previous research[1–4]. Construction sand is further categorized into natural sand (mainly from rivers, basins, shorelines and pits), manufactured sand (mainly from crushed rocks, quarry stones and tailings), and secondary sand (mainly from end-of-life (EoL) buildings). Manufactured sand refers to rock or mine tailings particles that are made by mechanically crushing and sieving[13]. We have identified and synthesized data in statistical yearbooks, official reports and other public information sources covering the full life cycle of sand in China. To enhance the credibility of our results, we further performed uncertainty analysis and validated the results (Methods and Supplementary Information 1).

Our results reveal that China's total sand supply increased approximately fivefold, from ~1.4 Gt yr^{-1} in 1995 to ~7.0 Gt yr^{-1} in 2020, to support its unprecedented urbanization and economic development. During this period, China's sand supply patterns fundamentally shifted, with the dominant source transitioning from natural sand to manufactured sand (Fig. 1a). This shift was accompanied by a range of regulations and policies targeting sand mining restrictions and the promotion of manufactured sand use. China's natural sand extraction had increased rapidly from ~1.1 Gt yr^{-1} in 2000 to the peak point of ~2.8 Gt yr^{-1} in 2010 when China launched its regulation on sand mining in rivers. After that, the natural sand supply nearly halved and then stabilized around ~1.5 Gt yr^{-1}. Its ratio in total sand supply was ~21% in 2020, down from ~80% in 1995 (Fig. 1b).

During the study period, China's manufactured sand increased quickly at an average annual rate of 13%. Before 2000, its manufactured sand supply stayed below 0.5 Gt yr^{-1}, but a surge occurred since 2001, making it exceed natural sand after 2011. Manufactured sand became the major source to support China's growing demand for buildings, roads and other infrastructures, with its ratio in total sand supply above 70% after 2012. This was mainly attributed to China's encouragement of expanded use of manufactured sand in building materials in 2011 (ref. 13). After 2015, China's manufactured sand supply stayed at ~4.7–5.5 Gt yr^{-1}, mainly due to the slowdown of China's urbanization progress.

We further traced China's sand flows throughout the whole life cycle in a Sankey diagram from 1995 to 2020 (Fig. 2a and Extended Data Fig. 1). During this period, China's cumulative supply of natural and manufactured sand reached a total of 108.4 Gt. Notably, due to high shipping costs, most of China's sand use was sourced locally with negligible international trade. Aside from 2.0 Gt of processing losses, approximately 94.0 Gt was used to produce concrete, and 12.4 Gt was used to produce mortar. They were consumed in transportation infrastructure (33.2 Gt), construction (42.1 Gt) and other end-use applications (28.8 Gt), with a total loss of 4.2 Gt during the manufacturing and use phases. From 1995 to 2020, 100.9 Gt of sand was accumulated as in-use stocks, and only 3.3 Gt entered the EoL stage along with obsolete products. Only 0.1 Gt was recycled among these obsolete products, while the remaining 3.2 Gt was landfilled because of various technical and economic barriers. We also specified China's intermediate products and final applications of sand in Fig. 2b and Fig. 2c, respectively. There was a remarkable increase

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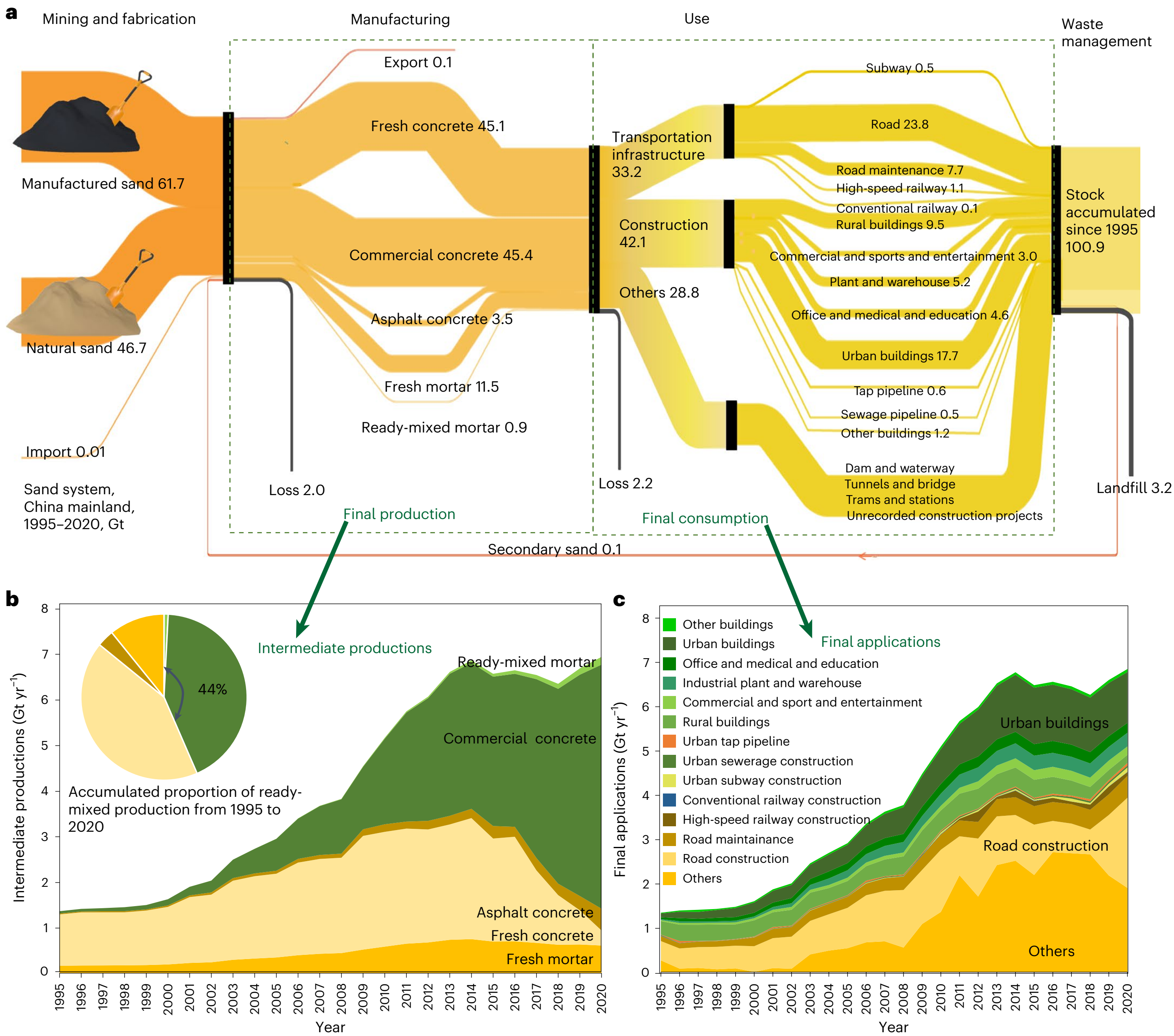

Fig. 2 | China's sand flows from 1995 to 2020. a, The cumulative flows of sand from 1995 to 2020, system boundary: sand system, China, 1995–2020, Gt. **b**,**c**, Detailed results for intermediate products (**b**) and final applications (**c**) in each study year, China, 1995–2020, Gt yr^{-1}. Note: in this MFA, sand is divided into natural, manufactured and secondary on the basis of the source materials. These types of sand are used to produce concrete and mortar and are ultimately consumed in construction projects. In **c**, 'others' mainly include dams and waterways, tunnels and bridges, trams and stations, and other unrecorded construction projects. The material flows may not be balanced due to the treatment of rounding numbers. More detailed results are presented in Supplementary Information 2.

in China's sand consumption starting in 1998, coinciding with the enactment of its housing reform policy[15]. Among the intermediate products, the proportion of ready-mixed mortar and commercial concrete surged from ~4% in 1995 to ~80% in 2020, indicating China's growing appetite for high-performance building materials. At the final application stage, China's sand consumption peaked at ~6.7 Gt yr^{-1} in 2014, then settled in a range of 6.2–6.6 Gt yr^{-1} between 2015 and 2019. This is equivalent to ~4.8 t yr^{-1} per person, more than twice the global average[10]. Furthermore, a noticeable increase in sand consumption occurred after 2019, primarily attributed to road expansion spurred by China's stimulus policies to boost infrastructure investment[16].

Overall, our findings provide evidence that China underwent a substantial shift in its main sand supply source, transitioning from natural sand to manufactured sand during 1995–2020. This shift can be attributed primarily to two key policy factors: (1) strict regulations on natural sand mining[11,12]; (2) the promotion of manufactured sand in building construction, mainly through updates to national construction standards[13]. Notably, such a supply shift was partly driven by economic incentives, since natural sand is more expensive than manufactured sand[17]. Moreover, a few studies have shown that manufactured sand is relatively safer and more sustainable, with lower impacts on the environment when compared to natural sand[18]. Concomitantly, the environmental consequences of this shift should be carefully anticipated and avoided. For instance, if quarrying sites for manufactured sand are developed in ecologically sensitive areas, they may induce adverse impacts and place pressure on ecosystems and biodiversity[6].

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China's practice provides a reference to the transition to alternative sand supplies for the world. However, some nations may face challenges in designing effective regulations and securing abundant tailings and waste rocks for producing manufactured sand. These challenges are particularly notable for countries that rely on market-based mechanisms, which often involve fewer direct regulations on natural sand mining. In such cases, given the lower price of manufactured sand compared with natural sand[17] and the global abundance of manufactured sand sources[19], there remains potential to develop a strong market for manufactured sand. This can be achieved through establishing standards, improving awareness among local sand consumers and promoting national cooperation in creating free trade of manufactured sand. Certain countries, such as Canada, Australia and South Africa, have the potential to become key players in the supply of manufactured sand[19].

This study has its limitations and uncertainties. The absence of direct data on natural sand supply and incomplete understanding of sand usage in various downstream products introduce some uncertainties into our findings. To address this, we performed an uncertainty analysis with a Monte Carlo simulation (1,000,000 iterations) for each sand flow, as detailed in Methods. Meanwhile, through comparison and validation with other studies, we found that our key results regarding the proportion of natural sand in the total sand supply align well with previously reported results of natural aggregate[20] (see detailed comparison results in Supplementary Information 2). We also suggest a need for scenario analysis to explore future trends in China's sand demand and the robustness of China's sand supply shift, considering the maintenance needs of existing buildings, newly added stock demand and varying lifetimes of different applications.

The findings of this study indicate a departure from earlier projections[2,4,10], suggesting that the rapid depletion of natural sand deposits may be mitigated. This can be accomplished through a shift from natural sand to manufactured sand. China's experience offers valuable insights for sustainable sand management, particularly for developing economies undergoing urbanization, which will probably fuel future demand for sand.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41561-024-01501-6.

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Methods

This study mainly applies the dynamic MFA[14] approach to trace the stocks and flows of sand along its life cycle within China annually from 1995 to 2020. The summary of our key steps is provided in this section, and the detailed quantification steps and the corresponding data sources are presented in Supplementary Information 1. The supplementary results can be found in Supplementary Information 2.

Sand definition

In this study, we focus on 'construction sand', which is the main concern in various studies[1–4]. Note that construction sand differs from industrial sand, such as high-purity quartz sand used to manufacture chips. We adopt the definition of construction sand from China's National Standard for Construction Sand (GB/T14684)[13,21], in which sand is defined as a naturally occurring or manufactured material composed of rock particles with a grain size less than 4.75 mm. In addition, the proportions of sand within different sizes are also strictly specified. For example, the proportion of sand with a grain size less than 0.15 mm should not be larger than 5%. It is also notable that China's standard of construction sand is not fully consistent with other countries. In the recently published report by United Nations Environment Programme/Global Resource Information Database Geneva[22], definitions of sand have been reviewed among countries. For example, the European Union adopts the ISO standard (14688-1:2018)[23], defining sand as "a coarse, natural mineral soil which does not stick together when wet and remoulded (that is, non-cohesive) and where the combined weight of 50% of the particles is smaller than 2 mm", and the United States adopts the ASTM D2487-00 (ref. 24) standard: "more than 50% is retained on n°200 sieve (75 µm) and 50% or more of the coarse fraction passes the n°4 (4.75 mm) sieve". Therefore, when carrying out sand MFA for a different country, it is necessary to use the corresponding standards of that country. In addition, since there is no clear definition of sand commodities in the international trade database (https://comtradeplus.un.org/), we assume that sand commodities imported to and exported from China meet the definition of this study.

Sand types

In general, construction sand includes natural sand, manufactured sand and secondary sand. The detailed classification of these three categories is clarified in Supplementary Fig. 1 in Supplementary Information 1.1. Natural sand is a naturally occurring material that is commonly found in the natural environment, mainly including river sand, lake sand, pit sand and desalinated sea sand[13,21]. Manufactured sand refers to rock or mine tailings particles made by mechanical crushing and sieving[13,21]. Note that the tailings in the mining stage can be used to make manufactured sand, such as iron ore tailings, but not all tailings from the beneficiation process can be used as manufactured sand because they may contain high amounts of sulfides or environmentally harmful additives, such as bauxite tailings. In general, manufactured sand has cost advantages over natural sand owing to its lower price in China[17]. Secondary sand refers to the sand that is recycled and reused from EoL buildings and other wastes[25,26].

Sand MFA framework

We apply the dynamic MFA approach[14] to develop a detailed sand MFA framework to trace national sand flows and stocks along its life cycle, which includes five main processes (mining, fabrication, manufacturing, use and waste management), over 40 types of flow (for example, extraction, production, consumption, losses and trade flows) and 14 types of in-use stocks (each as a final application) that are grouped into three categories—transportation infrastructure, construction and others. To improve the transparency of our MFA approach, the quantification framework with detailed steps and data sources for each stock and flow is presented in Supplementary Information 1.2. In the same section, we provide data for key MFA input parameters of sand intensity of buildings, sand loss coefficients and sand intensity of roads, railways, subways and pipelines. The results of our sand MFA are illustrated in a Sankey diagram in Fig. 1a and Extended Data Fig. 1.

Sand demand estimation

Sand demand can be divided into intermediate products (that is, sand in various cement products, including commercial concrete, fresh concrete, asphalt concrete, fresh mortar and ready-mix mortar) and final applications (that is, buildings: urban, rural, commercial and sport and entertainment, industrial plant and warehouse, office and medical and education, and other buildings; transportation infrastructure development: road and road maintenance, high-speed railways, conventional railways and city subways (in bridges, tunnels, foundations, station ancillary roads and so on), urban sewage pipelines and tap pipelines; and other applications). In general, we follow a bottom-up approach to estimate the sand demand in each intermediate product and final application. For each final application, the sand demand $\mathrm{Fin\_Sand}(i,t)$ is estimated on the basis of the building area or road length and its corresponding sand intensity at different layers (mainly from technical reports and literature related to building design; see details in Supplementary Information 1.2) in equation (1),

$$\mathrm{Fin\_Sand}(i,\ t) = A(i,\ t) \times C(i,\ t), \tag{1}$$

where $A(i,t)$ is the building area or road length in project i at year t, and $C(i,t)$ is the corresponding sand intensity per unit of building area or road length.

As for the intermediate product, the demand $\mathrm{Int\_Sand}(j,t)$ is quantified through the volume of various types of cement production with their corresponding sand additives from the designed cement-sand recipe in equation (2),

$$\mathrm{Int\_Sand}(j,\ t) = B(j,\ t) \times R(j,\ t), \tag{2}$$

where $B(j,t)$ is the cement consumption in sand-related cement product j (concrete or mortar) at year t, and $R(j,t)$ is the ratio of sand in sand-related cement product j. Those two demand categories were further cross-checked to obtain the demand of other applications based on mass balance principle.

Sand supply estimation

There are four supply sources to meet China's sand demand: natural sand, manufactured sand, secondary sand and sand from import sources ($\mathrm{I\_Sand}(t)$, quantified on the basis of international trade records; detailed in Supplementary Information 2.3). The secondary sand supply $\mathrm{S\_Sand}(t)$, normally in the form of aggregates from EoL waste back to the concrete and mortar production process[27], is quantified on the basis of China's records of EoL waste from all final applications with its sand intensity (detailed in Supplementary Information 1.2). The quantification of natural sand extraction in China is challenging due to the lack of direct statistics and the potential existence of informal extraction and other unregistered activities. In China, some organizations like China Aggregates Association and other market agencies have collected the records related to the total amount of manufactured aggregates (a mix of sand and crushed stone). Accordingly, we then quantified the manufactured sand $\mathrm{M\_Sand}(t)$ on the basis of its share $\mathrm{MR}(t)$ in total manufactured aggregates $\mathrm{MG}(t)$ at year t (detailed in Supplementary Information 1.2) as shown in equation (3):

$$\mathrm{M\_Sand}(t) = \mathrm{MG}(t) \times \mathrm{MR}(t). \tag{3}$$

Based on the mass balance principle, the natural sand supply $\mathrm{N\_Sand}(t)$ at year t can be obtained with equation (4),

$$\mathrm{N\_Sand}(t) = \left(\sum_j \mathrm{Int\_Sand}(j,\ t)/\ (1 - \mathrm{LR}\ (j,\ t)\right) \\ -\mathrm{M\_Sand}(t) - \mathrm{I\_Sand}(t) - \mathrm{S\_Sand}(t), \quad (4)$$

where $\mathrm{LR}\,(j, t)$ is the loss rate of specific intermediate sand product j at year t.

Given the very limited amount of imported sand and secondary sand (details in Supplementary Information 2.3–2.4), we measured the ratio of natural sand $\mathrm{NR\_Sand}\,(t)$ in the total amount of natural and manufactured sand as one key indicator to show the sand supply transition in equation (5):

$$\mathrm{NR\_Sand}(t) = \mathrm{N\_Sand}(t)/(\mathrm{N\_Sand}(t) + \mathrm{M\_Sand}(t)). \quad (5)$$

Uncertainty analysis and result validation

Despite the best available data, our MFA still exhibits certain uncertainties, mainly due to the lack of direct natural sand supply data as well as incomplete knowledge related to the sand intensity of various downstream products. Similar to other studies[28,29], we derived our quantitative uncertainty estimates of model inputs based on their data quality at three confidence levels (for example, high, medium and low; see details in the data sources for sand MFA in Supplementary Information 1.2) and applied Monte Carlo simulation (1,000,000 iterations) to quantify the uncertainties of each model result for final demand, intermediate demand and supply trends. The detailed uncertainty results are presented in Supplementary Information 2.6. We further validated our results with other available data shown in Supplementary Information 2.7, mainly the ratio of natural sand $\mathrm{NR\_Sand}\,(t)$ to total sand supply. Our results are supported by reference literature, which states that manufactured sand has been the dominant source for China's sand supply. In general, our results of natural sand's proportion to the total sand supply have a high compatibility with other diverse sources, including a study on China's natural aggregate[20], and some government reports stating that "the manufactured sand has gradually replaced natural sand to become the main source to meet China's sand demand"[30,31].

China's unreported natural sand supply and trade

Based on the mass balance principle, we estimated the historical trend of China's natural sand extraction, which might or might not include unreported (illegal) domestic mining and unreported trade of sand. Considering China's River Chief System was proposed and implemented in 2003 partly to prohibit illegal natural sand mining (see China's River Chief System to prohibit illegal natural sand mining in Supplementary Box 1 in Supplementary Information 2.5) and illegal sand mining or trade has been included in the 'Criminal Law' of China[32], large-scale illegal mining has been eliminated from the mainstem of the Yangtze River. For this dominant sand mining region in China, only small-scale illegal nighttime mining activities can be found[33]. We consider the proportion of illegal mining and unreported trade to be very limited compared with the huge amount of total sand supply.

China's sand management measures

On the supply side, China's early national sand management tools were the prohibition policies of natural sand mining, such as establishing forbidden mining areas and setting sand mining registration systems[11] (Supplementary Information 2.5). Since 2016, China has further strengthened its regulatory policies on the illegal mining of natural sand[34]. It is worth noting that China has not slackened its control of natural sand at any stage of development. On the demand side, the policy for promoting efficient sand products (ready-mixed products) was published to improve the quality of sand products and reduce sand loss. Since 2011, the national recognition policies, particularly the updated standard of construction sand (GB/T14684-2011)[13], have notably promoted the development and use of manufactured sand. At the same time, China has gradually strengthened the management of manufactured sand (mining, production and transportation) and has begun to guide the development of secondary sand[35].

Data availability

The data used in this study are presented in Zenodo at https://doi.org/10.5281/zenodo.12507736 (ref. 36).

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Author contributions
H.W., P.W., W.-Q.C. and J.L. conceived the study. X.Z., P.W. and H.W. performed the analyses, with support from H.S., Y.L. and F.M. on datasets and from T.F., H.S., A.T., Y.Y., M.A., C.Z., Q.Y. and C.B. on analytical approaches. W.-Q.C., J.L., Y.-G.Z., H.S. and T.D. advised the policy implications. H.W., P.W., A.T. and X.Z. led the writing with input from all co-authors. All co-authors reviewed and commented on the manuscript.

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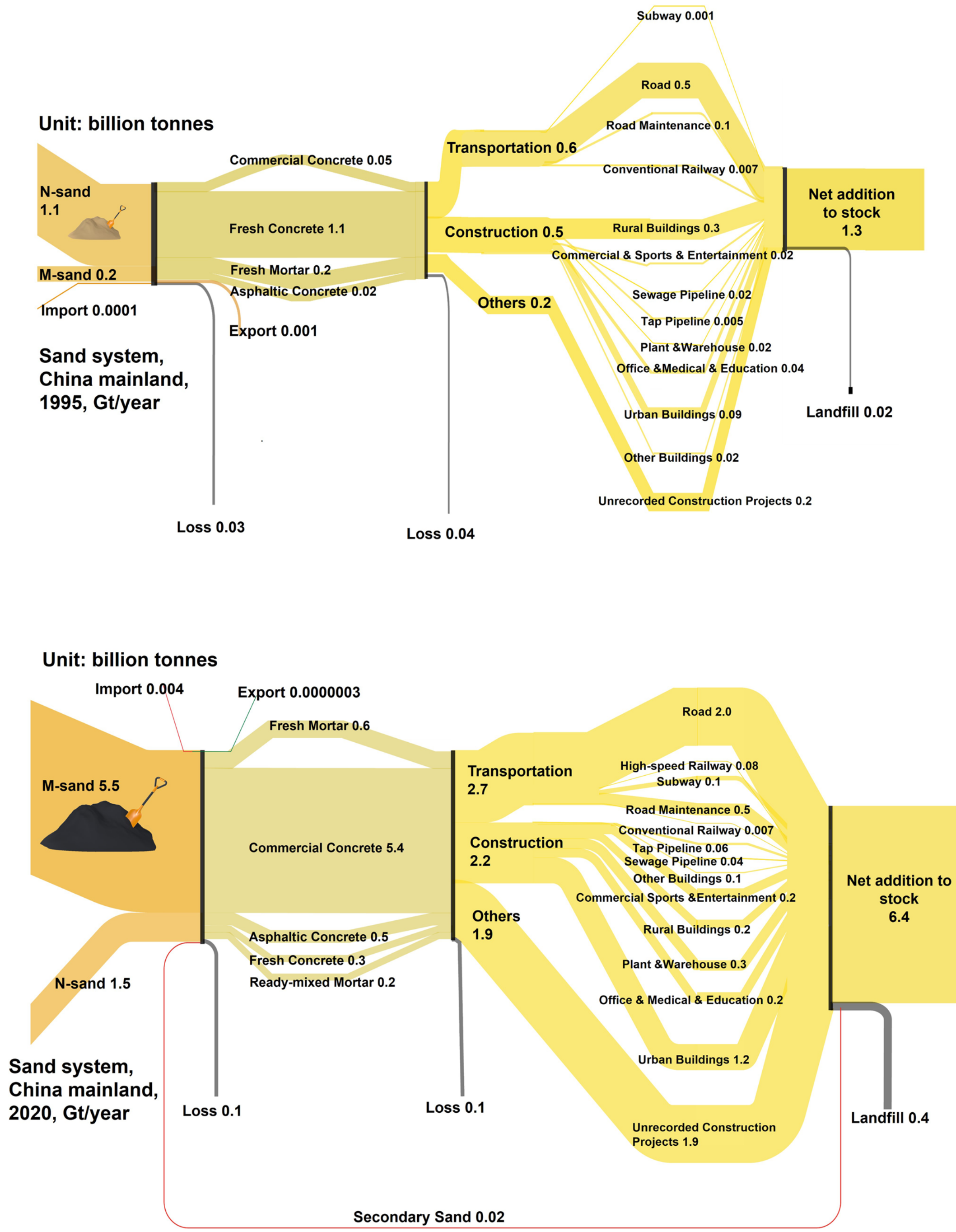

Extended Data Fig. 1 | Sankey diagram of China's sand cycles in 1995 and 2020. Top: Sand cycles in 1995. Bottom: Sand cycles in 2020. System boundary: sand system, China, Gt. Noted, we have no reference for this legend.

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Substantial increase in China's manufactured sand supply since 2010

In the format provided by the authors and unedited

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S1. Detailed methods

S1.1 Sand definition, sand types, and system boundary

Sand is a naturally occurring or manufactured material composed of rock particles with a grain size less than 4.75 mm[1,2]. Sand is used in several manufacturing processes, and this study focuses on “construction sand.” Construction sand usually comes from river and marine sand or crushed stones rather than desert sand (which is too round and smooth to provide desired functions[3]). In this study, sand is a major constituent in building adhesives (concrete and mortar) used in construction, excluding soft, weathered rock particles. It is notable that the standard of construction sand in China is not fully consistent with that of other countries[4]. When carrying out a sand material flow analysis (MFA) for a different country, it is necessary to use the corresponding standards of that country.

According to the source and processing technologies, sand can be divided into natural, manufactured, and secondary[5–7]. Detailed descriptions of the three types of sand are as follows (Fig. S1 and Table S1):

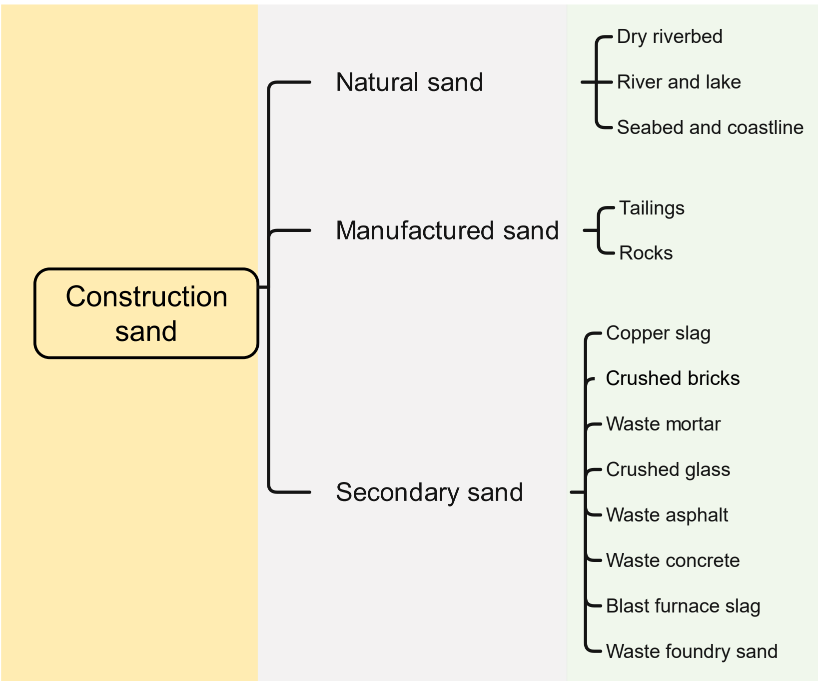

Fig. S1. Classification of natural, manufactured, and secondary sand. *Sources*: References 8–13

(1) Natural sand is a naturally occurring material that is commonly found in the natural environment, mainly including river sand, lake sand, pit sand, and desalinated sea sand[2]. Pit sand is produced on land, mostly in areas where rivers have dried up.

(2) Manufactured sand refers to rock or mine tailings particles that are made by mechanically crushing and sieving[2]. These tasks need technical monitoring to meet standards for concrete, mortar, and other specific products. It is worth noting that the tailings left in the mining stage can be used to make manufactured sand, like iron ore tailings[14], but not all tailings from the beneficiation process can be used as manufactured sand because they may contain high amounts of sulfides or environmentally harmful additives, like bauxite tailings. In general, the price of manufactured sand is lower than that of natural sand in China[15].

(3) Secondary sand refers to sand that is recycled and reused from end-of-life buildings and other solid wastes[2,7-13]. Normally, secondary sand needs technical testing to achieve the required performance. Furthermore, special chemicals need to be added when making concrete and mortar.

Table S1. Key properties of three sand categories in this study.

	Natural sand	Manufactured sand	Secondary sand
Sources	River sand, pit sand, seabed sand, coastline sand, dredging sand, etc.	Rock and tailings	Construction waste and industrial by-products.
Application	Multi-purpose	Sector specific	Sector specific
Price	Comparatively high	Fluctuates between natural sand and secondary sand	Comparatively low
Reserves	Comparatively scarce	Abundant	Depending on development stage
Main environmental impacts	Human toxicity, marine aquatic ecotoxicity, global warming	Soil erosion, biodiversity loss	——
Particle characteristics	Round particles	Angular particles	Angular particles
% Cubical particles	40%–95%	30%–50%	——
Grading	Open/straight	Packed/dense	——
Water absorption	Low	Low	High
Fineness modulus	Low	High	High
Durability	High	Fine	Fine
Compressive strength	Fine	High	High
Sieve analysis	Natural	Artificial	Artificial
Deleterious substances	Organic impurities	Clay and other fine materials	Clay and other fine materials
Advantages	Superior properties	Controllable quality and stable performance	Low price, wide range of raw materials, and environmentally friendly
Disadvantages	High mining costs and resource scarcity	Firmness is slightly poor; extensive technological processes are required.	The process is complex, and additional reagents are needed to improve firmness and other properties.

Sources: China Aggregate Association[16], China National Standards[2,17], references 18–26

S1.2 Sand MFA framework and data sources

In this study, we quantified the sand flow and stock along the life cycle (Fig. S2) within Mainland China by employing a dynamic MFA method (a widely adopted approach to account for the inflow and outflow of materials within specified time and space boundaries[27]). The life cycle of manufactured sand comprises five stages: mining, fabrication, manufacturing, use, and waste management.

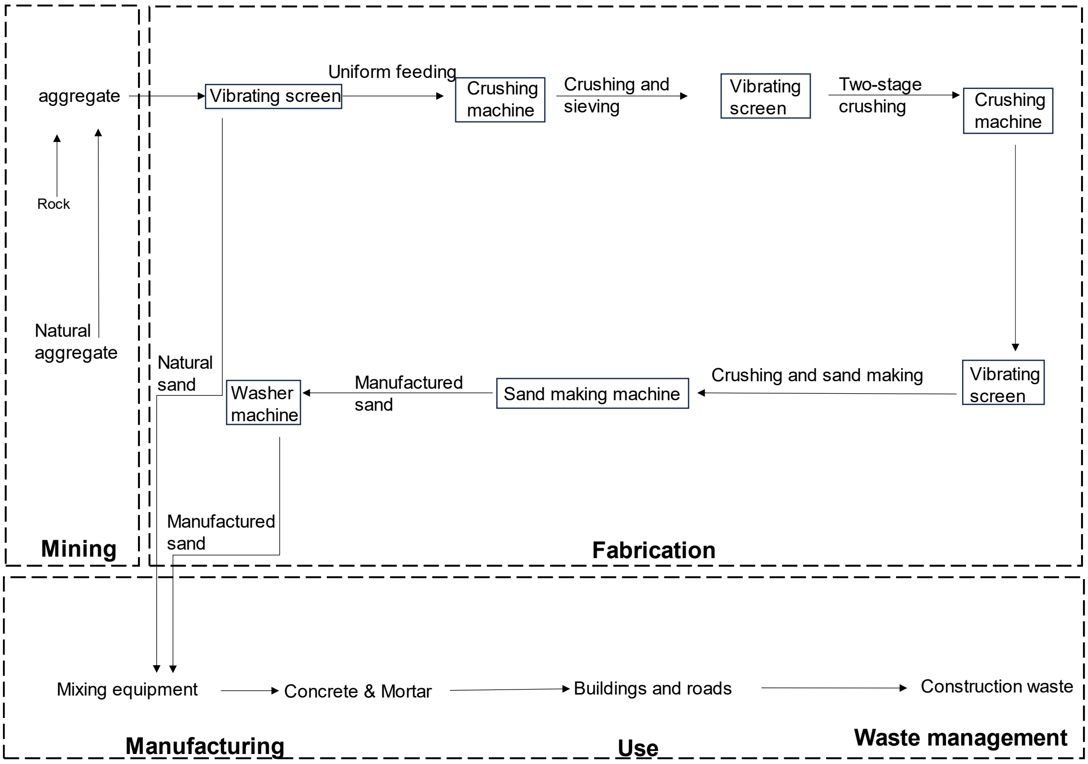

Fig. S2. Life cycle process of sand.

(1) In the mining and fabrication stage, manufactured sand is extracted from natural rocks and tailings. The main process is the crushing process, which has two types of technologies—dry craft and wet craft (Table S2). The main advantage of wet craft is that the product contains less mud and emits no dust pollution. The main disadvantage is that it may produce untreated wastewater that can pollute the environment. The dry craft does not generate wastewater during the production process, and the by-product (stone powder) can be used in construction. The disadvantage is that the production process is dusty. The two types of sand production lines have their advantages and disadvantages and need to be considered in conjunction with local environmental requirements.

Table S2. Comparison of manufactured sand craft.

Comparison	Wet craft	Dry craft
Production efficiency	75%	90%
Cost	Equipment costs and wastewater treatment costs	Equipment costs and dust removal treatment costs
Continuous gradation	No	Yes

Sources: References 28, 29

(2) In the manufacturing stage, sand is processed into concrete and mortar according to the proportion in the mixing station and then transported to construction sites. Depending on local environmental conditions (e.g., temperature, humidity) and construction requirements, the formulations of concrete and mortar vary from place to place.

(3) In the use stage, sand products circulate in society and form in-use product stocks to offer societal services such as buildings and transportation infrastructures.

(4) In the waste management stage, constructions are demolished when their valid lifetimes are reached. The sand in waste concrete and mortar is stacked and discarded as construction waste. A portion may be recycled back into the sand system for processing into aggregates.

Our sand MFA framework is depicted in Fig. S3. Sand flows are divided into sand trade flows, process inflows and outflows, and loss flows. The accounting process for each process stage is described in Table S3, and the detailed data sources are shown in Table S4. The sand coefficients of each stage can be found in Tables S5–S11. Specific accounting instructions are given below.

(1) Inflows and outflows. The total input flows of each stage include inflows and import flows. Each stage's total output flows are outflows, loss flows, and export flows. Total output flows plus net addition to stock are equal to the total input flows following the basic principle of mass conservation. Relevant data can be obtained from the National Bureau of Statistics, UN Comtrade, and China Aggregates Association.

(2) In-use stocks. The in-use sand stock is a summary of net addition to stock from the initial year (defined here as 1995) to a given year. Due to data limitations, we did not consider sand stocks before 1995. The net addition to stock of sand in each year can be calculated by the following equation:

$$\triangle S_i = I_i - O_i \tag{1}$$

where $\triangle S_i$ is net addition to stock, I_i is the total sand input flows, O_i is the total sand output flows. The sand flowing into the system ultimately exists in infrastructures and buildings, while the sand flowing out of the system exists in annual construction waste. The net addition to the stock of sand is the difference between the input flows and output flows.

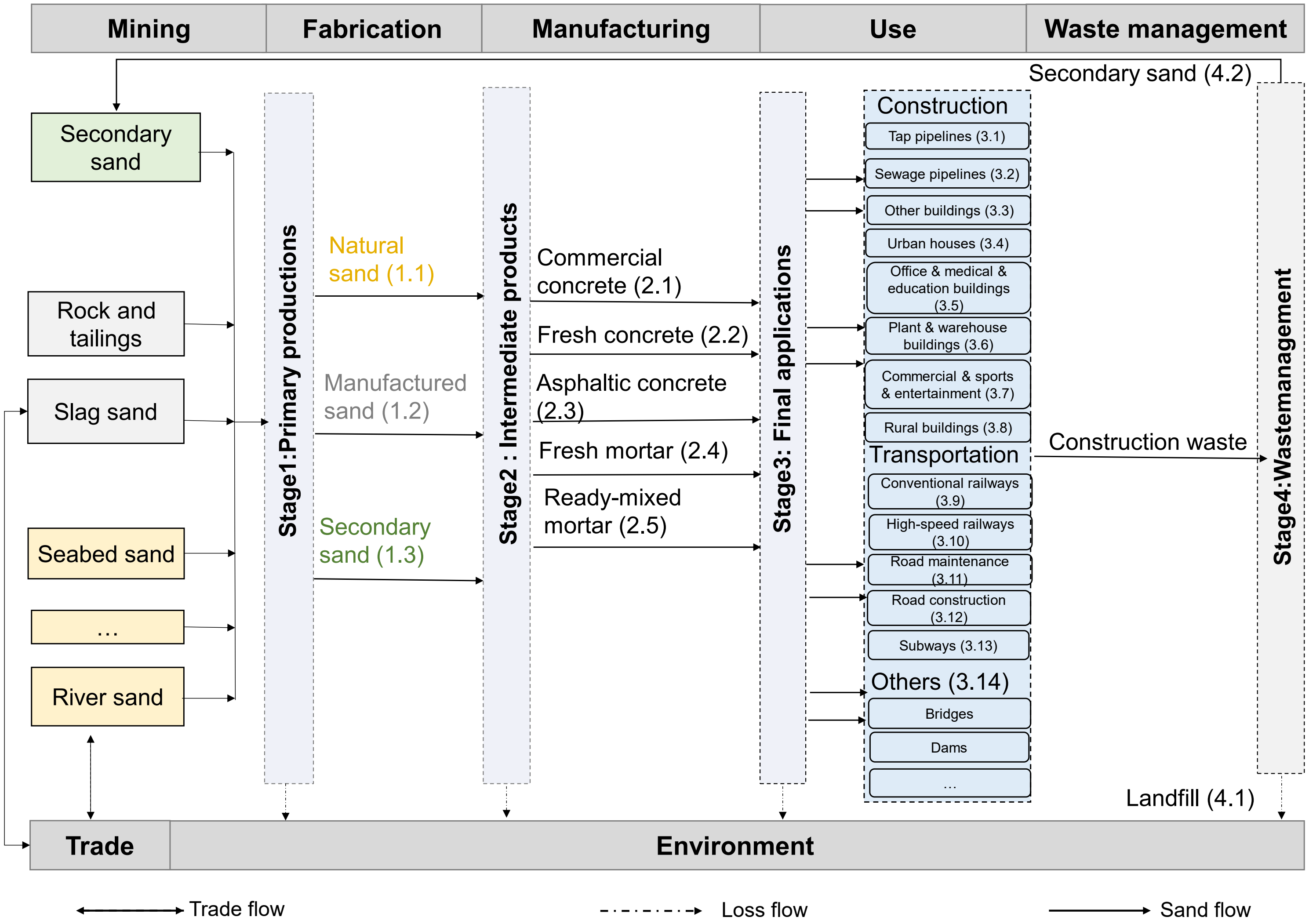

Fig. S3. Material flow accounting framework for sand. Numbers in parentheses are the code names of flows.

Table S3. Calculation information for each flow in the sand system. Numbers in parentheses are the code names of flows.

Processes	Flows	Description	Equations	Data sources
Stage1: Primary products	Inflow (1)	Sum of sand flowing into the system	$\sum_{i=1}^{3}$ Inflow (1.X)	Direct calculation based on mass balance
	Inflow (1.1)	The production of natural sand	Intermediate products / (1-Loss rata) − Amount of manufactured sand − Net increase in sand trade − Amount of recycled aggregate	Calculated by Equation (4) in Methods section
	Inflow (1.2)	The production of manufactured sand	Production of manufactured aggregate × Proportion of manufactured sand	Details in SI Tables S4 and S6, and Fig. S5
	Inflow (1.3)	The production of secondary sand (recycled from construction waste)	Production of construction waste × Concrete proportion × Formula coefficient of concrete × Resource utilization rate of construction waste	China Industrial Solid Waste Network[30], references 31 - 34
	Loss Flow (1)	Sand loss	$\sum_{i=1}^{3}$ Loss flow (1.X)	Direct calculation based on mass balance
	Loss Flow (1.1)	Loss of natural sand	The production of natural sand × Loss rate	Reference 35
	Loss Flow (1.2)	Loss of manufactured sand	The production of manufactured sand × Loss rate	Reference 35
	Import Flow (1)	Import of natural sand	$\sum_{i=1}^{n}$ Import volume	UN Comtrade[36]
	Export Flow (1)	Export of natural sand	$\sum_{i=1}^{n}$ Export volume	UN Comtrade[36]
	Outflow (1)	Sand output	Inflow (1) − Loss flow (1)	Direct calculation
Stage2: Final products	Inflow (2)	Sand in final products	$\sum_{i=1}^{5}$ Inflow (2.X)	Direct calculation
	Inflow (2.1)	Sand in commercial concrete	Production of commercial concrete × Sand proportion in concrete	China Concrete Association[37], reference 31
	Inflow (2.2)	Sand in fresh concrete	Cement consumption coefficient in fresh concrete × (Production of cement + Import of cement − Export of cement) × Proportion coefficient divided by cement and sand in concrete	UN Comtrade[36], National Bureau of Statistics, references 31, 38
	Inflow (2.3)	Sand in asphalt concrete	(Production of asphalt + Import - Export) × Sand proportion in asphalt	UN Comtrade[36],

Processes	Flows	Description	Equations	Data sources
				National Bureau of Statistics, references 39, 40
	Inflow (2.4)	Sand in fresh mortar	Cement proportion in mortar × (Production of cement + Import − Export) × Proportion coefficient divided by cement and sand in mortar × (1 − Proportion of ready-mixed mortar in the total mortar)	UN Comtrade[36], National Bureau of Statistics, references 39–41
	Inflow (2.5)	Sand in ready-mixed mortar	Cement proportion in mortar × (Production of cement + Import − Export) × Proportion coefficient divided by cement and sand in mortar × Proportion of ready-mixed mortar in the total mortar	UN Comtrade[36], National Bureau of Statistics, references 39–41
	Loss Flow (2)	Sand loss	$\sum_{i=1}^{5} \text{Loss flow } (2.X)$	Direct calculation
	Loss Flow (2.1) ~ (2.5)	Sand loss	Sand in final products × Loss rate	Reference 35
	Outflow (2)	Sand output	Inflow (2) − Loss Flow (2)	Direct calculation
Stage3: Final consumption	Inflow (3)	Sand input	$\sum_{i=1}^{14} \text{Inflow } (3.X)$	Direct calculation
	Inflow (3.1)	Sand in tap pipeline	New tap pipe length × Material intensity	References 42, 43
	Inflow (3.2)	Sand in sewage pipeline	New sewage pipe length × Material intensity	References 42, 43
	Inflow (3.3)	Sand in other buildings	New area in other buildings × Sand consumption coefficient	References 44–46
	Inflow (3.4)	Sand in urban houses	New area in urban houses × Sand consumption coefficient	References 44–46
	Inflow (3.5)	Sand in office & medical & education buildings	New area in medical, office and education buildings × Sand consumption coefficient	References 44–46
	Inflow (3.6)	Sand in plant & warehouse buildings	New area in plant and warehouse buildings × Sand consumption coefficient	References 44–46
	Inflow (3.7)	Sand in commercial & sports	New area in commercial, sports, and entertainment buildings × Sand consumption coefficient	References 44–46

Processes	Flows	Description	Equations	Data sources
		& entertainment buildings		
	Inflow (3.8)	Sand in rural buildings	New area in rural buildings × Sand consumption coefficient	References 44–46
	Inflow (3.9)	Sand in conventional railways	New conventional railway operating kilometrage × Sand consumption coefficient	References 47, 48
	Inflow (3.10)	Sand in high-speed railways	New high-speed railway operating kilometrage × Sand consumption coefficient	References 47, 49
	Inflow (3.11)	Sand in road maintenance	Road maintenance operating kilometrage × Sand consumption coefficient	References 47, 49–52
	Inflow (3.12)	Sand in road construction	Road construction operating kilometrage × Sand consumption coefficient	References 47, 49–52
	Inflow (3.13)	Sand in subways	New subway operating kilometrage × Sand consumption coefficient	Reference 53, 54
	Inflow (3.14)	Sand in others	Sand output (2) − Sand input (3)	Direct calculation
	Outflow (3)	Construction waste	Production of construction waste × Concrete proportion × Formula coefficient of concrete	References 30–34
	In-use stock (3)	Sand accumulated in the in-use construction stocks	Inflow (3) − Outflow (3)	Direct calculation
Stage4: Waste management	Inflow (4)	Sand input	Outflow (4)	Direct calculation
	Outflow (4)	Sand output	$\sum_{i=1}^{2}$ Inflow (4.X)	Direct calculation
	Outflow (4.1)	Landfill of sand in the environment	Production of construction waste × Concrete proportion × Formula coefficient of concrete × (1 − Resource utilization rate of construction waste)	References 30–34
	Outflow (4.2)	Recycling amount of secondary sand from construction waste	Production of construction waste × Concrete proportion × Formula coefficient of concrete × Resource utilization rate of construction waste	References 30–34

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Table S4. Data sources for sand material flow analysis.

Data description	Sources	Credibility
Trade data	UN Comtrade, details see Section S2.3	High
Construction waste production	China Industrial Solid Waste Network[30]	High
Concrete production	China Construction Concrete Association[37]	High
Cement production	The cement production data comes from the National Bureau of Statistics (1998–2020, and the literature (1995–1997)[38]	High
Mortar production	China Iron Armor Engineering Machinery Network[40]	High
Asphalt production	National Bureau of Statistics[55]	High
Tap pipe length	Statistical Yearbook of Urban Rural Development in China[42]	High
Sewage pipe length	Statistical Yearbook of Urban Rural Development in China[42]	High
Buildings area	China Statistical Yearbooks on construction[44]	High
Subway length	China Urban Rail Transit Association[53]	High
Conventional railway length	Statistical Bulletin on the Development of the Transport Sector[47]	High
High-speed railway length	Statistical Bulletin on the Development of the Transport Sector[47]	High
Road maintenance length	Statistical Bulletin on the Development of the Transport Sector[47]	High
Road length	Statistical Bulletin on the Development of the Transport Sector[47]	High
Loss rate for each process	Reference 35, summarized in Table S9	Medium
The resource utilization rate of construction waste	China Industrial Solid Waste Network[30], references 32–34	High
The production of manufactured aggregate and its manufactured sand proportion	The production data of manufactured aggregate are presented in Table S5. The manufactured sand proportion of manufactured aggregate is from reference 31.	Medium
Concrete content in construction waste	References 33, 34	Medium
Concrete formulation	Reference 31	Medium
Mortar formulation	References 39–41	Medium
Asphalt formulation	References 39, 41	Medium
Sand intensity in pipelines	Reference 43	High
Sand consumption coefficient in buildings	References 45, 46	Medium
Sand consumption coefficient in roads	References 49–51	High
Sand consumption coefficient in subways	Reference 54	Medium
Sand consumption coefficient in railways	References 48,49	Medium

Table S5. Sand intensity of buildings (kg/m^2).

Year	Urban commercial	Urban industrial	Urban residential	Rural
1995	658	518	454	418
1996	660	524	456	422
1997	669	536	462	427
1998	673	541	464	432
1999	675	547	466	444
2000	677	552	467	450
2001	668	548	460	450
2002	680	563	468	476
2003	678	566	467	481
2004	676	568	465	480
2005	674	571	464	480
2006	672	574	462	475
2007	670	576	461	485
2008	658	572	453	486
2009	666	581	458	485
2010	664	584	457	484
2011	662	586	455	479
2012	660	588	454	478
2013	659	591	452	473
2014	657	593	451	477
2015	655	596	449	477
2016	653	598	448	481
2017	652	600	447	507
2018	650	602	446	479
2019	649	604	445	474
2020	647	607	443	476

Sources: References 45, 46

Table S6. Historical data of China's manufactured aggerate with their data sources and credibility.

Year	Manufactured aggerate (sand, gravel, stone mix)	Data source	Credibility
1995	7.3	Similar to a previous study[56], we obtain the extrapolation of their historical trends based on their relationships with GDP (see Fig. S4)	Low
1996	8.3		Low
1997	9.0		Low
1998	9.7		Low
1999	10.5		Low
2000	11.9		Low
2001	13.2		Low
2002	14.8		Low
2003	17.5		Low
2004	20.8		Low
2005	25.0	Reference 57	High
2006	30.0	Reference 57	High
2007	37.0	Reference 57	High
2008	43.0	Reference 57	High
2009	52.0	Reference 57	High
2010	64.0	Reference 57	High
2011	91.2	References 58, 59	High
2012	106.6	References 58, 59	High
2013	123.0	References 58, 59	High
2014	131.7	References 58, 59	High
2015	125.9	References 58, 59	High
2016	129.5	References 58, 59	High
2017	133.7	References 58, 59	High
2018	130.6	References 58, 59	High
2019	141.1	References 58–60	High
2020	137.3	Reference 60	Medium

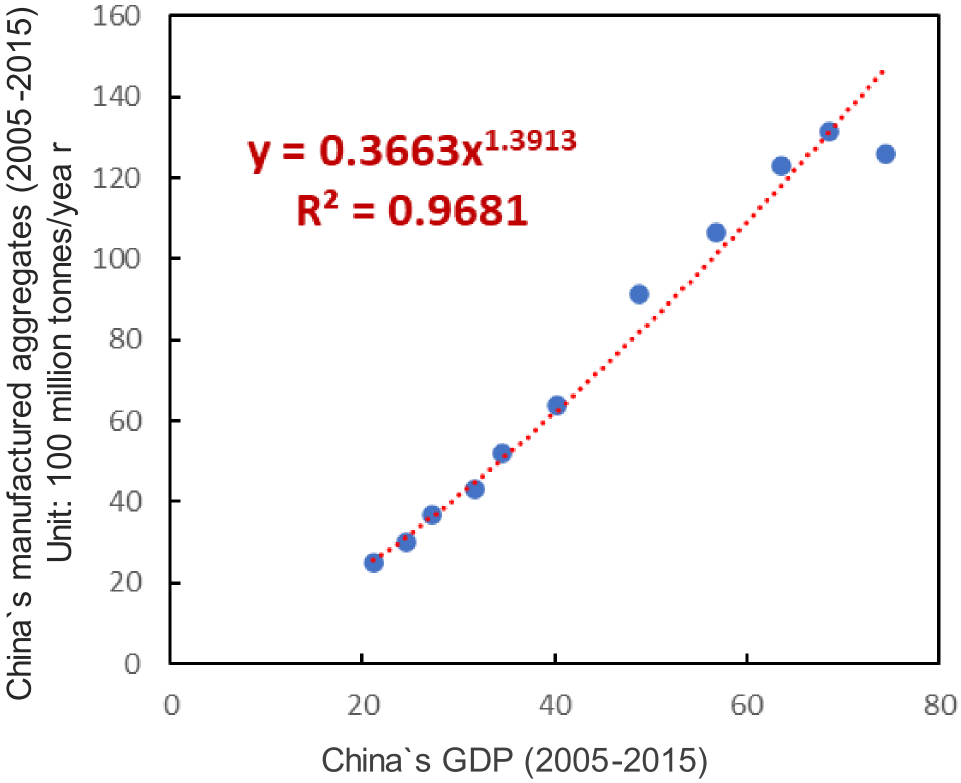

Fig. S4. The regression relationship between GDP (Trillion RMB) and manufactured aggerate during 2005-2015 to estimate the historical data of manufactured aggerate from 1995 to 2004.

Table S7. Sand intensity of roads (tonne/km).

Road projects	Road construction (1995–2000)	Road construction (2001–2020)	Road maintenance (1995–2000)	Road maintenance (2001–2020)
National high-speed roads	19868	14192	259	363
National Class 1 roads	6784	4846	76	106
National Class 2 roads	6103	4360	38	53
Other national roads	4744	3389	33	46
Rural roads	4010	2865	34	47

Note: The sand consumption coefficients of the highway were calculated based on the sand and gravel consumption coefficients and the sand and gravel ratio in the mix of sand and gravel. *Sources*: References 49–51.

Table S8. Sand intensity of railways, subways, and pipelines.

Construction projects	Sand intensity (tonne/km)
Conventional railways	1960[34,49]
High-speed railways	29451[49]
Subways	66885[43]
Pipelines	700[54]

Table S9. Sand loss coefficients.

The processes of sand production	Loss coefficients (%)
Primary production	2.0
Fresh concrete	3.0
Commercial concrete	1.0
Fresh mortar	2.5
Ready-mixed mortar	2.5
Asphalt concrete	2.0

Source: Reference 35.

Table S10. Ratio of sand to cement/asphalt based on designed product recipes.

Component	Cement concrete	Mortar	Asphalt concrete
Sand	2.583	3.57	6
Cement	1	1	/
Asphalt	/	/	1

Note: Different grades of concrete and mortar have different mix ratios. In this study, the mix ratio of M20 was used to calculate the proportion coefficient of sand to cement in the mortar, and the weight proportion was used for concrete. *Sources*: References 31, 39, 41.

Table S11. Cement consumption proportions in different cement products.

Year	Ready-mixed mortar (%)	Fresh mortar (%)	Commercial concrete (%)	Fresh concrete (%)
1995	—	9.00	3.85	87.15
1996	—	9.00	4.26	86.74
1997	—	9.00	4.87	86.13
1998	—	9.00	6.33	84.67
1999	—	9.00	6.86	84.14
2000	—	9.00	8.78	82.22
2001	0.01	8.99	10.49	80.51
2002	0.01	8.99	13.51	77.49
2003	0.02	8.98	17.20	73.80
2004	0.02	8.98	20.93	70.07
2005	0.08	8.92	25.09	65.91
2006	0.12	8.88	27.58	63.42
2007	0.14	8.86	30.96	60.04
2008	0.19	8.81	33.05	57.95
2009	0.21	8.79	32.30	58.70
2010	0.29	8.71	38.86	52.14
2011	0.35	8.65	60.93	30.07
2012	0.42	8.58	47.37	43.63
2013	0.48	8.52	50.21	40.79
2014	0.62	8.38	49.75	41.25
2015	0.76	8.24	53.85	37.15
2016	0.89	8.11	54.03	36.97
2017	1.08	7.92	64.77	26.23
2018	1.35	7.65	72.53	18.47
2019	1.62	7.38	78.81	12.19
2020	1.98	7.02	85.71	5.29

Note: For Table S4, we quantified the demand of sand through the volume of various types of cement production with their corresponding sand additives from the designed cement-sand recipes. The cement consumption of commercial concrete and ready-mixed mortar is obtained through their production and the proportion of cement, while the cement consumption of fresh mortar is obtained from the difference between the total cement consumption of mortar and that of ready-mixed mortar. The cement consumption of fresh concrete is obtained from the total cement production minus the total cement consumption of commercial concrete and mortar. *Sources*: References 31, 37–41

S2. Supplementary results

S2.1 China's sand supply

From the supply side, the development of the sand industry in China can be divided into three periods (Fig. S5). In the initial phase (1995–2000), sand extraction was relatively small (1.7 billion tonnes in 2000), and the annual growth of sand mining was low. In the development phase (2000–2010), the amount of sand mining increased rapidly, with extraction growing to 5.3 billion tonnes in 2010. As the mining scale grew rapidly, environmental impacts and insecurity of river basins garnered public attention. China's sand industry then entered the transitional phase (2011–2020). To reduce adverse impacts from sand mining, the Chinese government closely monitored illegal sand mining and set up the River Chief System to protect rivers, which contributed to the development of the manufactured sand industry. Specifically, the industry developed rapidly after national standards were published in 2011. By 2020, the proportion of manufactured sand supply had gradually increased to around 79% (5.5 billion tonnes).

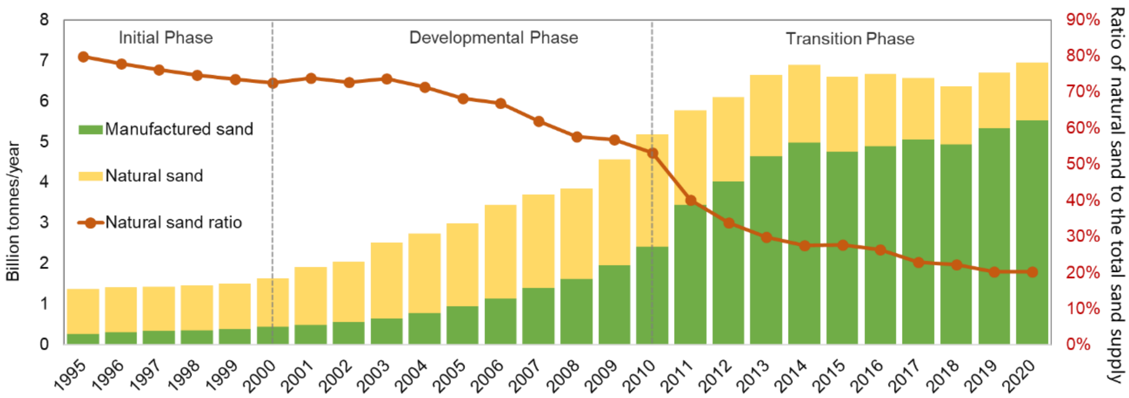

Fig. S5. Main changes in sand mining from 1995 to 2020 in China.

Economic development, urbanization, and industrialization in China have driven the increase in buildings and infrastructure[61], further stimulating the demand for construction sand[62]. Overall, China's sand use increased by a factor of 5.1, from 1.4 Gt in 1995 to 7.0 Gt in 2020 (Fig. S6). During our study period, manufactured sand sourced from mining rocks and tailings substantially replaced natural sand. Manufactured sand has now become the dominant supply in China (~80%).

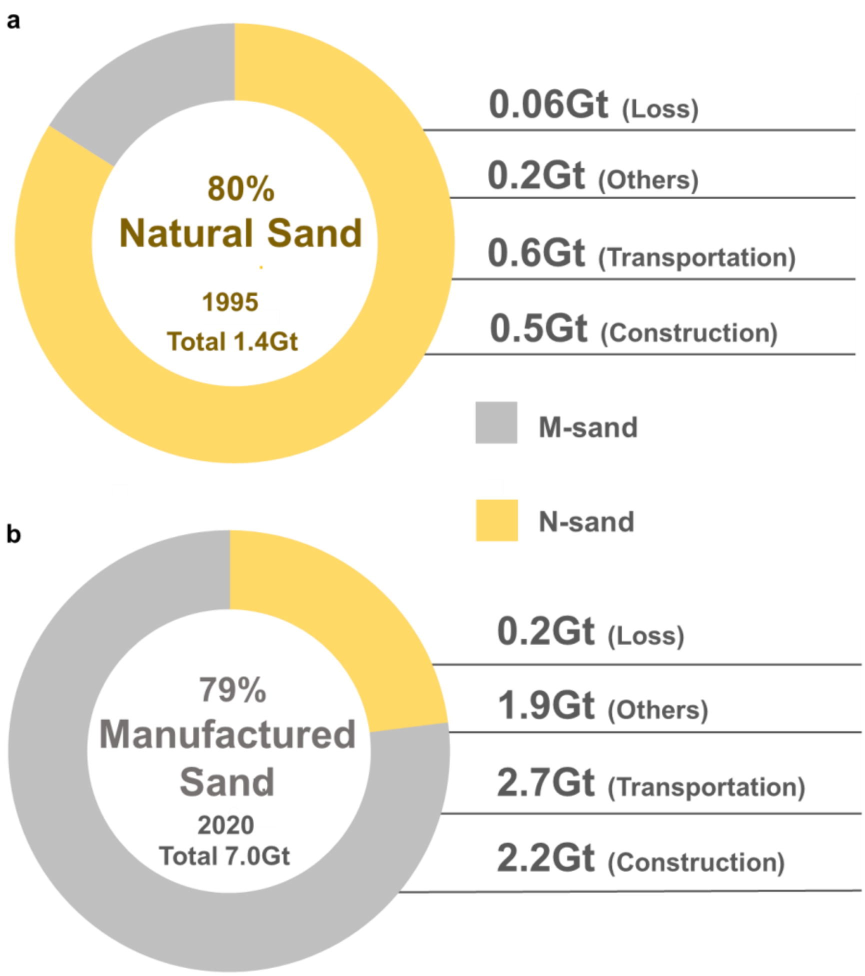

Fig. S6. Sand use evolution from 1995 to 2020. a, China's sand use in 1995. **b**, China's sand use in 2020.

S2.2 China's sand demand

From the demand side, Chinese sand is mainly used to produce adhesive (mortar and concrete) and consumed in buildings and infrastructure (Figs. S7–S8). Despite the relatively large share of concrete production in recent years, approximately 11% of sand was still used to produce mortar yearly. The difference between mortar and concrete is the absence of gravel in the former composition. Final sand productions can be divided into ready-mixed (ready-mixed mortar and commercial concrete) and fresh products (fresh mortar, fresh concrete, and asphalt concrete). The ready-mixed products are produced at specialized plants with low material consumption rates, consistent quality, and relative energy efficiencies. Fresh products are made on construction sites, which are low cost but vary in quality. In particular, the material consumption rate of fresh products is extremely high. To achieve low-carbon development and save resources, China launched the Circular Economic Promotion Law in 2008 to encourage using ready-mixed products. Accordingly, by 2020, the amount of sand used in ready-mixed mortar and commercial concrete had reached 5.5 billion tonnes (80% of total concrete supply).

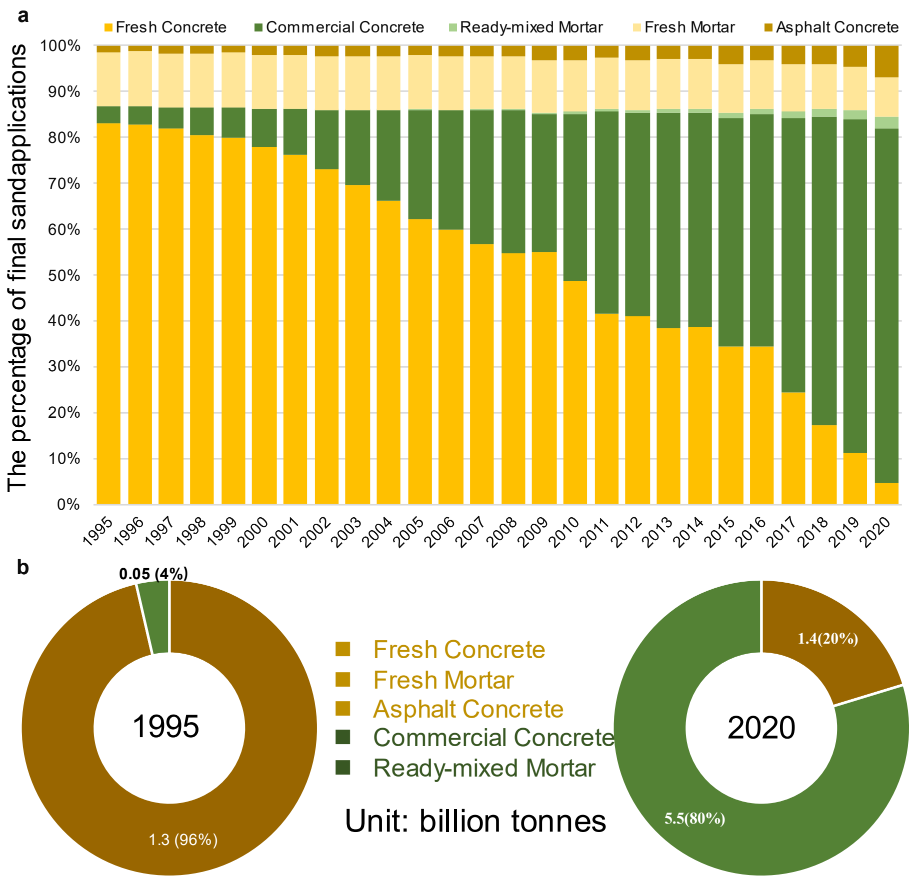

Fig. S7. Sand change in final applications. a, The percentage of sand intermediate products. **b**, The evolution of sand intermediate products.

Changes in the final use of sand in China from 1995 to 2020 are shown in Fig. S8. Sand has been utilized to support urban development and expansion. Furthermore, in response to the financial crisis of 2008, the Chinese central government issued a "4 trillion-yuan economic stimulus plan" to stimulate economic growth, which led to rapid infrastructure development. Consequently, sand consumption climbed sharply after 2008. It was not until 2014 that economic development entered a new phase, and overall consumption of sand declined slightly.

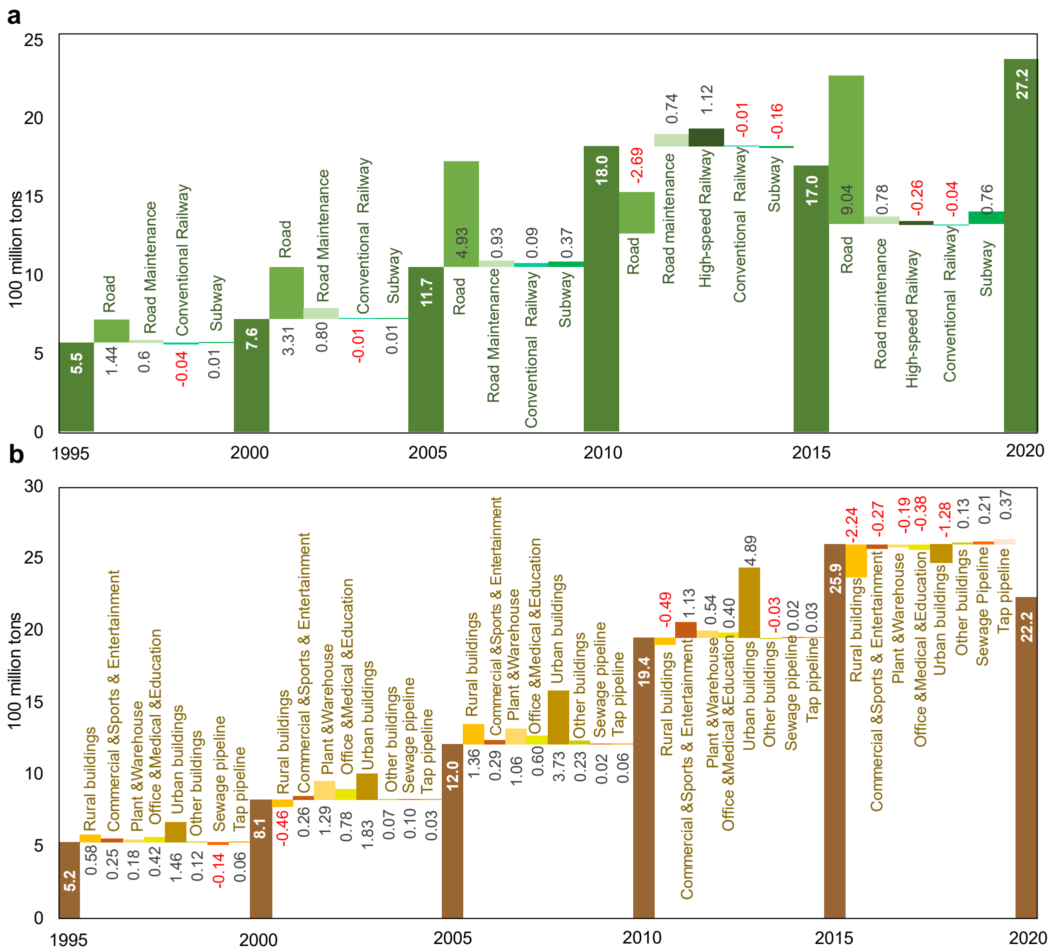

Fig. S8. Growth and driving forces of sand consumption in China from 1995 to 2020 in (a) transportation and (b) construction sectors. Red numbers represent the reduction in sand consumption compared to the previous period.

S2.3 China's sand trade

During our study period, China evolved from an exporter to an importer of sand (Fig. S9). The trade of sand can be divided into two categories: silica and quartz for industrial use, and natural and manufactured (slag) for construction use. Before paying attention to depleting natural sand resources, China was an exporter of sand. However, with the continuous increase of river disasters and expansion of demand, the import of construction sand in China exceeded its export after 2017. Nevertheless, the traded volume of construction sand is much smaller than the domestic supply. In comparison, the situation of industrial sand is the opposite, especially for high-purity quartz sand used to manufacture chips. As China does not have enough qualified high-purity quartz ores, China mainly imported them from foreign countries.

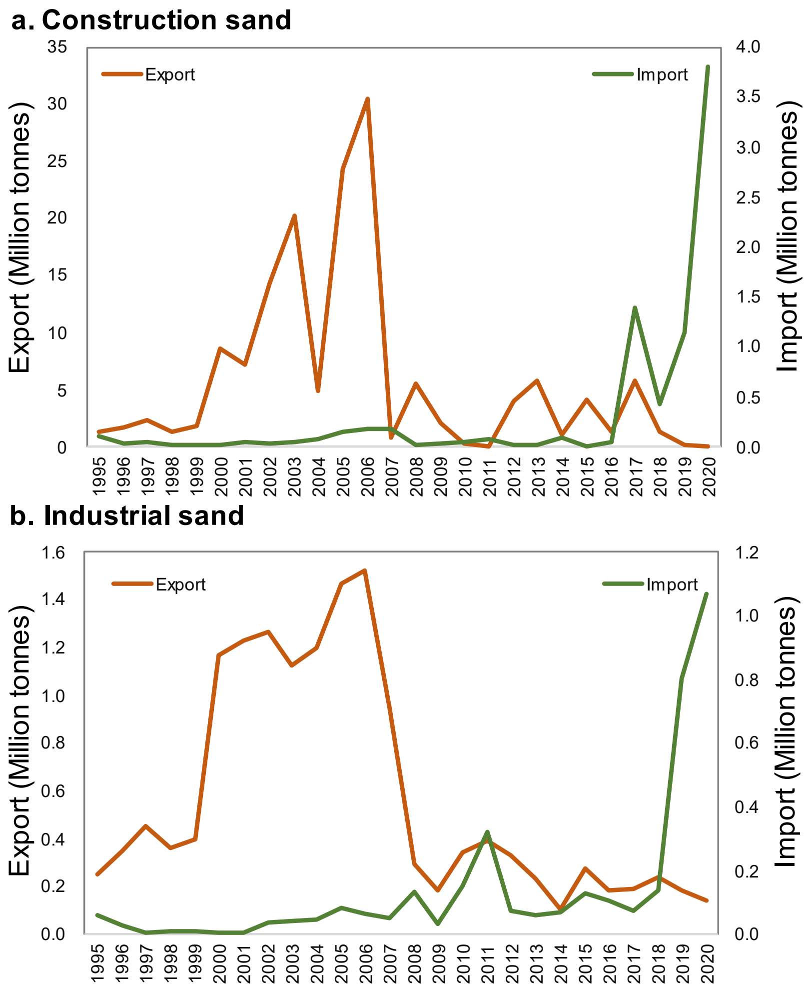

Fig. S9. Analysis of China's sand trade. a, The trade evolution of construction sand. **b**, The trade evolution of industrial sand. The data are from Uncomtrade[36].

S2.4 China's sand loss and recycling

Sand loss in China is much higher than recycled quantities (Fig. S10). The loss is mainly from the process of manufacturing, use, and landfill (construction waste sent to landfills), which was as high as 0.6 billion tonnes in 2020, and the cumulative loss of sand was 7.4 billion tonnes during 1995–2020.

The recycling of sand in China is quite limited due to its low prices and the misperception of sand abundance. Our results indicate there was little recycled sand in China until 2007, when it increased from 0.8 million tonnes to 20.9 million tonnes in 2020. The main reason was the high cost of recycling construction waste. Recycled construction waste is mainly broken into reused aggregates, which can replace the gravel component in building materials, and rarely processed into sand due to the expense. The recycled aggregates route has been applied in projects such as airports[63], large buildings[64], and other large construction projects. Secondary sand in the form of concrete rather than reused aggregates returned into the sand system has not been used on a large scale.

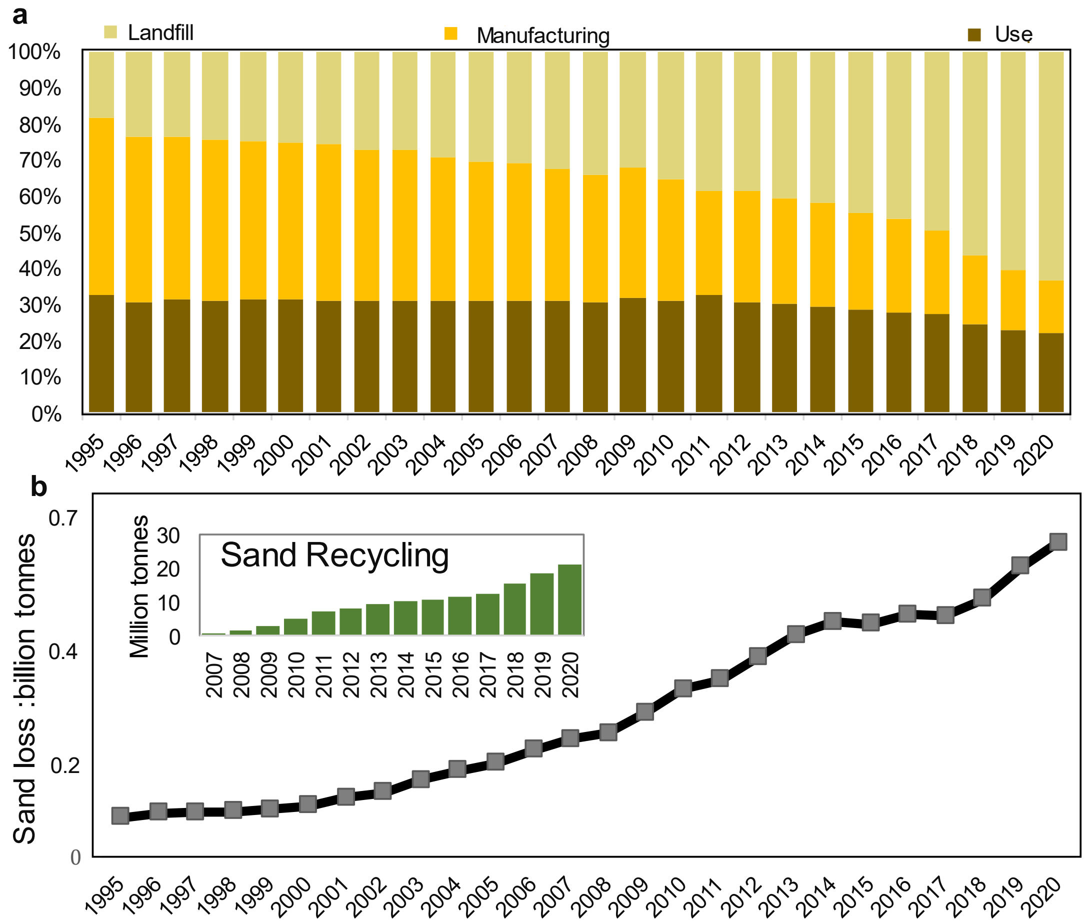

Fig. S10. Sand loss and recycling in China from 1995 to 2020. a, The percentage of loss in different sand stages. **b**, The annual amount of sand loss and recycling.

S2.5 China's sand management policies

Tracking China's sand management history[1,65–86], we found that on the supply side, the early national sand management tools were the prohibition policies of natural sand mining, such as establishing forbidden mining areas and setting sand mining registration systems (Fig. S11). At the same time, on the demand side, the policy for promoting efficient sand products (ready-mixed products) was published to improve the quality of sand products and reduce sand loss. The natural sand policies triggered the beginning of the manufactured sand industry. The national recognition significantly promoted its development, and many construction projects began to use manufactured sand. Since 2015, China has strengthened its regulatory policies on natural sand. For example, China issued the River Chief System and regulated illegal sand mining activities. At the same time, China gradually strengthened the management of manufactured sand (mining, production, transportation) and began to guide the development of secondary sand. It is worth noting that China has not slackened its control of natural sand at any stage of development.

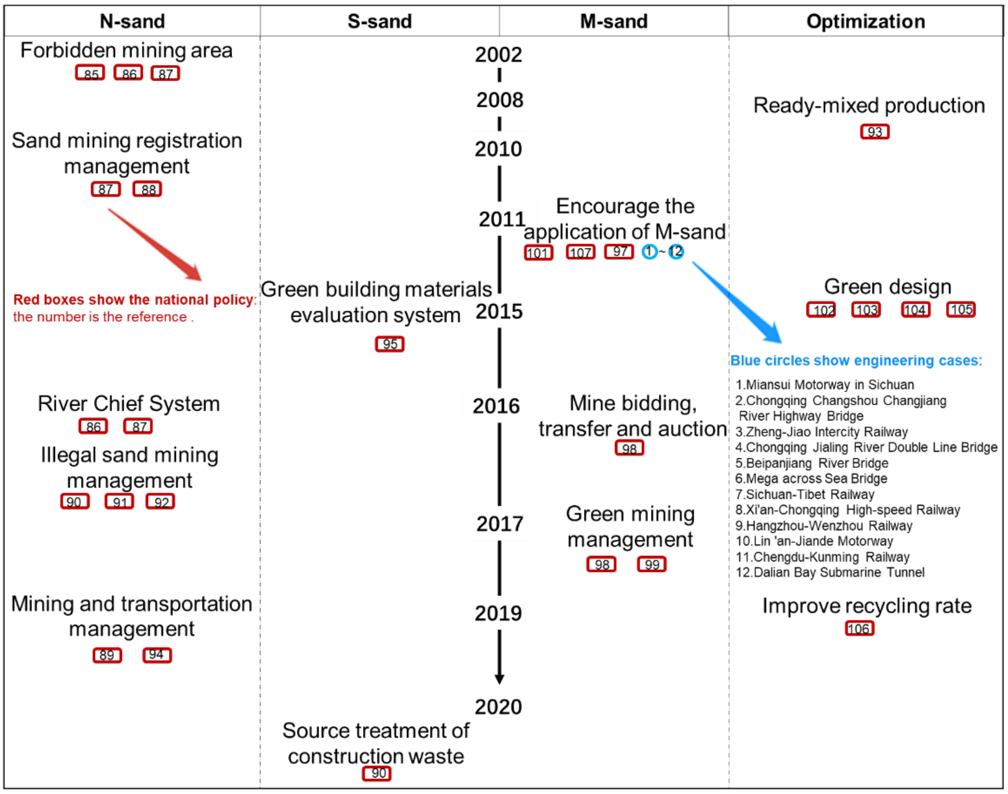

Fig. S11. China's journey to tackle the sand crisis. The red boxes represent references to national policies (regional policies are not shown). The blue circles are engineering cases. Note: M-sand, manufactured sand.

BOX S1: China's River Chief System to prohibit illegal natural sand mining

The "River Chief System" (or "河长制" in Chinese) is a unique river management policy that requires the main governors at all governance levels (from local to provincial) to take responsibility as River Chiefs in the management and protection of certain rivers and lakes in their jurisdictions. This policy was proposed and enacted in 2003 in Changxing County of Zhejiang Province. In 2007, Wuxi City (Jiangsu Province) took the lead in implementing the River Chief System. Finally, the National State Council officially launched it nationwide in 2016.

River chiefs at all levels are responsible for the supervision and management of the rivers and lakes, including protection of water resources, coastline management, water pollution control, water environmental management, traffic control of rivers, participating in the reclamation of lakes, and monitoring excessive sewage, illegal sand mining, destruction of waterways, illegal fishing, etc. By June 2018, there were more than 300,000 River Chiefs in China to frequently monitor the status of their rivers and lakes.

Related links:

http://www.mwr.gov.cn/zwgk/gknr/201612/t20161219_1442337.html;

https://english.www.gov.cn/statecouncil/ministries/202209/14/content_WS63210c0ec6d0a757729dff12.html;

http://www.mwr.gov.cn/hd/zxft/zxzb/fbh20180717/xgzl/201905/t20190523_1208944.html;

http://www.ce.cn/xwzx/gnsz/gdxw/201902/25/t20190225_31550707.shtml.

BOX S2: Improvements in China's National Construction Sand Standard

The sand use standard for the building sector, the main sand consumer, plays a vital role in reshaping the sand supply structure. In China, the National Standard for Construction Sand is one of the most important guidance documents for such purposes.

In 2011, the updated standard of construction sand (GB/T14684-2011), for the first time, proposed and clarified manufactured sand for construction purposes. After 2011, there was another construction boom in China, and various building contractors began to widely adopt the use of manufactured sand in new buildings. Due to the rich availability and cost competitivity of manufactured sand vs. natural sand, the supply of manufactured sand quickly replaced that of natural sand and dominated the market.

Meanwhile, this construction standard also updated the raw material standard, the inspection standard, and the method standard (dry craft or wet craft request, the process, the essential factor, instructions in the crafts, etc.) of manufactured sand, which helps ensure the technical quality of manufactured sand products and avoid the use of poor-quality sand in buildings. This improvement boosts technical advances and sustainable development of manufactured sand usage.

In 2021, the Ministry of Housing and Urban Rural Development of the People's Republic of China issued the National Standard of General Code for Concrete Structures, which further regulates the use of manufactured sand in concrete structures.

Related links:

https://www.chinesestandard.net/PDF/English.aspx/GBT14684-2011.

https://www.chinesestandard.net/PDF/English.aspx/GB55008-2021.

S2.6 Uncertainty analysis

(1) Uncertainty analysis of sand demand in intermediate products

We performed the Monte Carlo simulation of sand demand in intermediate products with around 1,000,000 runs. The corresponding results for each intermediate product with its uncertainty zone are presented in Fig. S12.

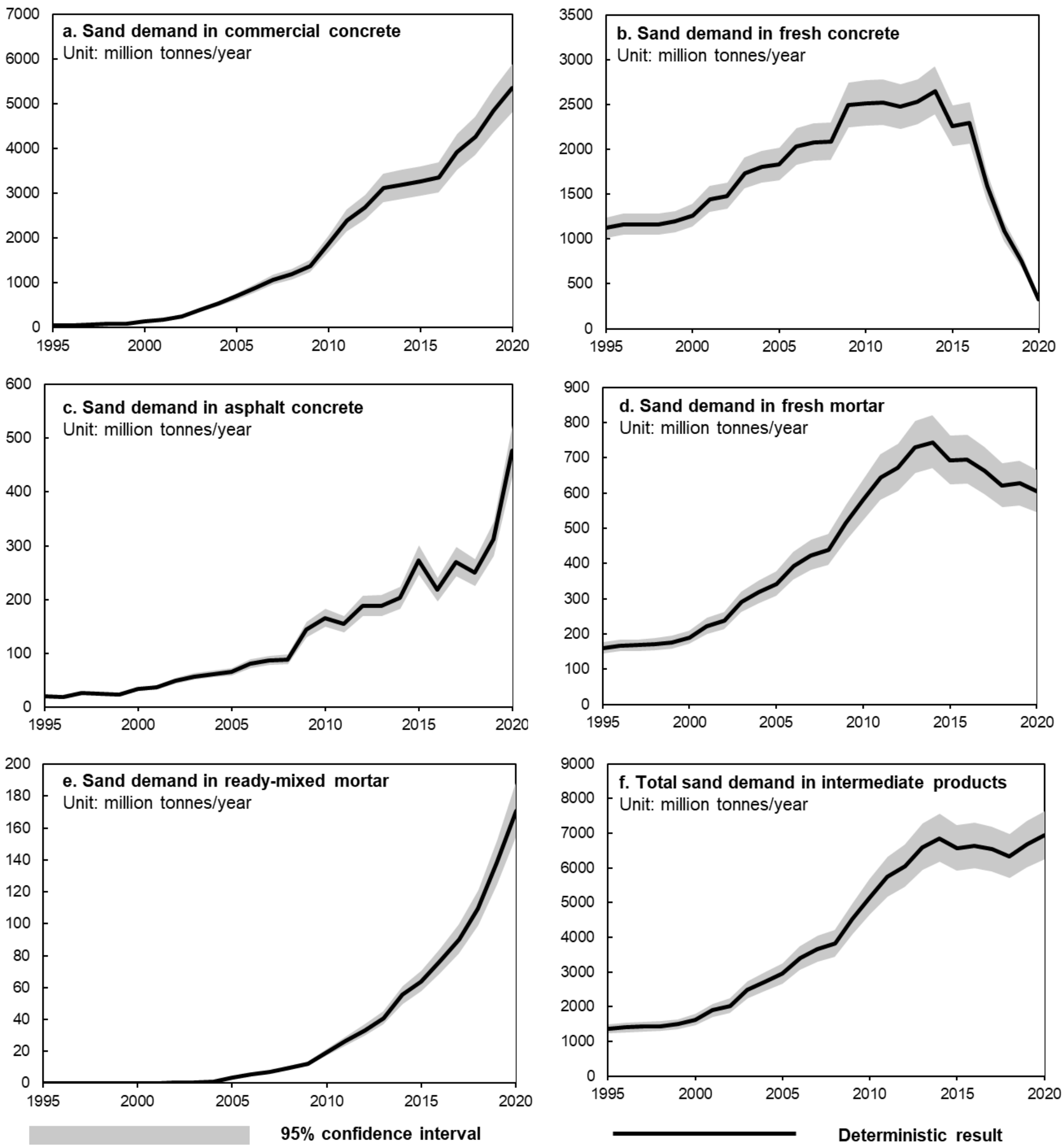

Fig. S12. Uncertainty analysis of China's sand demand in various intermediate products. **a-f** present the demand (for each figure, 95% confidence interval for the error bands and center as the mean value of Monte Carlo simulation) of commercial concrete, fresh concrete, asphalt concrete, fresh mortar, ready-mixed mortar, and total amount, respectively**.**

(2) Uncertainty analysis of sand demand in final applications

Similar to the processes illustrated in Fig. S12, we performed the Monte Carlo simulation of sand demand in final applications with around 1,000,000 runs. The corresponding results for each application and their specific products with uncertainty zones are presented in Figs. S13–S16.

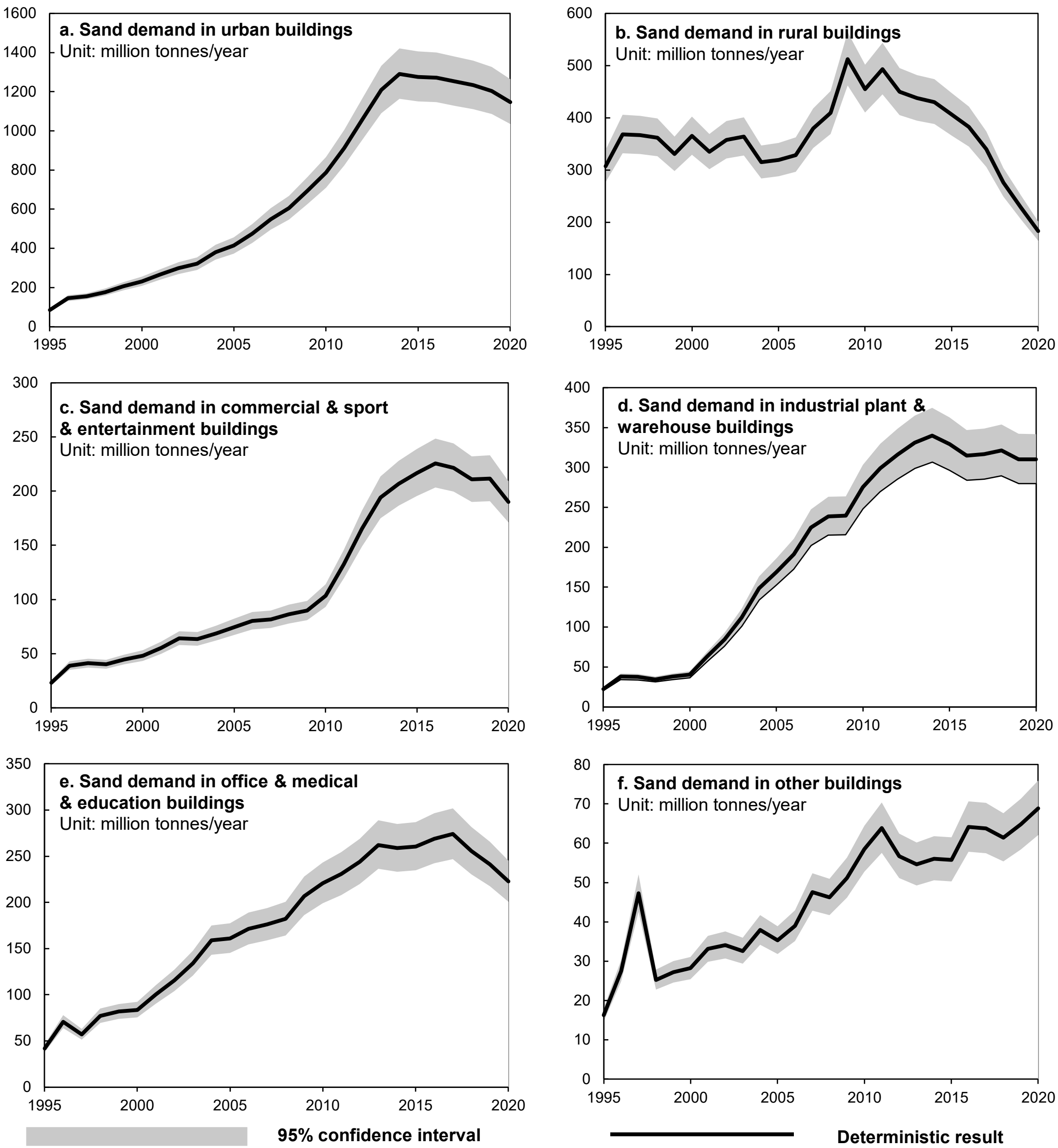

Fig. S13. Uncertainty analysis of China's sand demand in various buildings. a–f present the demand (for each figure, 95% confidence interval for the error bands and center as the mean value of Monte Carlo simulation) of urban, rural, commercial & sport & entertainment, industrial plant & warehouse, office & medical & education, and other buildings, respectively.

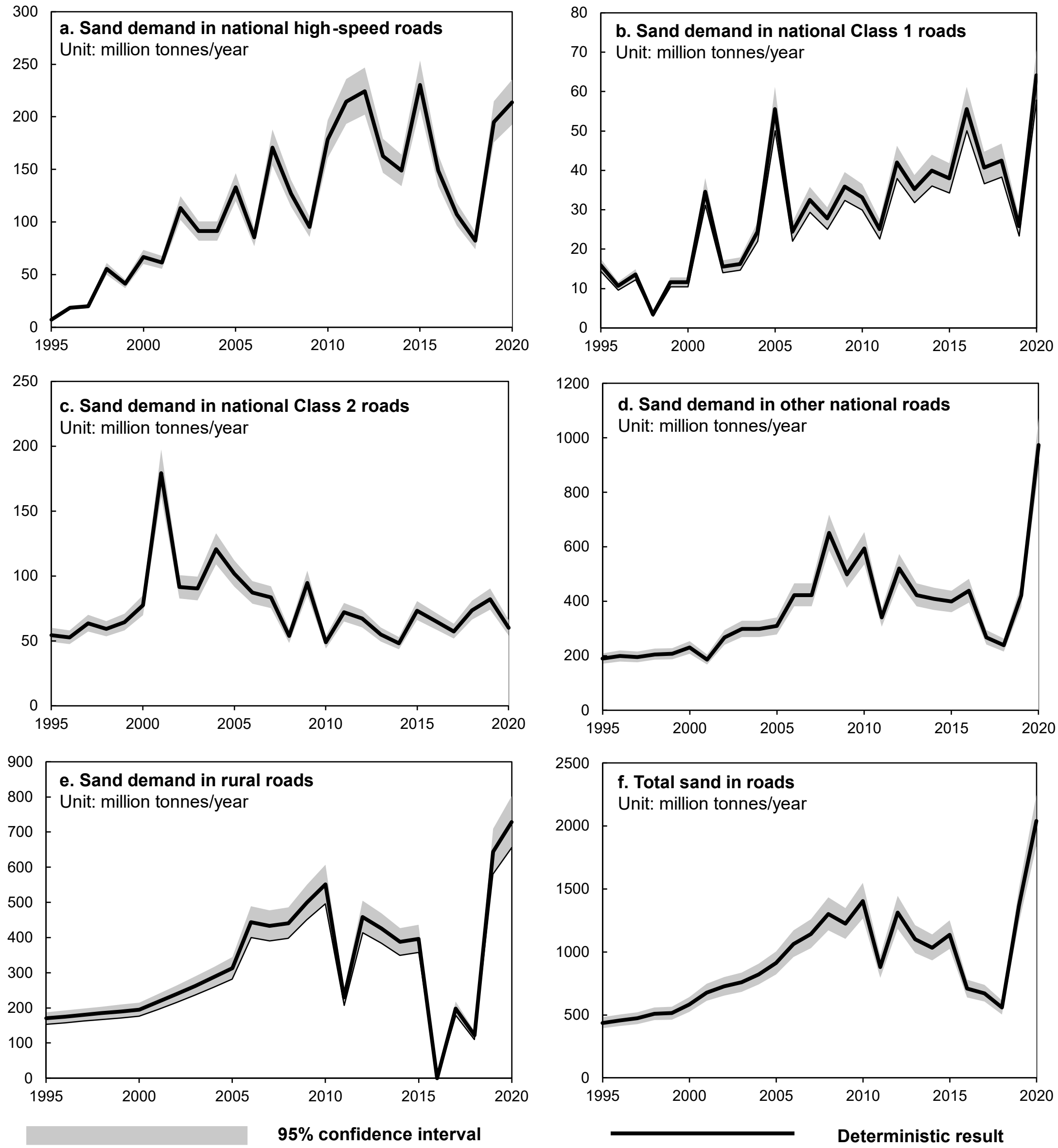

Fig. S14. Uncertainty analysis of China's sand demand for various roads. a–f present the demand (for each figure, 95% confidence interval for the error bands and center as the mean value of Monte Carlo simulation) of national high-speed, national class 1, national class 2, national other classes, rural, and total roads, respectively.

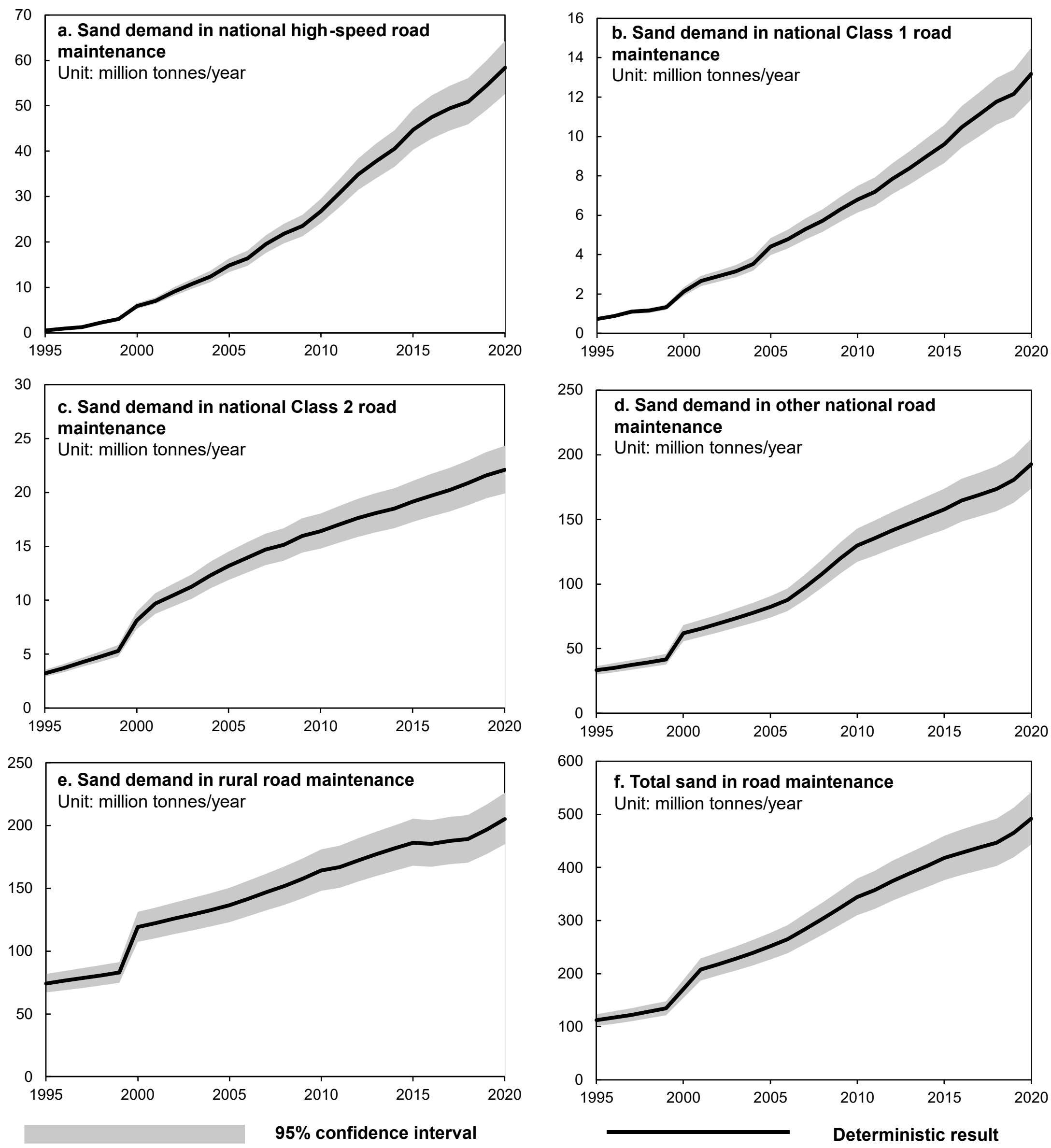

Fig. S15. Uncertainty analysis of China's sand demand for maintenance of various roads. **a–f** present the sand demand (for each figure, 95% confidence interval for the error bands and center as the mean value of Monte Carlo simulation) for maintaining national high-speed, national class 1, national class 2, and other national roads, rural roads, and total sand for road maintenance, respectively.

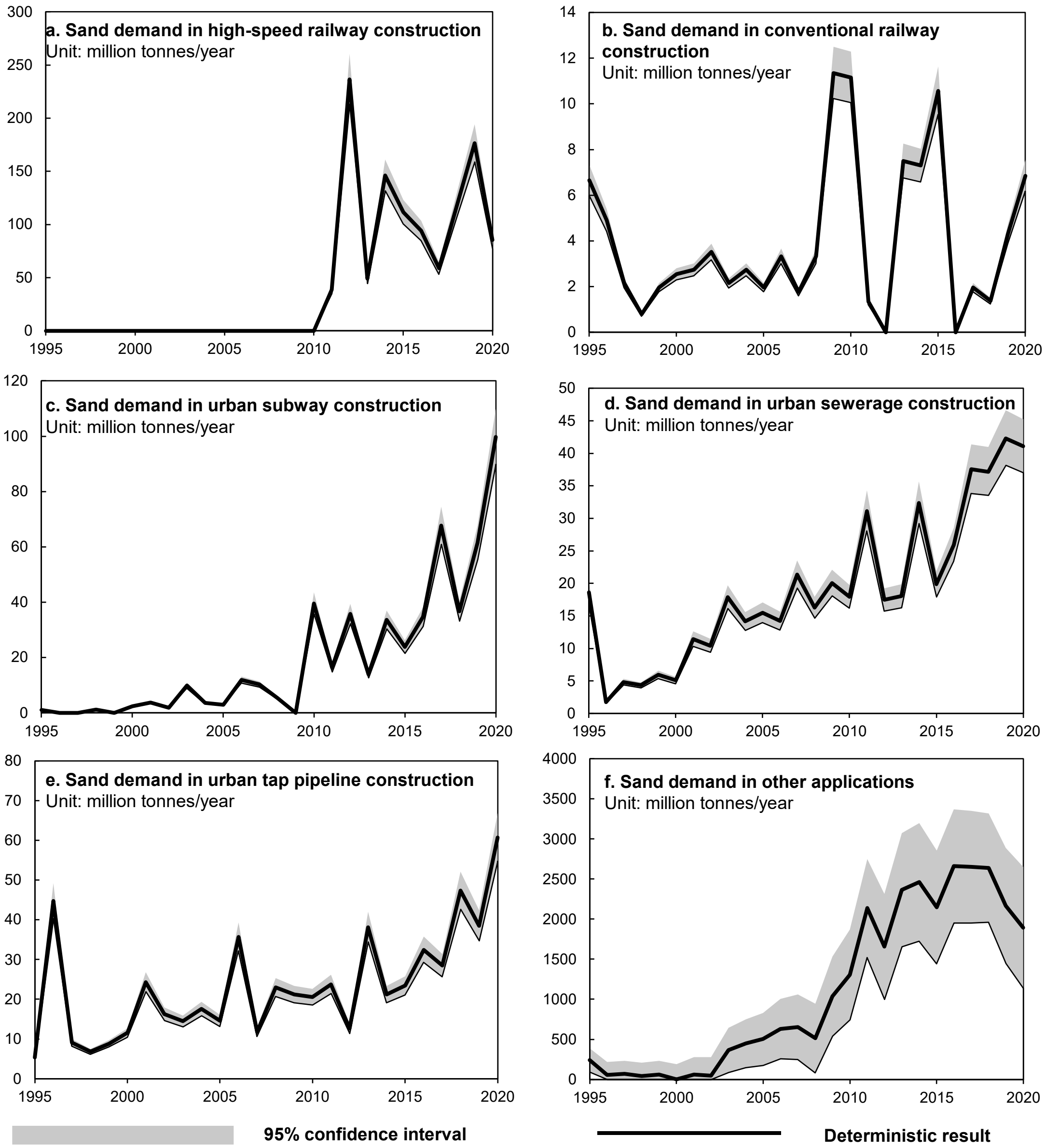

Fig. S16. Uncertainty analysis of China's sand demand for construction of other infrastructure. a–f present the sand demand (for each figure, 95% confidence interval for the error bands and center as the mean value of Monte Carlo simulation) for construction of high-speed railways, conventional railways, urban subways, urban sewerage, urban tap pipelines, and other applications, respectively.

(3) Uncertainty analysis of sand supply from different sources

We performed the Monte Carlo simulation of sand supply from four supply channels with around 1,000,000 runs, and present the corresponding results for each supply trend with uncertainty zones in Fig. S17.

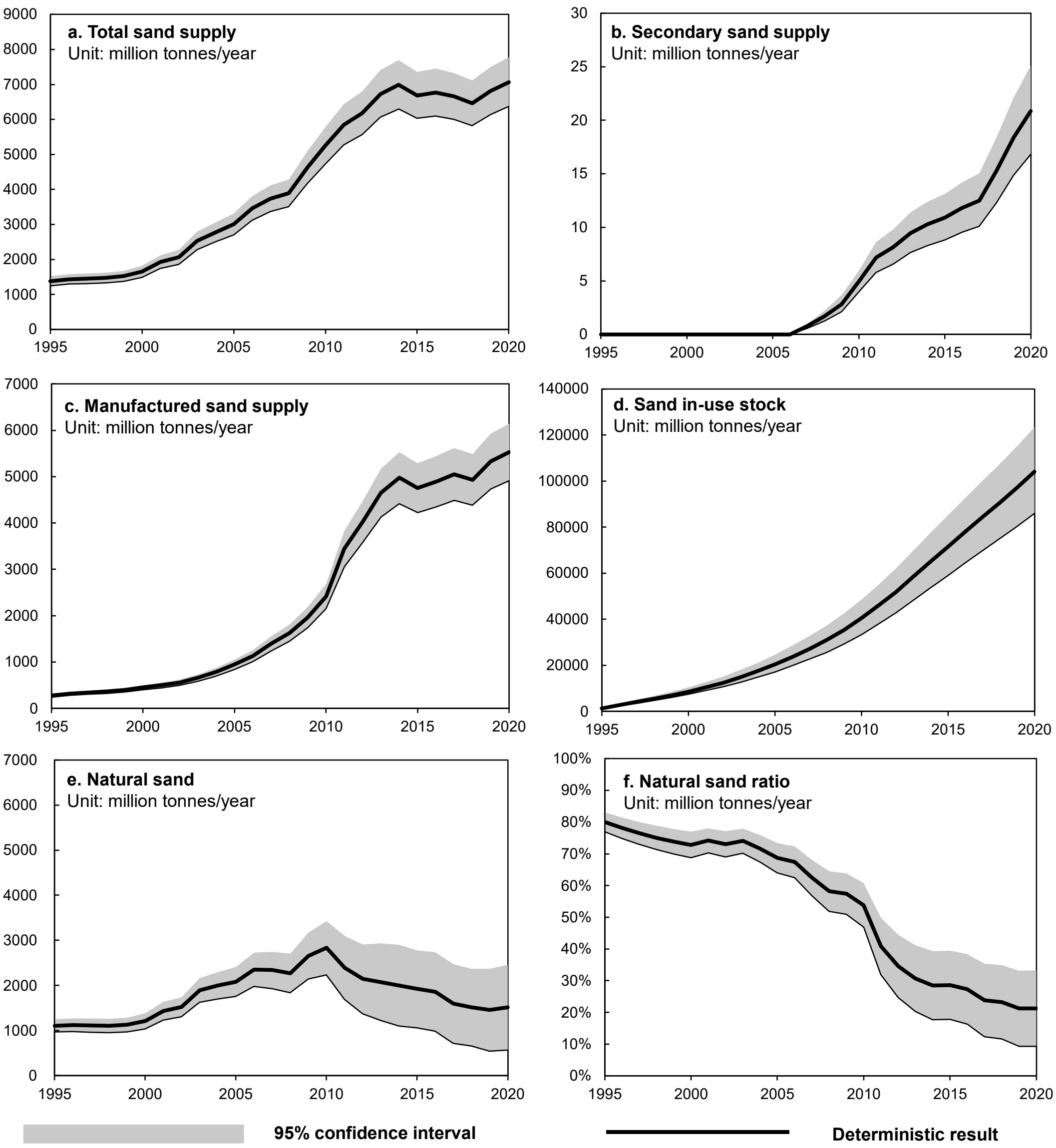

Fig. S17. Uncertainty analysis of China's sand supplies, in-use stock, and natural sand supply ratio. a–c and **e** present the total, secondary, manufactured, and natural sand supplies (for each figure, 95% confidence interval for the error bands and center as the mean value of Monte Carlo simulation), respectively. **d** and **f** present the historical trend of China's in-use sand stock and natural sand ratio, respectively.

S2.7 Result validation

(1) Comparison of our results for natural sand's proportion with other studies. We validated our results of natural sand's proportion to the total sand supply by finding our results are highly compatible with other diverse sources (Fig. S18).

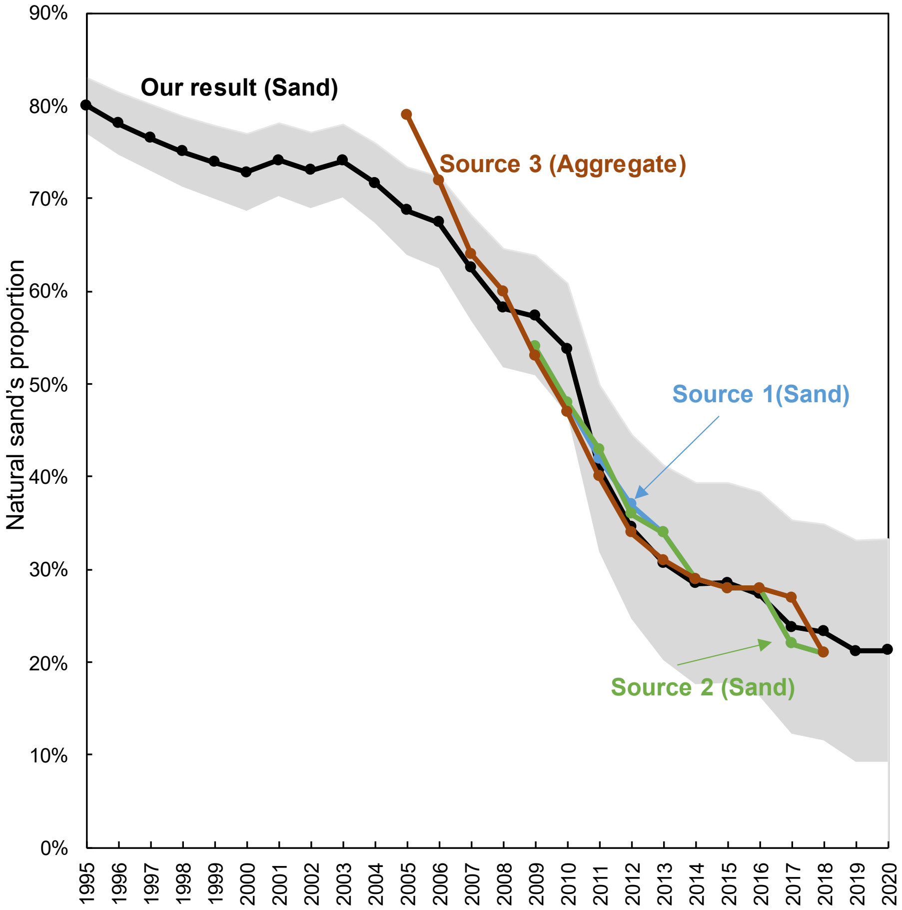

Fig. S18. Comparison of our results for natural sand's proportion to the total sand supply between our work and other studies[87–89]. In this figure, the error bands and center value represent the 95% confidence interval and the mean value of our Monte Carlo simulation. *Data sources*: Source 1[87] Source 2[88] and Source 3[89].

(2) Literature stating China's manufactured sand as the dominant source. We list the literature stating China's manufactured sand as the dominant source (Table S12). We find this literature can support our results that China's manufactured sand has dominated the total sand supply.

Table S12. Related literature stating China's manufactured sand as the dominant source.

Agency	Statement	Reference
Ten Departmental Committees	Manufactured sand and gravel have gradually become the main source of construction aggregate in China.	Reference 77
Zhiyan Consulting, Anxin Stock Research Center	The proportion of manufactured aggregate has increased from 58% in 2011 to 75% in 2019.	Reference 90
Breitbart Architecture Network	The price of natural sand has risen in the past five years, and the proportion of manufactured sand has increased significantly.	Reference 91
Xiamen Architectural Research Institute	In the past decade, the use of manufactured sand in China has been increasing compared to natural sand, and by 2021, the proportion of manufactured sand will reach 80%.	Reference 92
China Aggregates Association	Reduce costs by 51.3 million yuan and achieve a 100% utilization rate of manufactured sand. This highway fully utilizes manufactured sand.	References 93, 94
Sina Finance	The report on the development trend of China's manufactured sand equipment market released by China Industry Research Network believes that in the context of relatively tight natural sand resources and increasingly strict mining regulations, the proportion of manufactured sand has significantly increased from 46.6% in 2009 to 78.3% in 2019. In recent years, due to the comprehensive impact of factors such as increased demand for manufactured sand, increased application proportion, and overall increase in aggregate prices, the sand and gravel aggregate industry has had an impact on upstream crushing. The procurement demand for screening equipment has significantly increased.	Reference 95
China Aggregates Association	The price of natural sand and gravel has doubled in three years, and the proportion of manufactured sand has significantly increased.	Reference 96
Shenzhen LiMu Consulting	Against the background of relatively scarce natural sand resources and increasingly stringent mining supervision, the proportion of manufactured sand in the total domestic supply continues to rise, rising sharply from 46.6% in 2009 to 78.3% in 2018, while production increased from 5.69 billion tonnes to 13.96 billion tonnes in the same period. The average annual compound growth rate is 10.48%. It is estimated that by 2020, the proportion of manufactured sand and gravel will reach at least 80%, and it is estimated that the consumption of manufactured sand and gravel in China will exceed 16 billion tonnes.	Reference 97

S3. Figure Legends

Fig.1 | Historical trends of China's natural sand and manufactured sand supplies. a, Changes in supplies of natural sand and manufactured sand. **b**, Shares of natural and manufactured sand supplies. The orange and green dots in **a** represent the times when specific sand management policies were enacted. The solid lines are presented as the deterministic results, and the shaded areas indicate the 95% confidence interval of the estimates. The detailed introduction of China's sand management measures is presented in Methods, and the additional results are presented in Supplementary Information S2.

Fig.2 | China's sand flows from 1995 to 2020. a, The cumulative flows of sand from 1995 to 2020, system boundary: sand system, China, 1995–2020, Gt; **b** and **c**, Detailed results for intermediate products and final applications in each study year, China, 1995–2020, Gt/year. Note: In this material flow analysis, sand is divided into natural, manufactured, and secondary based on the source materials. These types of sand are used to produce concrete and mortar and are ultimately consumed in construction projects. In **c**, 'others' mainly include dams and waterways, tunnels and bridges, trams and stations, and other unrecorded construction projects. The material flows may not be balanced due to the treatment of rounding numbers. More detailed results are presented in Supplementary Information S2.

Extended Data Fig. 1| Sankey diagram of China's sand cycles in 1995 and 2020. a, Sand cycles in 1995. **b**, Sand cycles in 2020. System boundary: sand system, China, Gt.

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