



Using earth observation for national high resolution dynamic material stock modelling through time; assessing sand consumption in Malaysia from 1989 to 2020

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Abstract

Understanding the spatio-temporal dynamics of volumes of construction materials is becoming crucial for environmental sustainability and achieving long-term development goals. Whilst direct data collection is always the preferable option it is not always practical. This study presents a new methodology for quantifying national-scale material stocks in Malaysia using high-resolution Earth Observation (EO) data. The study includes construction materials; sand, crushed rock / gravel, bricks, tiles, and cement but particular focus is given to sand as it generates the greatest risks to the supply chain, the most significant environmental and social impacts and exhibits the most persistent data gaps. The study integrates EO-derived building footprint and elevation data with deep learning-based classification of building types and ages. Material Intensity coefficients, adapted from regional literature, are applied to estimate material volumes across ~9.1 million buildings. Results reveal that modern Malaysia's building stock has consumed approximately 5.8 billion tonnes of construction materials. Modelled sand consumption shows a good correlation to reported national level production but only when the full value chain for sand, including transport and major infrastructure projects, are factored in. Demonstrating requirements for location specific knowledge when modelling for construction material use and the deficiencies of using simple proxies based on limited parts of the supply chain. This methodology offers a scalable mechanism for capturing data for construction material flows with a high spatial and temporal resolution when directly collected data is not available. It supports evidence-based policymaking for resource governance, circular economy planning, and mitigation of impacts from primary resource consumption.

Keywords Industrial ecology · Sand · Construction materials · Earth observation · Material intensity

1 Introduction

The raw materials and minerals we rely on to underpin our daily lives are being increasingly put in the spotlight in terms of how they benefit society, providing the building blocks for new technologies for decarbonisation but also how they can cause harm through the damaging effects of extraction (Franks, 2020; Torres et al., 2022). What is clear is that ever-increasing levels of data regarding raw material supply chains are required to quantitatively understand and balance the positive and negative effects of society's consumption of mineral based raw materials. Such understanding is essential to ensure that appropriate evidence-based policy interventions can be implemented to mitigate the negative consequences of extraction, whilst ensuring adequate supply to maintain our quality of life. However it is widely recognised that for many countries and regions this data does not exist,

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leaving significant gaps in understanding (Vander Velpen et al., 2022). Presented here is a methodology for the quantification of material stocks based on the mapping of buildings and infrastructure from EO data, and analysis of how such data can be used to model consumption for the case study of bulk construction materials (sand, crushed rock / gravel, bricks, tiles and cement). These commodities are chosen due to the significant volumes required in urban infrastructure as well as the effect their extraction has on the urban hinterland due to the proximity of extraction. This approach is applied at national scale.

1.1 The importance of sand

This study particularly focuses on sand. This is a material that exemplifies the issues of sustainable raw material supply chains, it is essential for the construction sector and much of the built environment we rely on in our daily lives. However, this means, in many parts of the world, it is extracted and consumed in enormous volumes, this has resulted in wide-ranging, negative environmental, social and economic impacts. The environmental, social and economic issues associated with sand extraction and consumption are both significant and well documented (Bisht, 2021; Hackney et al., 2021; Hung Anh & Schneider, 2020; Koehnken & Rintoul, 2018; Marschke & Rousseau, 2022; Torres et al., 2021; Vander Velpen et al., 2022). These problems are so great that in a matter of a few years sand has gone from being a relatively forgotten commodity to something that is now recognised as a major global issue of resource consumption (Bendixen et al., 2019). However, one notable issue with trying to understand the impacts of sand extraction and how these can be mitigated is that for many countries it is almost impossible to get accurate quantitative data on sand resources, production or consumption in contrast to other, higher value, raw materials. The problem around such quantitative data is summarised in UNEP's report on better sand resource governance (Gallagher & Peduzzi, 2019). Essentially, sand extraction in many countries has little state control, has a substantial informal sector due to the low barriers of entry to the sand market in terms of capital requirements and sand serving largely local markets. This makes collection of primary data very difficult. For instance reported sand production in Vietnam does not meet rates of consumption (Novellino et al., 2021) suggesting a significant component is missed. Significant mismatches in import/export data are common (Tweedie, 2018). Although these factors are the most acute for sand supply, equivalences can be drawn to other bulk minerals used in construction, such as clay and crushed rock and gravel. These materials are also included in this study. Without this data the cumulative impact cannot be understood and evidence based targeted strategies to reduce future consumption and move to

responsible sourcing policies are difficult to plan for, from extraction, recycling or alternative materials.

1.2 Issues with current quantitative data on sand supply chains

One of the most comprehensive reviews on the subject by Gallagher and Peduzzi (2019) makes no attempt to measure global sand production or consumption directly due to the seemingly insurmountable factors listed in their review and the resultant absence of data, but instead relies on proxies from datasets that are available. Friot and Gallagher (2021) gives a detailed review of the importance of quantifying material flows, the proxies involved as well as the significant problems in undertaking such studies (such as a lack of disaggregated data, inconsistent standards and definitions, lack of data on specific value chains, lack of spatial components. Many national scale studies attempting to model stocks and flows of sand and construction raw materials using techniques such as Material Flow Analysis (MFA) and dynamic stock modelling, require the use of a variety of different proxies in an absence of real data. Such studies rely on assumptions made using national level datasets, often not specific to raw materials, such as population change, national economic growth, indicators relating to the construction industry etc. (Müller, 2006; Ren et al., 2025; Sandberg et al., 2017; Yang et al., 2022; Zhuang et al., 2025). Such studies often appear to significantly underestimate material consumption when compared with measured data. Little analysis has been undertaken as to how robust these proxies, assumptions or methodologies are, or, if they can be applied on a range of scales, looking at country or regional level data.

1.3 Cement as a proxy data for sand production

One of the most commonly used proxies for sand production is cement (or more specifically cement clinker). This is a logical assumption as much of sand production is consumed alongside cement in the manufacture of concrete for construction purposes. Concrete ranges in composition with different ratios of water, sand, gravel / crushed rock and cement. Cement is a much higher value commodity compared to sand, with production confined to sites requiring high capital investment commonly associated with taxes on sales, so statistics are captured by many more countries compared to sand extraction. Therefore, using cement production figures and a constant ratio for the sand content (The Concrete Society, 2022) sand production can be estimated. Using this method, UNEP calculate that global sand consumption (for construction purposes only) would be in the range of 40–50 billion tonnes per year (Gallagher & Peduzzi, 2019).

This figure has now become widely cited as the reference value of global sand production (Cousins, 2019).

Gallagher and Peduzzi (2019) note that for the USA, which has both well reported figures for the production of both cement and sand and gravel, there is a very close relationship between the two. Simple regression analysis shows this to be the case with an R^2 value of 0.76 (Fig. 1). However, this relationship is very different in other countries, where correlation is often very poor (Fig. 1). It may be that the relationship is dependent on the structure of the industry, trade, and/or construction practices within a country (i.e. how much of the built environment/infrastructure requirements depend on concrete). If this a typical pattern, then countries with similar development status would show similar trends, i.e. the UK (where there is a strong relationship) should compare well with Germany (where there is almost no relationship). However, it is very difficult to observe any pattern in the cement/sand production ratio when looking on a national basis suggesting a much more complex relationship. This suggests that the link between cement production and sand is not a global constant and the use of cement data as a proxy for sand is questionable.

1.4 The applicability of EO data

With the availability of open, globally freely available Earth Observation (EO) data (Novellino et al., 2024), several studies of material flow analysis have been carried out to attempt to quantify construction materials (Bide et al., 2023; Esch et al., 2022; Sirko et al., 2021; Takahashi et al., 2010). Additionally, with the larger amount of data at our disposal studies increasingly rely on machine learning methods to automatically extract relevant information from EO and then

retrieve any relationship between building information and satellite data (Esch et al., 2022; Novellino et al., 2021).

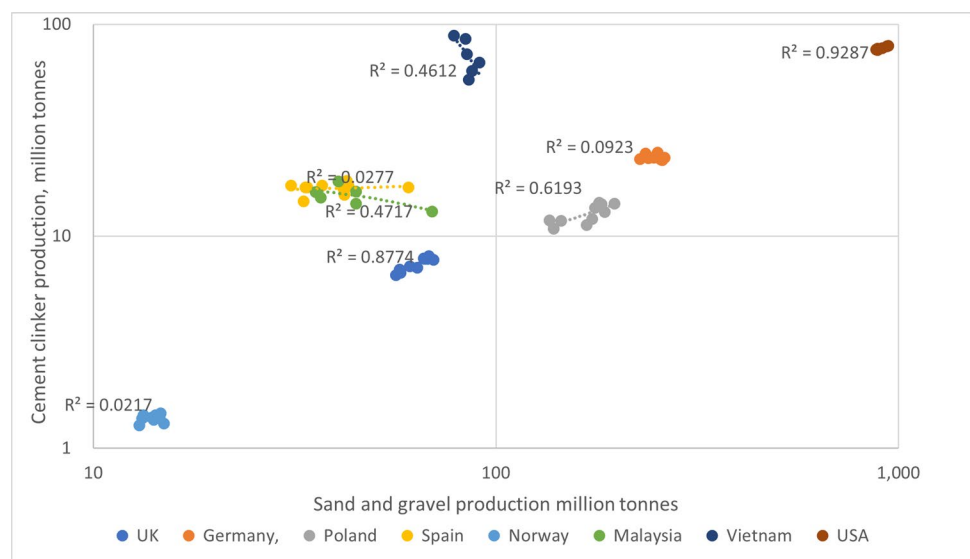
EO techniques can be challenging as a means of observing extraction directly as sites are often small, temporary and obscured by water and vegetation. To overcome this alternative features can be used as proxies for sand extraction e.g. transport infrastructure (Smigaj et al., 2022) or land use change shown by light emissions (Peled & Fishman, 2021). Another approach is to use detailed data on building projects to assess the quantity of materials consumed (Material Intensity, MI) and use consumption as a proxy for production. Such approaches require detailed information from building planning documents which may not be available or are incomplete, especially at national scales (Fernandez, 2007; Gontia et al., 2018; Heeren & Fishman, 2019; Marinova et al., 2020; Nguyen et al., 2019). At small scales (such as at a national level) the use of generalised MI data is a commonly accepted method to assess stocks and consumption this requires detailed data on the size, location and typology of buildings, this can be generated using EO.

2 Methods

The authors have previously outlined the use of high-resolution EO datasets can provide direct measurements of sand consumption using MI on a city level (Bide et al., 2023). In this study, we expand on this to explore the potential to scale up and introduce a temporal aspect for dynamic stock modelling.

This analysis considers Malaysian building stock and transport infrastructure for the period 1988–2020. Malaysia presents an ideal case study as it is a country with significant sand consumption, and high resolution statistical

Fig. 1 Sand and gravel data compared to cement clinker. Individual points represent annual production data for 2011–2020 for specified countries. The data for Fig. 1 can be found in Supplementary Information S11



data on construction material production, published on a regional basis by Jabatan Mineral dan Geosains Malaysia (JMG) (Department of Mineral & Geoscience Malaysia, 2023). This allowed for appropriate ground truthing of modelled results. The specific materials considered were: sand, crushed rock / gravel, clay for bricks, tiles and cement. These materials were chosen as they are those with the most significant data gaps and most significant local footprints in the urban environments and the urban hinterland regarding their extraction and transport. It is recognised that other materials such as steel and glass also have significant impacts, especially when considering carbon emissions, however, these materials are often manufactured considerable distances from where they are consumed and are associated with a different set of environmental, social and supply issues.

The study methodology includes the combination of EO data with information on construction material production from published and freely available datasets. This provided information on building and infrastructure footprints (Sect. "Building footprints"), height (Sect. "Building elevation"), type and age (Sect. "Building type and age"). This enabled building volumes to be inferred and MI to be calculated (Sect. "Building volumes and Material Intensity"). As buildings are not the only consumer of sand additional steps for the inclusion of transport infrastructure (Sect. "Transport infrastructure") and land reclamation (Sect. "Major land reclamation projects") have been included. A simplified version of the methodology is shown in Fig. 2.

2.1 Building footprints

Building footprint was determined using the Google Open Building (GOB) dataset (version 3 released in 2023) and a U-Net model (Sirko et al., 2021) applied on high-resolution satellite imagery from Maxar Technologies and CNES/Airbus. For Malaysia, we have selected a building detection confidence interval of 0.75 for precision (Fig. 3 and see Supplementary Information SI2 for more details).

2.2 Building elevation

This study utilized a deep learning-based Building Height Estimation Network (BHE-NET) to generate building height maps for Malaysia at a 10 m resolution, leveraging data from the Sentinel constellation of the European Space Agency (ESA). BHE-NET is a dual-branch network designed for building height regression, demonstrating notable spatial generalization capabilities (Cai et al., 2023, 2024). A total of 281 Sentinel-2 (optical) and 271 Sentinel-1 (SAR) images were acquired and processed on the Google Earth Engine (GEE) platform for the annual synthesis of building height mapping in 2020. The resulting building height data product achieves Level of Detail 0 (LOD-0) at a 10 m resolution, depicting buildings as pixel cubes with defined heights. In comparison to the 150 m resolution reported by Ma et al. (2024) and the 90 m resolution of the World Settlement 3D dataset, the 10 m resolution heights obtained from BHE-NET provide enhanced spatial detail and more accurate coverage. Where geometric distortions determine shadowing effects in the SAR data (Del Soldato et al., 2021), elevation

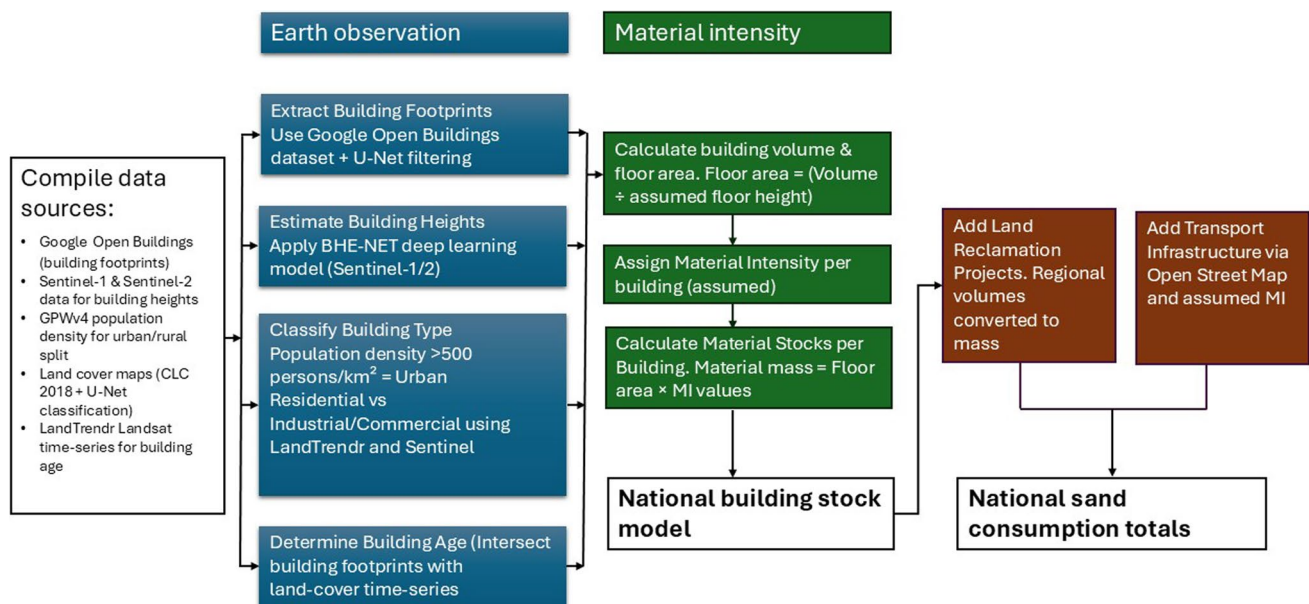


Fig. 2 Simplified diagram of methodology steps

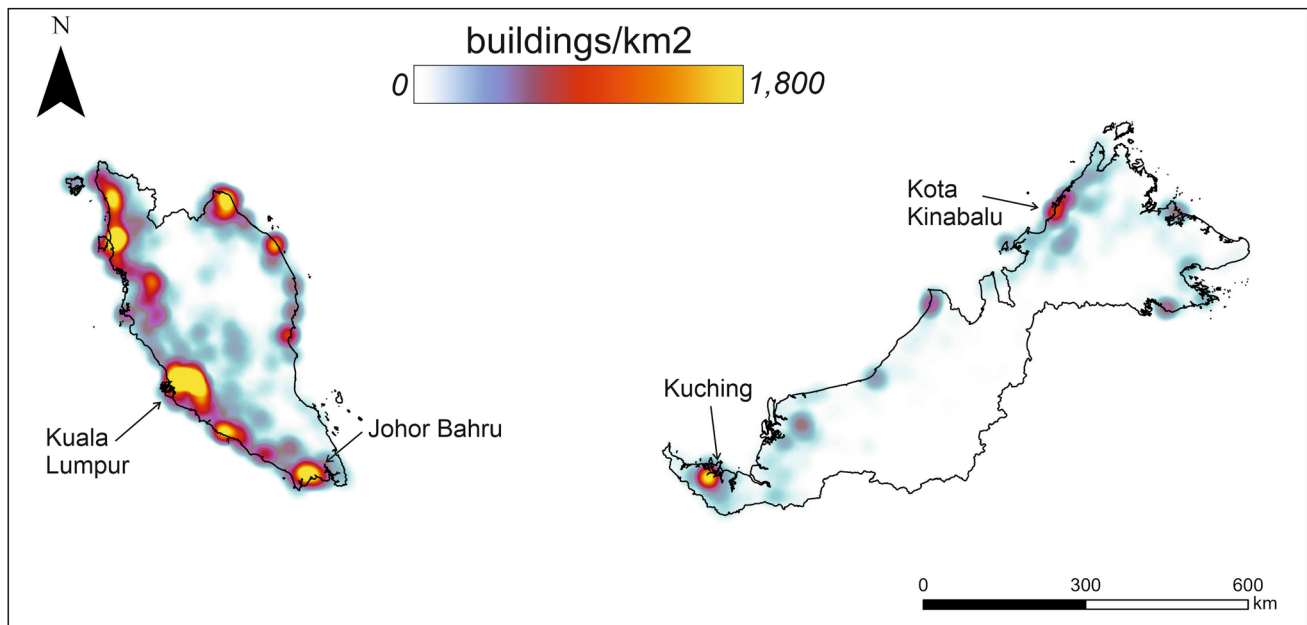


Fig. 3 Spatial density of the building stock in Malaysia from GOB. The Google Open Buildings is licensed under the Creative Commons Attribution (CC BY-4.0) license and the Open Data Commons Open Database License (ODbL) v1.0 license

values are also affected, such an effect is often associated with low-rise buildings surrounded by higher buildings and can provide values as low as 1 m. This is why the minimum elevation value for any building was set to 3 m and converted any lower value to this threshold.

BHE-NET values have been compared against ~1,000 building for which ICESat-2 data were available and showed a Root Mean Square Error of ~9m and mean absolute error of ~5m.

2.3 Building type and age

Given the differing MI for buildings, we have considered a hierarchical classification which accounts for two levels: a major discriminant based on the urban and rural settings and a second order discriminant based on the building use (commercial/residential vs industrial).

For the first level classification we adopted a population threshold of > 500 persons/km² to distinguish buildings in urban locations from those in rural settings (Wineman et al., 2020). The population density information is taken from the NASA's Gridded Population of World Version 4 (GPWv4), Revision 11 model for 2020 at approximately 1 km resolution.

For the second level classification, we generated land cover maps. Buildings were classified as either residential (houses, small shops) or industrial and commercial (warehouses, factories) using the 'Urban fabric' and 'Industrial, commercial and transport units' Corine Land Cover (CLC) 2018 classes respectively. For this classification, we first ran

a pre-trained U-Net deep learning land cover classification model on a cloud free Sentinel-2 composite from 2020 to produce a land cover classification following the CLC 2018 scheme. We then manually defined training area polygons (totalling 25,428 km²) encompassing urban areas and used these to subset the classified 2020 output. These subsets were used to retrain the U-Net model on a 2020 cloud-free Landsat composite image generated using Landtendr (Kennedy et al., 2018). The retained model was then applied to a timeseries of Landtendr Landsat composites dated 1988, 1993, 1998, 2003, 2008, 2013, and 2018. Overall accuracy is on average > 85%.

Landcover maps were then used to calculate building age by spatial intersection of the building footprints (see Sect. 'Building footprints'). We used the presence of built-up areas in the land cover map to assign a specific decade to each building footprint. Considering the year of the imagery used we distinguished building before 1990, 1990, 2000, 2010s and younger than 2010.

2.4 Building volumes and material Intensity

The use of MI to estimate the volumes of materials in building stock by assuming, or applying measured typical quantities of materials per floor area is a well-established method (Marcellus-Zamora et al., 2016; Stephan & Athanassiadis, 2017; Tanikawa & Hashimoto, 2009). Typically floor area rather than volume is used as standard measurements as traditional building data systems record floor area for estimating demand, taxation, planning, energy modelling purposes

whereas total building volume is rarely recorded. Methodologies that can quickly calculate total building volumes, which may present a better indicator of contained raw materials, such as proposed by this study, may challenge this in the future. For accurate, high-quality, representative results, data is required for the relevant composition of buildings and infrastructure. For detailed local studies such data may be available from building specific sources, such as architectural plans, Bills of Quantities or Building Information Management (BIM) systems (Condeixa et al., 2017; Gao et al., 2020; Stephan & Athanassiadis, 2018; van der Hoek et al., 2017; Voskamp et al., 2017). Such data is not available, or feasible on a national scale, such as is being undertaken for this study. As a result assumptions on typical building compositions are required. Various comprehensive databases exist for MI data (De Wolf, 2014; Fishman et al., 2024; Heeren & Fishman, 2019; Marinova et al., 2020). Such databases are becoming the definitive source for national scale MI data, however, due to a lack of MI data specific to Malaysia this study has used data from a comprehensive review of MIs from China (Yang et al., 2020) (Table 1). The reasons for the use of this source, incorporating data collected from China rather than Malaysia, and modelling implications are covered in the discussion. MIs are given as follows:

Here we assume the brick- concrete buildings, defined by Yang and Guo represent rural construction, whereas steel concrete is more representative of urban construction.

MI data is given as a function of floor area, however using satellite data total building volume is calculated, and assumptions are required to convert this to total floor area. This requires assumptions for a typical building floor height and multiplying this by the total building footprint to give the total floor area. Various MI studies, such as Yu et al. (2022) give average floor height for Chinese examples as 3

m, a detailed study of multiple building types by Evans et al. (2019) give a median floor height of 3.2 m. Floor height will be dependent on building type, i.e. industrial buildings will have greater floor heights. The values used for this study, based on these studies is 3 m for residential/commercial buildings and 3.5 m for industrial buildings.

2.5 Transport infrastructure

Linear infrastructure takes into account both roads and railways. This dataset has been retrieved from Open Street Map through GeoFabrik (May 2023 version) and included 1.46M items. To extract the construction year for each element, we considered the centroid of the segment of each line and overlapped it with the landcover maps described in Sect. "Building type and age". We considered three groups: surfaced—major (motorway, primary, trunk); surfaced-minor (living street, service, secondary, residential) and unsurfaced (tertiary, track, unknown, unclassified). We sampled the landcover maps using those centroids and extracted the construction year as the first year of occurrence for the built-up categories (e.g., Urban fabric, Industrial and transport units, Mine dump and construction sites). For primary roads, given their size we were able to double-check the construction date against high-resolution Google Earth Pro imagery. Linear infrastructure includes ~ 1.5M elements with a combined length of almost 400M km. Finally, we divided the infrastructure in different categories based on type of construction material in pedestrian, rail, road—major, road—minor and road—unsurfaced (as done in Bide et al. (2023)).

Material intensity data for transport infrastructure followed the same process as used by Bide et al. (2023), by assuming average road/rail widths and applying a tonnes per area calculation with values taken from Miatto et al. (2021).

Table 1 Typical building MI's assumed for SE Asia, adapted from Yang et al. (2020). The values consider building age, urban and rural settings and building use (commercial/residential vs industrial)

Building age	Building type	Material T/100 m ²			
		Cement	Brick and tile	Sand	Gravel/ crushed rock
< 1988	Industrial, urban	12.51	57.74	66.18	39.59
	Industrial, rural	11.25	75.98	50.04	48.94
	Residential, urban	22.14	51.79	47.28	60.19
	Residential, rural	7.99	89.18	45.81	40.55
1989–1998	Industrial, urban	21.05	55.65	80.75	64.72
	Industrial, rural	15.57	83.42	65.73	43.95
	Residential, urban	14.75	11.74	42.34	44.60
	Residential, rural	15.51	83.63	66.32	38.35
1999–2023	Industrial, urban	21.05	55.65	80.75	64.72
	Industrial, rural	15.64	46.86	72.44	24.61
	Residential, urban	21.05	14.68	36.34	64.72
	Residential, rural	15.11	53.07	59.74	33.13

To ensure maintenance of roads is included in the figures a typical lifespan for a road was assumed to be 20 years and that all road construction would need to be repeated during that timeframe (Trunzo et al., 2019).

2.6 Major land reclamation projects

Malaysia is active in land reclamation for coastal defence and infrastructure projects, such as port development. This will consume significant volumes of sand (and rock) and can be a major driver for consumption. Such projects will not be identified by earth observation datasets focusing on buildings and transport infrastructure and therefore need to be included separately. Between 1991 and 2021, an absolute area of 82.64 km² has been or will be reclaimed (Chee et al., 2023). A total of 55% of this area is in the 2011–2021 period. Such projects will consume very large volumes of sand. This study has attempted to incorporate these via a decadal scale aggregation of projects. The total area reclaimed by major projects in km² can be converted into tonnage of sand by using a density of 1.5t/m³ (The Crown Estate, 2024) and an assumed t/m² of 2.25 (Environmental reporting collective, 2023). Note this is a very conservative estimate, the material required for such projects will be variable, and may be a mixture of materials, recent projects in the Maldives give a t/m² value of 3.9 (Boztas, 2022).

3 Results

With a national extent of ~330,803 km², the built-up surface in Malaysia in 2020 covers ~1830 km² (<1% of the country surface) which includes the footprint of ~9.1 million buildings. The area covered by buildings corresponds to ~80% of the entire built-up area land use category of the country (also including the transport network and mine sites). The proportion of building area as part of the whole built-up areas has increased steadily across the decades: it was only ~49% in

1988, ~53% in 2003 and ~66% in 2013. Further details highlighting data functionality can be found in the ArcGIS story map (Watkins et al. 2025).

The histogram of the GOB building distribution show that half of the building stock has an area of 100,000 m² (Fig. 4). In terms of elevation the distribution of values is even more non-homogeneous with ~88% of buildings showing an elevation <6.6m and less than 1% of buildings with elevation >14m. Although the BHE-NET height product shows an RMSE of ~9 m and an MAE of ~5 m (see Supplementary Information–SI2), this error must be interpreted in the context of the actual height distribution of buildings in Malaysia shown in Fig. 4. Specifically that almost 90% of all buildings in Malaysia are below 6.6 m in height (corresponding broadly to 1 to 2 storey structures) and less than 1% of buildings exceed 14 m. This means that height-derived volume is dominated by low-rise buildings, where even a 3–5 m error represents less than one storey and therefore has limited influence on total national stock volumes. Over- and under-estimations tend to average out due to the very large sample size (~9.1M buildings in total). Thus, although height uncertainty exists at the individual-building level, its net effect on large-scale totals is strongly reduced.

Malaysian building stock has been constantly growing through the last four decades with almost 40% of the entire building stock erected before the 1990s. In terms of location, 32% of the buildings are placed into an urban setting, with the value higher along the coastlines of Peninsular Malaysia.

The data resolution and attributes allow spatial resolution of stocks of construction materials through time and can be used to show different stages of development and different building practices in different areas. For example, Fig. 5, shows total stocks, split by commodity and state, using the three time periods set by the three building typologies used by this study (greater temporal resolution is possible).

Almost as much sand, gravel and crushed rock is contained within buildings built after 1998 than the entire period preceding it. However, for cement and brick much more is

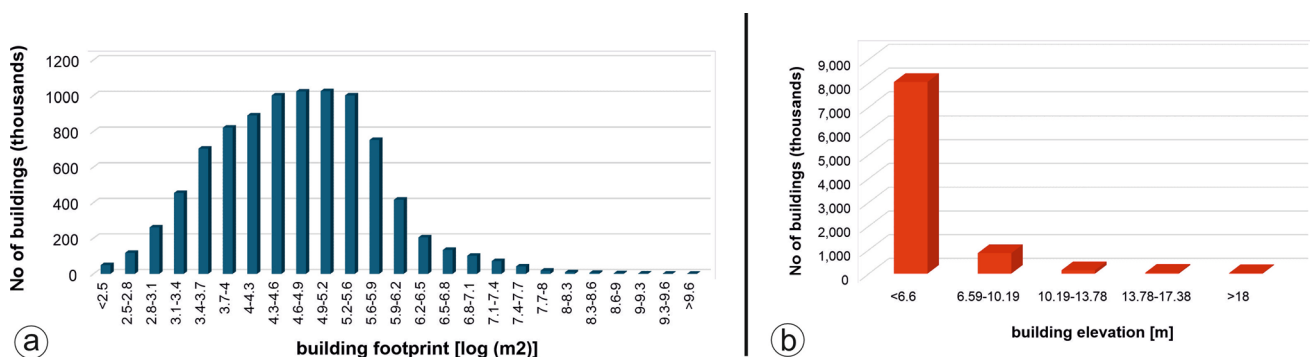
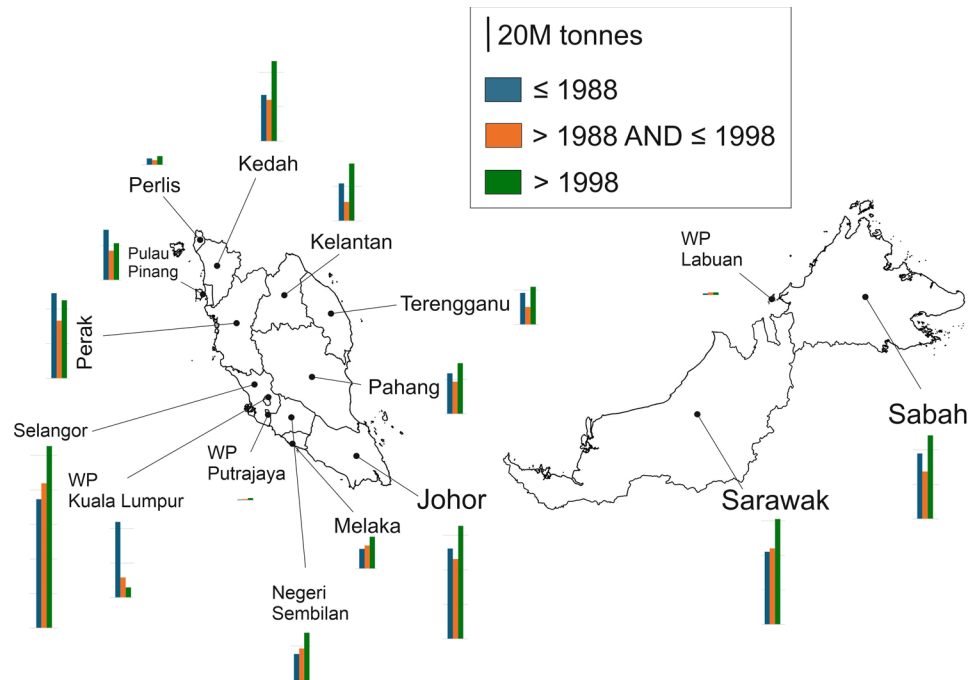


Fig. 4 Histogram of the log10 distribution of building footprint areas **a** and building elevation **b**. The data for Fig. 4 can be found in Supplementary Information SI3

Fig. 5 Stocks of sand material by state and time for buildings. For the data including other commodities covered see Supplementary Information SI4. Administrative outlines ©OpenStreetMap contributors and the GIS user community



contained within older buildings, perhaps unsurprisingly considering changes to building practices, away from brick and more towards concrete. Analyses at state level however reveal further complexities. For example, Sarawak consumes considerably greater amounts of bricks and tiles compared to sand and gravel / crushed rock due to the rural setting and the older age of buildings, whereas in Selangor the dominant material consumed is sand given the largely urban setting. Overall, across the different provinces we can see: (i) a reduction in the use of brick and tile, (ii) an increase in the use of gravel / crushed rock and (iii) a fluctuation in cement based on the region.

Similarly, through time Sarawak consumes much less material in building older than 1998, compared to Selangor, reflecting different rates of urbanisation. This demonstrates the utility in understanding spatial and temporal trends in consumption of construction materials and how such resolution is required to understand local variations.

4 Discussion

Although limited by the assumptions made in calculations of MI and the resolution of satellite imagery, the detailed dataset of over 9 million buildings created, using freely available sources with global spatial coverage created by this study, is a powerful tool that can be deployed where systems for capturing data directly, either for building properties or raw material consumption, are not developed or are too resource intensive. As such this methodology is proposed as a way of estimating material consumption as a proxy for production

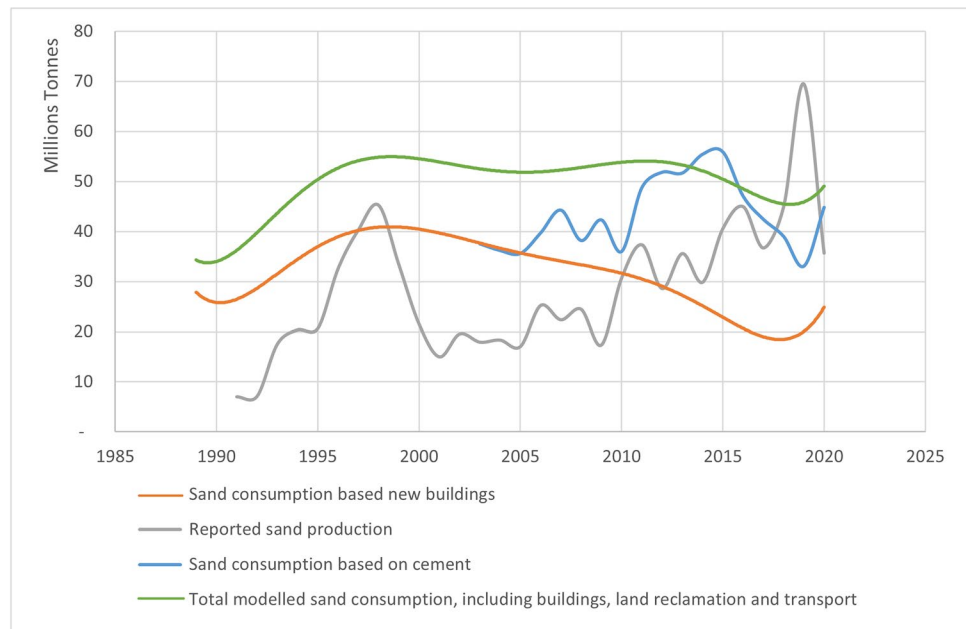
for sand and crushed rock construction minerals, where no other data is available. This methodology can take into account the entire sand supply chain and local building practices which the use of the currently used alternative method of cement as a proxy does not (a likely reason why it is unreliable, as shown in Fig. 1 and Fig. 6).

The time series element of this study allows for prediction of when buildings may be demolished and when the stocks of building materials contained within them may potentially be released back into the market for recycling. For example, this study estimates around 326 million tonnes of sand, and 356 million tonnes of crushed rock are contained with buildings built before 1988 in Malaysia, and it is likely that many of these will be reaching their end of life. With production of sand around 30 million tonnes and crushed rock 100 million tonnes per year such stocks may comprise important future supplies if suitable policies and infrastructure for recycling and re-use are implemented. Additionally, such understanding of the quantities of material consumed, at a local level is vital to understand the viability of different alternatives.

4.1 Uncertainty for material intensity

Assumptions regarding material intensity bring in the greatest degree of errors in the process, with much higher levels of interference compared to the high-resolution satellite data. Care needs to be taken to ensure values used accurately represent local building practices and reflect how building practices have varied over time and in different geographic regions (Arceo et al., 2023; Zhang et al., 2022). Sensitivity analysis of (Bide et al., 2023) and

Fig. 6 comparison of sand consumption, production and production based on cement as a proxy. The data, including other commodities included in this study, can be found in Supplementary Information SI5



(Zhang et al., 2022) show how this is a critical factor in calculating material stocks so accurate MI inputs are of great importance.

Previous work by the authors of this study (Bide et al., 2023) attempted to collate a variety of sources to create representative averages for Vietnam, such studies showed the large variation of report MI's and the typical uncertainties that are involved. The comparison of different MI studies by Bide et al., showed that typically for common construction materials the range of estimates available relevant for the case study of Vietnam between the 5th and 95th percentile was in the region of $\pm 30\%$ but this could be as high as 70%.

MI values used in this study are not specific to Malaysia. The most up-to date and comprehensive MI databases, i.e. Fishman et al. (2024), contain very limited suitable data for Malaysia specific MI data which necessitated the need for proxy data. As described by Ju and Omar (2010) in terms of current stage of urban development as well as typical building typology there are significant commonalities between China and Malaysia for modern concrete buildings. As this is the dominate building type (Fig. 5 and Supplementary Information SI4) it was assumed that these MI figures were suitable for this study. Significant architectural (and therefor MI) differences may be present in rural and older buildings. This may present less of an issue for sand consumption calculations due to brick rather than concrete being the dominate material type in older buildings. This study aims to produce a methodology that is repeatable and scalable for other regions with standard data inputs it is therefore reliant on existing published MI data.

4.2 Modelling sand consumption

Malaysia forms an excellent case study area in this regard as it is a country that produces detailed production data for construction minerals, along with other commodities, at a state level published annually in the Malaysian Minerals Yearbook (Department of Mineral & Geoscience Malaysia, 2023). This can be used to compare against the values for material consumption estimated by this study based on new building development.

Figure 6 shows the sand consumption, related to new buildings, calculated by this study versus the reported sand production (data for other commodities is contained within Supplementary Information SI5). The time series from the EO data has been calculated by taking a five-year average of the calculated figures from the time periods stated in Table 1. This shows a generally good match between the two, though the construction boom in the late 90's to the slow down following the Asian Financial Crisis, and the recovery thereafter. The consumption trend shows a lag compared to production as this has been measured every five years as opposed to every year and reflects the difference of the raw production vs the in-use stocks. However, if only buildings are considered, the trends diverge significantly around 2012, with the reported sand rapidly increasing but the amount of sand consumed in new buildings declining. The trends however show a much better match if land reclamation and road construction is included, showing how consumption has changed in more recent years nationally. This demonstrates the complexity in understanding sand consumption at a national level and the need for a detailed local level understanding that includes multiple metrics.

Other factors outside those considered by this study may also include:

- Significant quantities of exported sand. This is not as simple a factor to consider as may first appear. Trade data for sand is freely accessible using the UN Comtrade database. Reported data for sand exports for Malaysia show it to be an order of magnitude less than production, at such a level it does not materially affect national level consumption. However, if sand imports from Malaysia as reported by the rest of the world are used, for 2017 and 2018 levels of exports (as reported by other countries) exceed reported production, with 87 million tonnes in 2017. These are almost entirely imports as reported by Singapore. Such high values may reveal an unreported flow of material in official data, but it is difficult to comprehensively include in the modelling process due to the political sensitivities over such relationships often leading to opaque and incomplete data (Ungku & Latiff, 2019).
- External events outside ‘normal’ supply chain parameters. Reported production data in Malaysia shows strong growth post 2015 with an outlying peak in 2019. Discussions with in-country industry experts suggest this is driven by the 2015 Sabah earthquake. This event caused numerous significant landslides, burying infrastructure and infilling valleys. Significant efforts have been undertaken to remove this material, much of which has been sold for sand, especially for land reclamation. This is supported by the corresponding rapid rise in land reclamation projects.
- Changes in legislation in Malaysia leading to better reporting of data causing a false impression of production increases. In 2008, due to issues over illegal sand mining, a state-run sand mining company, KSSB (Kumpulan Semesta Sdn. Bhd) was established, as a result informal mining, which may have not been included in production statistics, decreased.
- The MI values used in this study only consider one building typology between 1999 to present, a higher resolution MI dataset may explain this divergence.

Also included in Fig. 6 is an example of the current standard method of estimating sand production via using cement production as a proxy. This study has further refined this by using cement apparent consumption to take into account international trade of cement. This shows the difficulties of linking the two, firstly calculated sand production based on cement appears to be very high compared to reported sand production in Malaysia, this may be due to sand being historically underreported, From the period of 2003–2009 (data from cement is not available prior to 2003) cement consumption is matching, or higher than sand production which seems unlikely. Secondly

although the trends of cement and reported sand production do share similar trends for 2003–2012, they significantly diverge in recent years. This is further evidence for significant volumes of sand being used in land reclamation and transport rather than building infrastructure for the most recent decade and thus the link between sand and cement consumption becoming broken. Whilst uncertainties are inevitable with the assumptions made (especially concerning MI which may be around 30% as discussed in Sect. 4.3) the trends can be considered reliable as proven by comparison to reported production, unlike the trends shown when using cement as a proxy for sand.

4.3 Limitations

This methodology only recognises new areas of construction and change in land use. It does not take into account areas of older buildings that may be demolished and new buildings built in their place. It is considered for the example of Malaysia which is undergoing an initial phase of urbanisation and over 60% of the stock of material contained within buildings being less than 30 years old this is an acceptable level of error. Studies suggest the average lifespans of buildings in Malaysia is 50 years (Rashid et al., 2012), outside the 40 year timespan of this study. Therefore, refurbishment should not constitute a major driver of consumption. For more mature urban environments where the bulk of construction is on brownfield sites this methodology may not be applicable.

The methodology only takes account of major land reclamation works at a decadal scale. Such projects are often detailed in national planning documents and although outside the scope of this study further work may incorporate sand consumed in such projects on an individual basis separately. It may be that a higher temporal resolution analysis of coastal reclamation projects will show a more complex pattern.

Applying age of construction to the transport network can be problematic if major new road and infrastructure projects follow existing infrastructure, as the date of construction of the original infrastructure may be erroneously applied (e.g. if a minor road is upgraded to a motorway). It may be more appropriate to model such projects separately, as has been done for reclamation. For example, many large projects have been initiated in Malaysia in recent years: The Pan Borneo Highway 2015–2025; West Coast Expressway (WCE) 2014–2026; East Coast Rail Link (ECRL) 2017–2026; Klang Valley Mass Rapid Transit 2011–2021; and the Johor Bahru–Singapore Rapid Transit System (RTS) 2020–2026.

5 Conclusions

Sand production and consumption is poorly understood on both global and local scales. Simple proxies such as cement production do not take into account country level drivers of consumption and are overly simplistic omitting many major consumers of sand outside concrete, for example changes in building practices or markets where sand is consumed. In this work we adopted an inverse approach where we estimate sand produced by analysing where it is consumed by collating and analysing open source EO data to calculate construction materials used in buildings over time.

By analysing ~9.1 million buildings across Malaysia, we estimate that a total of ~4 billion tonnes of construction material has been used, rising to 5.8 billion tonnes if transport and infrastructure projects are included. Comparison with reported sand production for specific time intervals show the relationship sand has with different consumption sectors, and that when construction of new building ceases to be the dominant end use understanding the role of other markets, such as infrastructure and land reclamation becomes critical. Simple proxies, such as consumption of cement, cannot capture these market changes. However, the relationship between reported and modelled data show the complexities in understanding material consumption at a national level and highlight uncertainties inherent in the assumptions required, especially regarding MI values.

This national level assessment gives strategic information to monitor resource consumption, assess the availability of materials for trade and guide future production policies. By understanding past consumption patterns, we can better assess future demands and potential scarcities which might require government interventions. For example, the temporal dimension of the model allows for forecasting future material availability through demolition and recycling, supporting circular economy initiatives. With over 680 million tonnes of sand and crushed rock embedded in buildings constructed before 1988, Malaysia holds substantial potential for secondary resource recovery, if supported by appropriate policy and infrastructure. This proactive approach allows for informed decision-making and the development of strategies to mitigate risks associated with resource shortages. This methodology provides a way to do this, providing a scalable framework to calculate a comprehensive picture of the building stock at high-resolution due to its use of detailed EO datasets and may be a way to vastly improve current methods of estimating sand supply. Such a methodology can be used for other regions facing similar data gaps and sustainability challenges.

6 Summaries:

Supplementary Information S11: This supporting information provides data for figure 1, a comparison of sand and gravel production for selected countries compared to production of cement clinker.

Supplementary Information S12: This supporting information provides additional detail as to how both building detection confidence intervals have been calculated and how elevation data for building heights has been validated.

Supplementary Information S13: This supporting information provides raw data used to create figure 4 as well as additional information as to how this data has been compiled.

Supplementary Information S14: This supporting information provides data for figure 5, modelled material stock by type split by province for selected time periods.

Supplementary Information S15: This supporting information provides data for figure 6, raw data calculated from model including Sand consumption based new buildings; Reported sand production; crushed rock reported; Cement apparent consumption; Sand consumption based on cement; cement based on sand in buildings; sand used in land reclamation; Sand consumption based on transport infrastructure; Gravel consumption based on transport infrastructure; Total modelled sand consumption, including buildings, land reclamation and transport; Total modelled gravel consumption, including buildings, land reclamation and transport; Total modelled clay for brick consumption; total modelled cement consumption; Reported clay production; Reported cement production.

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Data availability Data available in article supporting information.

Declarations

Conflict of Interest The authors declare no competing interests.

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