Sand supply in The Gambia, recommendations for resource management

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Former sand workings from coastal dunes © BGS UKRI

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Summary

This report discusses the critical issue of sand supply in The Gambia, highlighting its importance in construction and the potential environmental impacts associated with its extraction. It emphasizes the challenges posed by rapid urbanisation, the need for effective regulatory oversight and the potentially negative consequences of sand mining such as erosion, habitat loss, and pollution. Without sustainable resource management, the future supply of sand in The Gambia cannot be guaranteed, which may result in serious impacts to both infrastructure projects and economic growth.

The work summarised by this report was completed as part of the International Geoscience Research Programme (IGRD) programme in BGS, under the 'Sand and Sustainability' project. The Gambia was deemed an ideal case study for application, and testing of, good practice guidance produced by the BGS, due to the ongoing work in-country by stakeholders to improve the resilience of the national sand supply chain.

Coastal sand resources, which were historically the main source of sand in The Gambia, are now virtually depleted. Alternative sources of sand include inland and offshore deposits of sand. The inland sand deposits are of variable quality and face considerable opposition to their development from local communities. The marine (offshore) sand deposits could provide good quality sand, but their extraction must be carefully managed to avoid coastal erosion and environmental damage, considering predicted shoreline retreat and the country's reliance on tourism.

Good resource governance is a complex issue that requires the collaboration of all interested parties. The first step is ensuring a good baseline understanding of the geological extent and physical properties of known sand resources. This report covers key geological formations known to be suitable for construction sand in The Gambia and gives a brief overview of their physical properties based on field observations and laboratory analysis of sand samples.

Although systematic sampling was not conducted as part of this project, a number of sand samples were collected and analysed to determine their particle size distribution (PSD). The particle size data was compared to UK and European industry standards for construction sand to give an indication of relative performance. The geological assessment of resources in The Gambia highlights the dominance of fine-grained clastic sediments. These resources are subdivided into inland, coastal and marine (offshore) sand deposits.

Based on particle size and compositional analysis, the inland sand deposits sampled are classified as medium to fine sands mainly composed of quartz grains. These are too fine to meet current European and British standards required for concrete. The coastal sand deposits sampled are classified as medium to fine sands. Depending on the amount of reworking of these deposits, either by coastal processes or heavy mineral extraction, the coarser size fractions are dominated by shell or lithic (rock) fragments. High shell contents are considered deleterious for aggregate use as shells are considerably weaker than quartz or other lithic fragments. Processing to remove shell fragments would be required for the sand to be made suitable for use as a construction material.

The marine sand deposits sampled mostly consist of medium grained quartz sand with a high proportion of shell fragments in the coarse size fractions (>1mm), of both unprocessed and processed materials. Processing to remove weak shell-fragment material would greatly improve the quality of the sand; however, the current processing (washing) plant is not effectively removing the shell-fragments from the marine sand. Further discussion of the sand samples collected in The Gambia is provided in section 3 of this report.

This report explores various alternatives and new sources of sand supply to address the critical shortage in The Gambia, including marine sand, new onshore deposits, manufactured sand and recycled materials.

The following could help improve sand supply sustainability in The Gambia:

- **Increased geological understanding:** Enhanced understanding of onshore and offshore sand resources through geological characterization and mapping, including the creation of regional-scale sand potential maps.
- **Improvement of industry practices:** Investment in basic washing plants to process sand, thereby improving product quality and broadening end-uses. Knowledge sharing with stakeholders from the UK's minerals industry may facilitate this.
- **Research into alternative materials:** exploration of alternative construction materials, such as clay or earth blocks, in collaboration with local academics and the construction sector.

This is a complex issue that has social, environmental and land use planning considerations which are outside the scope of this work. Before such considerations can be properly assessed, baseline data on the physical availability of materials need to be understood.

1 Introduction, the issue of global sand supply

Sand is an important construction raw material. Building materials like mortar and concrete, which contain significant amounts of sand, form the metaphorical (and often literal) foundations of our modern society. However, sand is often a victim of its own usefulness. Countries that are undergoing rapid growth and associated urbanisation extract and consume large volumes of construction raw materials, including vast quantities of sand. Estimates by the United Nations Environment Programme (Gallagher and Peduzzi 2019) predict that sand is the second largest flow of material moved by humans, after water. Such a large movement of material needs to be carefully manged to avoid negative unintended consequences. However, extraction in low to middle income countries, where demand is highest, often takes place in the absence of effective regulatory and environmental controls. This is often due to a lack of adequate enforcement and application of existing regulations and laws.

The mining of construction sand can have significant environmental and social impacts on active river systems and beaches, including:

- erosion
- damage to infrastructure
- increased flood risk
- habitat loss
- pollution
- soil degradation
- destruction of farmland

Lack of adequate planning and resource management also leads to material shortages and price spikes, which fuels illegal mining. This can cause severe delays to national infrastructure projects and can have a negative impact on economic growth.

Ensuring an adequate supply of sand can be complex and rely on a combination of local market conditions and the physical properties of available resources. Sand is a high-bulk, low-value commodity and is usually mined close to where it is needed. Data from the UK suggests that on average sand typically travels around 30 to 40 km by road from the site of extraction (Mineral Products Association 2018). Additionally, not all sand is suitable for construction, it must meet specific technical requirements for size, shape and composition of the sand grains. Sands that are too fine, too rounded, have high silt and mud content, contain certain deleterious minerals e.g. sulphides or organic material, or have high shell content may only be suitable for a very limited number of applications and may not be suitable for construction.

Comprehensive information around the issues of global sand supply can be found in the following reports:

- Sand and Sustainability (Gallagher and Peduzzi 2019) https://wedocs.unep.org/20.500.11822/28163

- 10 Strategic Recommendations to Avert a Crisis (Gallagher and Peduzzi 2019) https://www.unep.org/resources/report/sand-and-sustainability-10-strategic-recommendations-avert-crisis

- Illustrative good practice guide for sand mining (Bide 2023) (https://www2.bgs.ac.uk/mineralsuk/download/mines/Illustrative-good-practice-for-sand-mining.pdf)

2 Sand supply in The Gambia

The BGS ‘Sand and Sustainability’ project, part of the International Geoscience Research and Development (IGRD) programme, is working to reduce the impact of sand mining, focusing on areas where sand is sourced from unsuitable or environmentally damaging sources. Discussions between the BGS and the Geological Department of the Gambia, highlighted that sand supply was noted to be a particularly significant problem in The Gambia for a variety of reasons. The Gambia was deemed an ideal case study for application, and testing of, good practice guidance produced by the BGS, due to the ongoing work in-country by stakeholders to improve the resilience of the national sand supply chain. The country aims to achieve its ambitious targets for economic growth whilst minimising negative environmental and social impacts, whilst balancing the need for housing and large civil engineering projects, such as road building programs and new port infrastructure. Without adequate sand supply it will be difficult to complete such projects.

It is clear, through discussions with regulators and stakeholders in the Gambian construction minerals sector, that sand supply issues are acute and have reached crisis point. The concrete, mortar and foundation materials currently underpinning the current Gambian construction boom are essential for delivery of current and planned infrastructure projects. Historically, one of the main sources of construction sand in The Gambia was the coastal dunes that occur along the southern part of the Gambian coastline. However, these coastal dune sands are now largely depleted. This is causing an acute shortage of raw materials for construction and is delaying or even halting projects. Extraction from nearshore dune environments is also damaging to delicate ecosystems and can lead to coastal erosion. Other sources of sand, from inland deposits, are often of poor quality and are subject to access issues due to the concerns of local residents. Resources in known sand mining areas are often severely depleted. This has led to supply shortages and illegal mining, contributing to further environmental degradation.

Marine sand deposits have been suggested as an alternative source of material. Whilst it is perfectly feasible to extract such sands in a responsible way, if local conditions are not considered, it is likely to cause increased coastal erosion and significant long term environmental damage. This is something that requires considerable care, as shorelines in The Gambia are predicted to retreat in many places by 25 to 50 m during the next 50 years,(Royal HaskoningDHV 2021). The impacts of this are serious, not only because of the potential damage to habitats and infrastructure, but also impacts on tourism, which accounts for about 20% of the national GDP.

The Gambia, like many countries also has issues regarding access to land for mineral extraction. Mineral extraction is unpopular, and often for good reason, due to poor historic resource governance that has led to land degradation. As a result, there is significant community opposition to new mineral operations in The Gambia. However, despite well publicised opposition to formal mining operations, communities are willing to allow or become involved in informal sand extraction. This highlights the complexity of the issue regarding land use planning, local regulations and laws, and community relations. These are outside the scope of this study. Many of these issues are under the remit of a newly formed interdisciplinary technical committee on sand set up by the Ministry Petroleum and Energy (MoPE), this work attempts to aid the goals of this group by contributing technical information produced by a preliminary resource assessment and highlighting international good practice that may be applicable to The Gambia.

3 Assessment of resources

Many countries face issues with the supply of sand. Local alternatives do exist, but they may be more technically challenging, energy intensive or expensive to extract compared to river or beach sand. A particular issue in The Gambia is a lack of suitable resources for construction sand, and a lack of suitable alternatives. This is linked to the geology and geography of the country and makes sand supply a particularly complex subject. Minerals can only be worked where they are found. Regardless of market factors, the main constraints on attempting to increase the supply of sand are the lack of sand with the required physical properties or sand resources that are spatially constrained making it difficult to work them (as is the case in The Gambia). It is important to understand the geological extent and the physical properties of sand resources to assess their potential for alleviating supply issues in the most sustainable way.

3.1 CONSIDERATIONS FOR SAND RESOURCE ASSESSMENT

The quality of sand resources, and the end-uses they are suitable for, depends on several factors. The most important being grain size, grain shape, clay and silt content, and the presence of overburden. Sand resource assessments are an exercise in understanding the spatial extent of the sand (typically based on geological or geomorphological mapping), and the physical properties of the sand by sampling the deposits at relevant depth intervals and undertaking mineralogical analysis (e.g. particle size analysis). Sampling can be carried out using hand augers, small drill rigs or backhoe mechanical excavators. The sampling techniques employed depend on the scale and application of the assessment. The most important factor is to ensure samples are representative of the deposit and that the relevant properties are accurately recorded. An example field investigation sampling sheet is given in Appendix 2. Geophysical techniques such as electrical resistivity can also be used to map properties of the subsurface (British Geological Survey 2023). Examples of national scale sand and gravel assessments, including the assessment methodology, are given in the BGS Industrial Minerals Assessment Unit reports (https://www2.bgs.ac.uk/mineralsuk/mines/IMAU.html). It may be relevant to include consideration of social / environmental impacts in the assessment of the areas considered for extraction.

During BGS's visit no systematic sampling was undertaken. However, during training exercises with staff from the Geological Department in sand sampling using a hand auger, several samples were taken from known resource areas (Figure 1.). The results from the analysis of these samples are included below. Grain size distribution has been calculated using the freely available Gradistat software. (https://onlinelibrary.wiley.com/doi/10.1002/esp.261)

Sand samples from The Gambia were collected for particle size analysis. This involved carefully weighing and sieving each sample, and inputting the mass and size fraction data in to the Gradistat software of Blott and Pye (2001).A qualitative estimate of the amount (%) of quartz, lithic (rock) fragments and shell fragments was made for each sample. . The particle size distribution data for each sample was compared against the Aggregate Industries Garside Sands washed sharp sand product (Aggregate Industries UK Limited 2013). The Garside Sands is a good example of a washed sharp sand product which conforms to the following British and European Standards:

- (BS EN): BS EN 12620 for use in concrete
- BS EN 13043 for use in bituminous mixtures and surface treatments for tarmac surfaces
- BS EN 13139 for use in mortar

As such, this provides a useful comparison for the purpose of this study. The product is extracted from the Woburn Sands Formation of the Lower Greensand Group, in Leighton Buzzard, Bedfordshire, United Kingdom. Geologically this sand was deposited in a shallow marine, tidal environment. The product comprises sub-angular to rounded medium to carse grained quartz sand (Aggregate Industries UK Limited 2013). However, it should be noted there are many other types of sand available that may be suitable for a wide variety of end-uses and this is not a comprehensive construction material assessment, further investigation of the sample materials is required. This study makes comparison to European standards as this is a useful reference for construction materials of good quality, however it should be noted that different specifications may be relevant, or more suitable in The Gambia. This study did not have the opportunity to gather information on the market requirements and local building practices and specifications. Therefore, discussions made herein regarding suitability of materials are to be considered illustrative, and not indicative due to the limitations of this study.

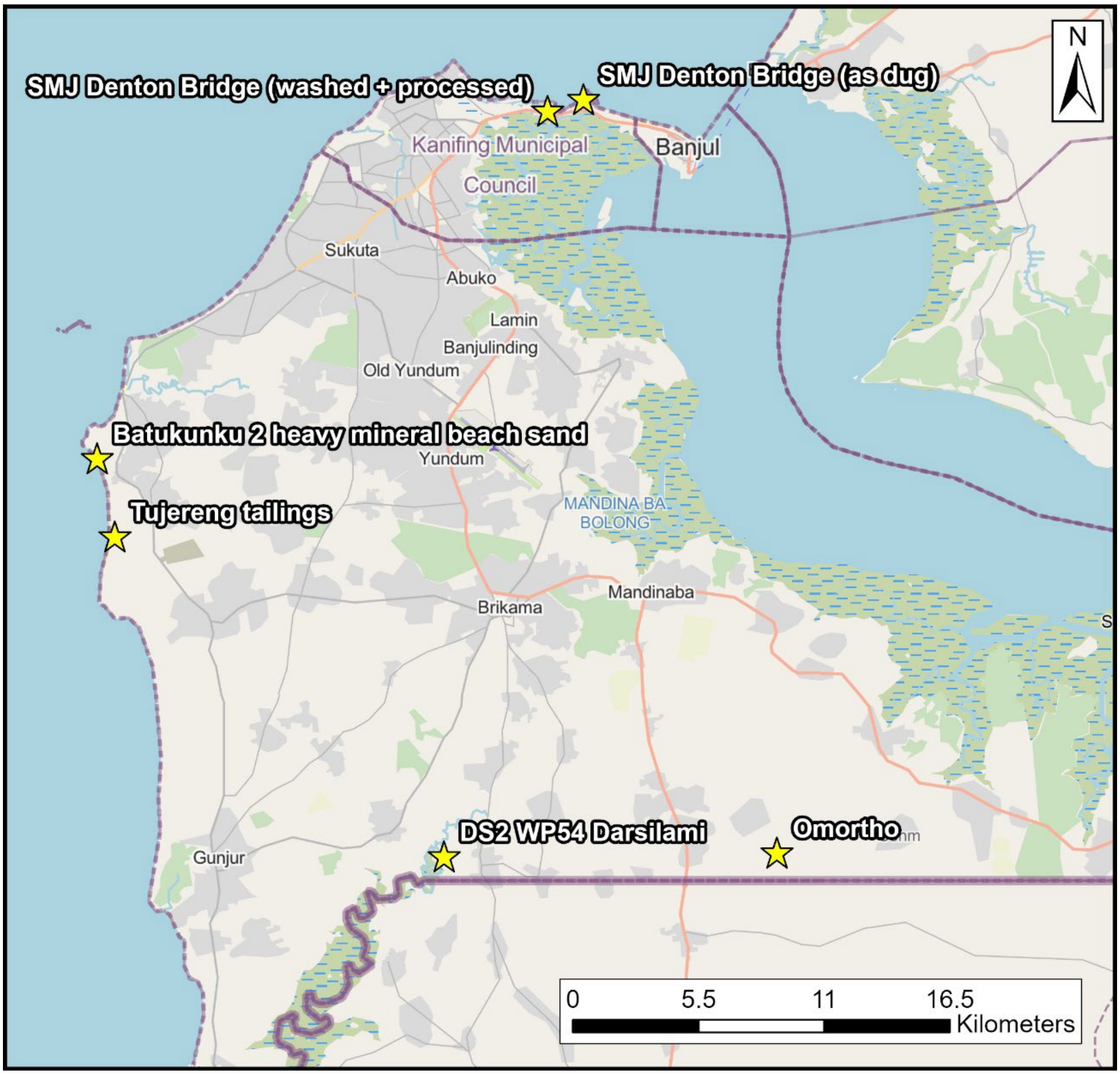

Figure 1. Sand sites sampled in The Gambia. Map data © OpenStreetMap contributors (2024).

3.2 GEOLOGICAL DESCRIPTION OF RESOURCES

The current understanding of the geology of The Gambia is based on 1:250,000 scale mapping undertaken between 1992–1995. This was based on a combination of satellite imagery analysis and fieldwork (China National Complete Plant Import and Export Group and Geological Unit 1995). This work was primarily focused on the mineral potential of the country. The formations defined by this work have been used here. The present BGS sand study has not undertaken any work to improve the mapping or to add to the understanding of the stratigraphy. However, a more detailed understanding may be beneficial for a full resource assessment to delineate the spatial extent of sand bearing geological formations.

The Geology of The Gambia is dominated by fine grained clastic sediments (sands, silts and clays) deposited during the Pleistocene (2.58 million to 11,700 years ago) by the River Gambia, its tributaries, and shallow seas, during times of higher sea level. Away from the coast and river channels, the geology is dominated by older sandstones and clay deposits that have been extensively altered by tropical weathering to hard lateritic deposits and kaolinitic clays. Some deposits from the Pleistocene fluvial and marine sediments have formed economic sand deposits that are currently worked on a small scale. Lateritic soils have limited resource potential for sand and are not discussed here, although they do form one of the only hard rocks in The Gambia and are crushed for use as gravel and coarse aggregate. The following formations are identified as having varying degrees of potential for sand resource.

3.3 INLAND SAND DEPOSITS.

3.3.1 Darsilami Formation

This formation consists of clay, silt and clean quartz sands interpreted to be a mix of fluvial and marine sediments, due to the presence of cockle shells. It has been worked extensively around the village of Darsilami. It dominantly occurs around the Allahein river and its tributaries in the southwest of the country, as well as around the mouths of some smaller rivers around the coast. It is understood that known sand deposits associated with the Darsilami Formation have been largely worked out, but it is possible that updated geological mapping in other areas where the formation is thought to occur may identify new resources.

The areas of greatest resource potential are related to sands deposited from nearshore processes during periods where the sea level was higher than at present and flooded the current network of minor rivers. These natural processes have sorted and cleaned the sand. It is predominantly used for mortar and block production as the fineness of the grain size (fine to medium) limits its application in concrete (which generally requires coarse sand).

During the BGS visit several sites were visited, where the Darsilami Formation has been worked, at Omortho and Darsilami. These consist of shallow workings, down to around 2 m deep, which is the usual level of the dry season water table. Although thicknesses of several meters of sand were observed during hand auguring, layers of clay and sandy clay were also present. The sites visited had been largely worked-out but unlicensed extraction continues to take place.

3.3.1.1 Sample Analysis

Two samples were collected from the Darsilami Formation, specifically at Omortho and Darsilami (Figure 1). These samples were analysed using the methods stated in Appendix 4. The composition of the Darsilami Formation samples is presented in Figure 3 and Table 4.

Darsilami sand deposit: The Darsilami sand sample is a moderately sorted medium sand with most of the sand particles between 125 and 500 µm in diameter (Figure 3). The +2 mm size fraction is mainly composed of lithic clasts (approximately 87.5%) with minor proportions of quartz (approximately 12.5%). The quartz and lithic clasts are poorly rounded with a low sphericity. The size fractions between 2 mm and 125 µm, are mainly composed of quartz grains (between 97 and 99%) with a small proportion of lithic clasts (approximately 2%) and shells (approximately 1%). The quartz and lithic clasts are rounded with a medium sphericity.

Omortho sand deposit: The Omortho sand sample is a poorly sorted fine sand with most of the sand particles between 125 and 500 µm in diameter (Figure 3). The size fractions, between 2 mm and 125 µm are mainly composed of quartz grains (98 to 99%) with minor proportions of shell and lithic clasts (between 1 and 2%). The clasts are rounded with a medium sphericity.

The samples at Darsilami and Omortho are both mainly composed of sand (97.1% and 91.9% respectively) and contain minor proportions of mud (2.9% and 8.1% respectively). Sand in the samples is coarse to very fine, which agrees with previous descriptions of the formation.

The PSD of the Darsilami Formation samples are plotted in comparison to Garside Sharp Sand. The Omortho and Darsilami sand samples have a higher proportion of sand in the -500 to +250 µm and the -250 to +125 µm size fractions compared to the Garside sand. This indicates that sampled materials are too fine for use in concrete.

Figure 2. Photomicrographs of the Darsilami Formation samples.

The photographs show: a) the retained '+2 mm ' Darsilami sample sieve fraction, illustrating one quartz grain and lithic clasts; b) the retained '-1 mm to +500 µm ' Darsilami sample sieve fraction; c) the retained '-2 mm to +1 mm ' Omortho sample sieve fraction; d) the retained '-1 mm to +500 µm ' Omortho sample sieve fraction; e) photomicrograph of the quartz grains of the Woburn Sands Formation quarried for the Garside Sharp Sand aggregate product.

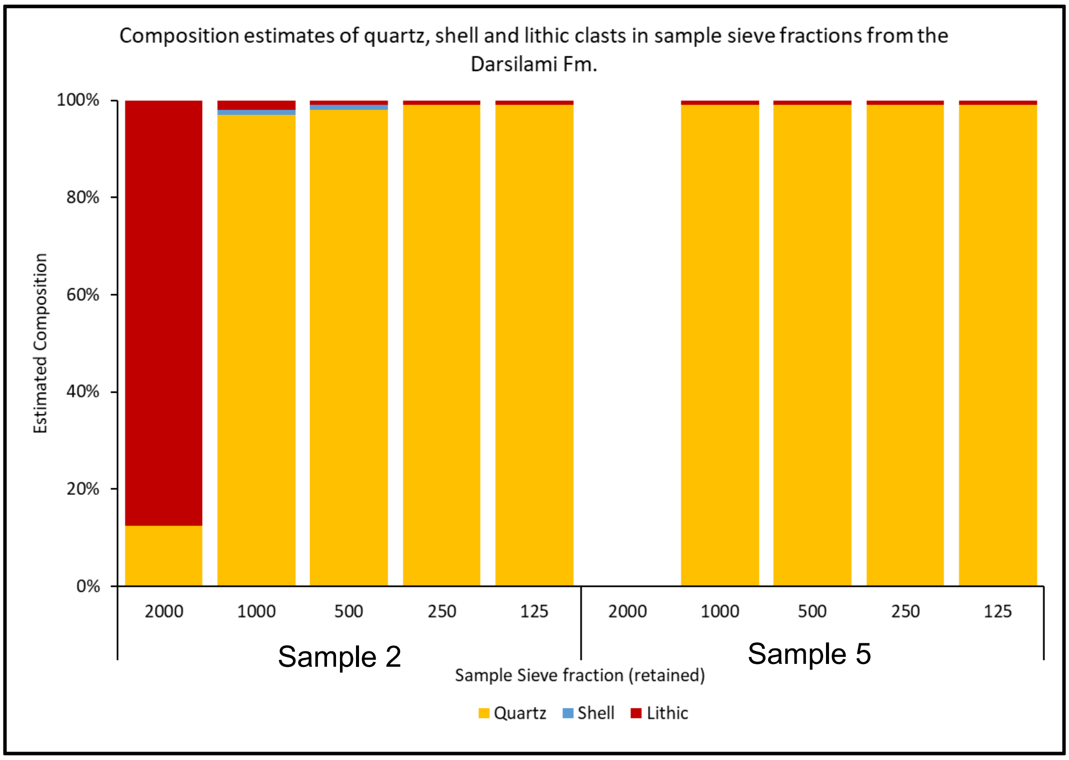

Figure 3. Mineralogical composition of the Darsilami Formation sand samples.

These show the material retained from sieving at the associated sieve size, for example '+ 2000 µm', collected from the Darsilami Formation. Sample 2 is the Darsilami sample, and sample 5 is the Omortho sample. No mass was retained from the '+2000 µm' in sample 5.

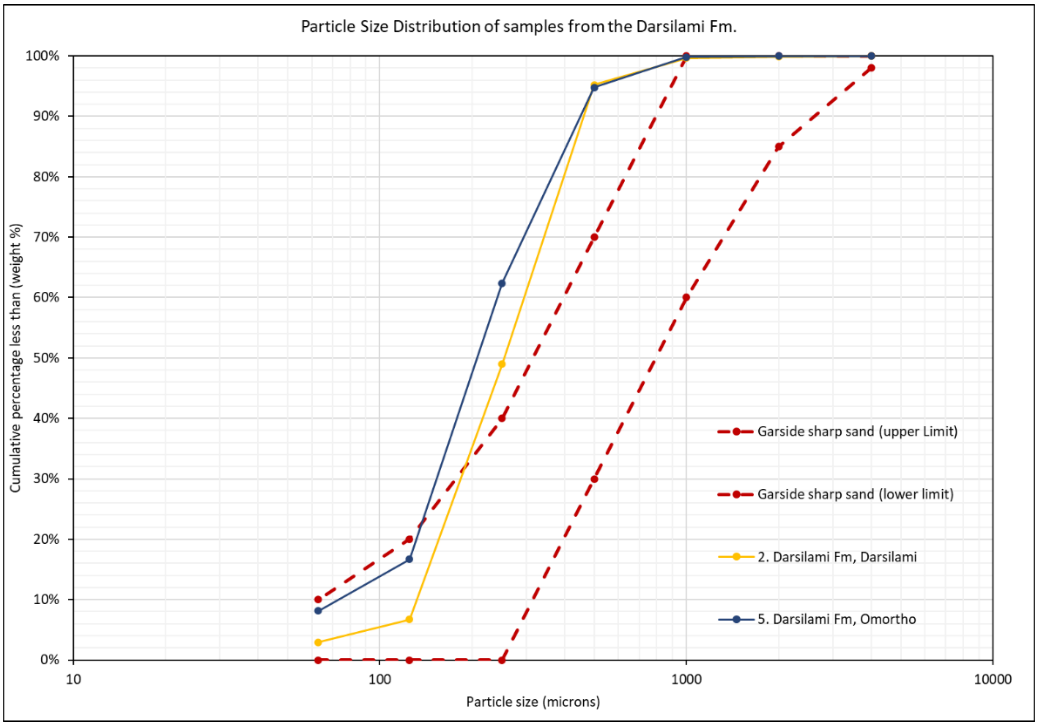

Figure 4. Particle size distribution of samples from the Darsilami Formation.

Samples from Darsilami and Omortho are plotted against the upper and lower limit for the Garside Sharp Sand aggregate. The Garside Sharp Sand aggregate conforms to the BS EN 12620, BS EN 13043, and BS EN 13139 European standards, stating the properties of aggregates to be used in concretes, tarmac surface and mortars. Garside sharp sand data published by Aggregate Industries UK Limited (2013).

3.3.2 Basse Formation

This underlies the Darsilami Formation and dominantly comprises clay with some fine sand horizons. It is fluvial in setting, forming terrace deposits along the River Gambia. It has low resource potential due to the high clay content. The formation is variable and can contain 2 m thick horizons of sand and gravel. It has been worked around Basse for sand resources. The very high clay and silt content is a limiting factor to its potential to be a source of sand.

3.3.3 Yundum Formation

The Yundum Formation is a red sandy clay. It formed as a result of the erosion and subsequent fluvial deposition of older lateritic soils. It is sandier in the east of the country (due to a higher energy depositional environment). Occurrences of the Yundum Formation are widespread across the west of The Gambia. Its resource potential is uncertain. It does contain sand rich layers but is worked less frequently than the Darsilami Formation. It may generally be finer with a greater proportion of impurities and thick layers of clay and silt.

3.4 COASTAL SAND DEPOSITS

The Essau Formation occurs as a thin strip along the coastline of The Gambia. It is a sequence of thick (10 to 30 m) dune deposits underlain by nearshore and beach deposits. The dunes consist of clean, medium to fine-grained sand, these have been extensively worked for sand and are now severely depleted. Additionally, the dunes form a delicate ecosystem and are an important coastal defence. Extraction of sand can impact beach quality, which is one of the main attractions of the tourism industry. It is difficult to justify further extraction from these deposits, therefore, the resource potential from coastal dunes is considered to be low.

Underlying the dunes is a thick sequence of tidal marine sands. These are worked at several localities for 'black sand', which is a heavy mineral rich sand worked for iron, titanium and other heavy minerals, such as ilmenite, rutile and zircon. These are industrial minerals and are worked in much smaller volumes compared to construction sands and are not comparable in terms of markets or properties. However, at these sites overburden material and by-product sand is sold into the construction market. These sands, due to their medium-coarse grain size are one of the few resources in The Gambia that are suitable for high strength concrete. However, supply is limited, and as for other coastal deposits, additional extraction is not advised due to the environmental and economic implications.

3.4.1 Sample Analysis

Two samples were collected from the Essau Formation, at Batukunku, and Tujereng. The samples were analysed applying the methods stated in Appendix 4.

Batukunku sand deposit: The sample taken at Batukunku was classified as a moderately well sorted fine sand. It is mainly composed of medium (41.9%) and fine grain (55.5%) sand, with minor proportions of coarse and very coarse sand (1.5%), and very fine sand (1.1%).

The +2 mm and -2 to +1 mm size fractions are mostly composed of shells (81 to 100%) with minor proportions of quartz and lithic grains. The quartz, shell, and lithic clasts are rounded with a low sphericity. The size fractions between 1 mm and 125 µm are mainly composed of quartz grains (90 to 96%) with minor proportions of shell and lithic clasts (approximately 5%). The quartz, shell and lithic clasts are rounded with a medium sphericity.

The greater proportion of shell fragments and clasts, and the lower proportions of lithic clasts (polycrystalline clasts likely loosely bound by red-yellow iron oxide cement, heavy minerals and iron oxide grains) suggest the natural reworking of the former heavy mineral sand operation, introducing shell fragments into the sample.

Tujereng sand deposit: The sample taken at Tujereng was classified as a well sorted medium sand. The sample collected at Tujereng is mainly composed of medium sand (83.1%) and minor proportions of coarse and very coarse sand (3.3%) and fine sand (13.5%).

The +2 mm size fraction is composed of lithic clasts (approximately 66.7%) and quartz grains (approximately 33.3%) that are poorly rounded and of low sphericity. The size fractions, between 2 mm and 125 µm are mainly composed of quartz grains (60 to 95%) with variable proportions of lithic clasts (5 to 40%). Quartz and lithic clasts in the finer sieve fraction are rounded with a medium sphericity. The lithic clasts contain black heavy minerals as well as polycrystalline clasts loosely bound by a red-yellow iron oxide cement or white-translucent silica or carbonate cement. This reflects the source of the sand from active heavy mineral extraction by Gach Mining.

The composition of the Essau Formation samples is shown in Figure 6 and Table 4. The PSD of the Essau Formation samples in Figure 6 shows that the majority of the sample mass comprises particles between 125 and 500 µm in diameter. The PSD of the Essau Formation samples are plotted in comparison to Garside Sharp Sand.

The weight percent retained in the -1 mm to +500 µm fraction for all sand samples is greater than the upper limit of the Garside Sharp Sand. The weight percent retained in the -500 to +250 µm size fraction of the Batukunku sample exceeds the Garside Sharp Sand upper limit. These observations indicate that the sampled materials do not meet European standards for construction aggregates used in concrete, mortar and tarmac surfaces.

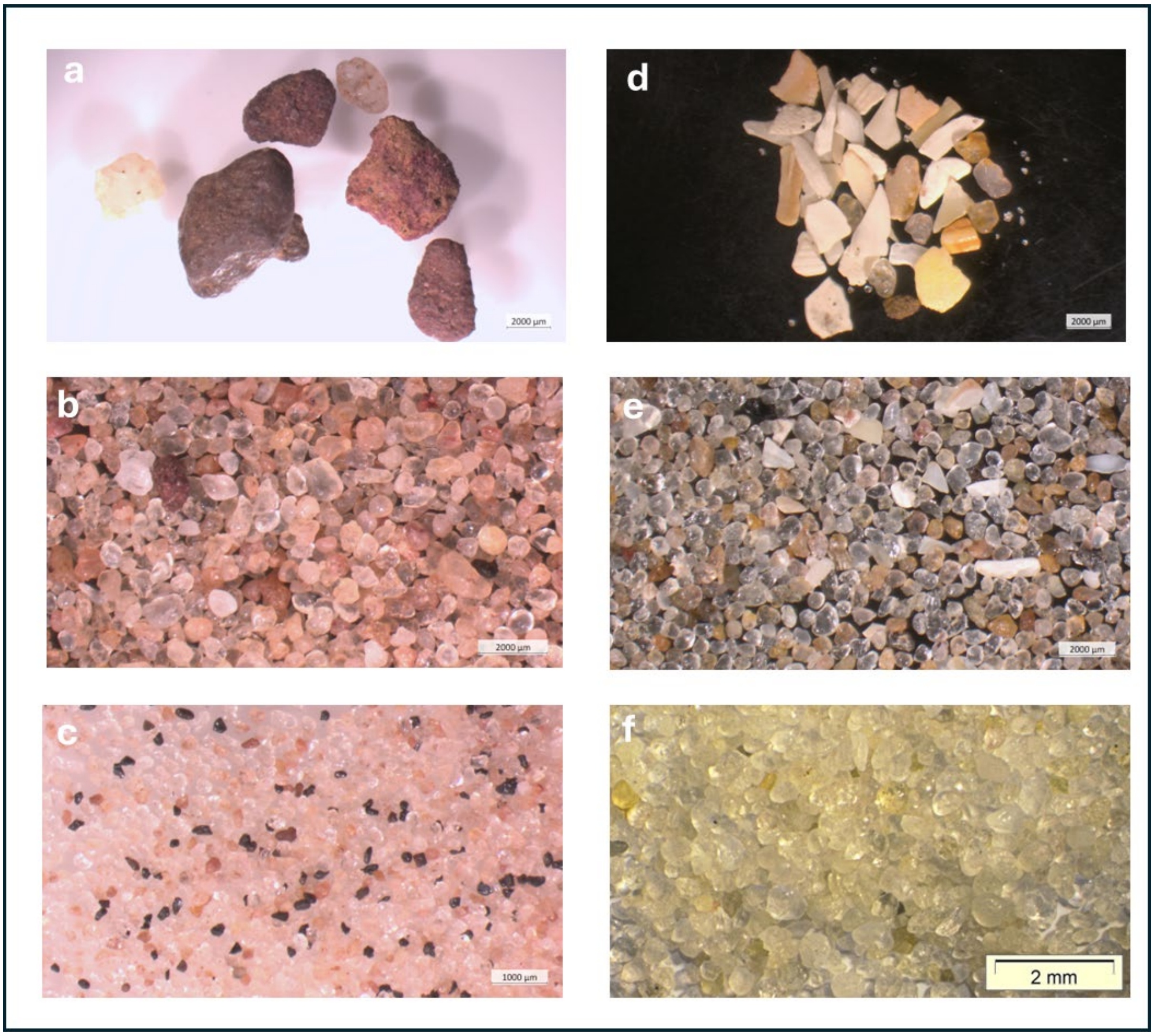

Figure 5. Photomicrographs of Essau Formation samples.

These illustrate: a) the retained '+2 mm ' Tujereng sample sieve fraction, illustrating two quartz grain and lithic clasts; b) the retained ' -1 mm to +500 µm ' Tujereng sample sieve fraction; c) the retained '-250 µm to +125 µm ' Tujereng sample sieve fraction; d) the retained '-2 mm to + 1 mm ' Batukunku sample sieve fraction; e) the retained '-1 mm to +500 µm ' Batukunku sample sieve fraction; f) photomicrograph of the quartz grains of the Woburn Sands Formation quarried for the Garside Sharp Sand aggregate product.

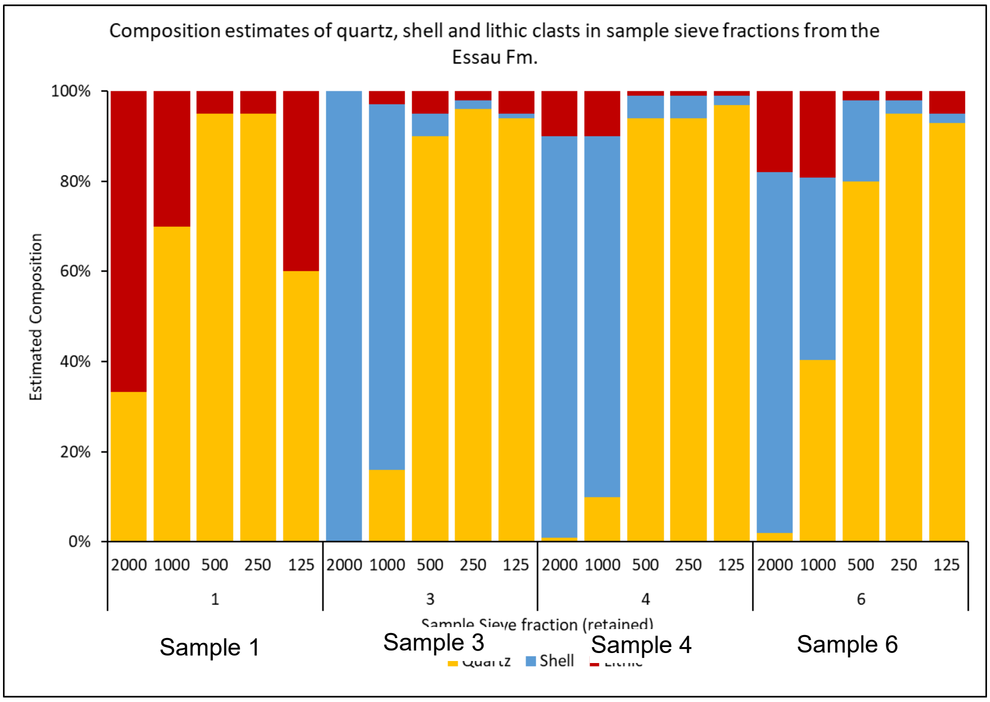

Figure 6. Mineralogical composition of the Essau Formation sand samples.

Composition estimates of sample sieve fractions, retained from sieving at the associated sieve size, for example +2 mm, collected from the Essau Formation and marine sand deposits. Sample 1 represents the Tujereng sample, sample 3 represents the Batukunku sample, sample 4 represents the SMJ Denton Bridge 'as dug' sample and sample 6 represents the SMJ Denton Bridge 'washed and processed' sample.

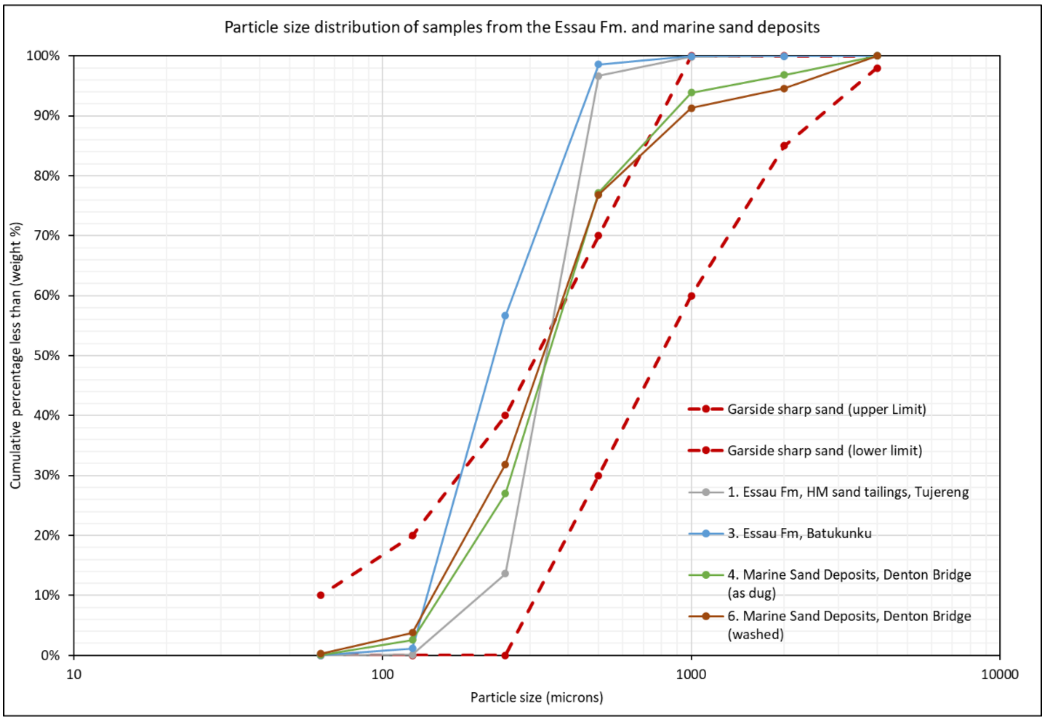

Figure 7. Particle size distribution of Essau Formation and marine sand samples.

The samples plotted, including from Tujereng, Batukunku, and Denton Bridge, are plotted against the upper and lower limit for the Garside Sharp Sand aggregate. The Garside Sharp Sand aggregate conforms to the BS EN 12620, BS EN 13043, and BS EN 13139 European standards, stating the properties of aggregates to be used in concretes, tarmac surface and mortars. Garside sharp sand data published by Aggregate Industries UK Limited (2013).

3.5 MARINE SAND DEPOSITS

Many of the deposits described in this report also extend offshore, where they were deposited at times of lower sea level and are combined with recent marine mobile sand deposits. Marine sand has been suggested as a possible solution to the sand shortage in The Gambia. However, there is currently little geological information as to the location and extent of potential resources. Apart from published reports about coastal erosion and beach nourishment (e.g. Royal HaskoningDHV 2000; Bijl 2011; Royal HaskoningDHV 2021) there is little information or data on the hydrodynamic conditions and offshore sediment circulation systems, which need to be properly understood to avoid negative impacts on biodiversity and coastal erosion. Good practice in marine sand extraction (British Marine Aggregates Association 2013, British Marine Aggregates Association 2017) highlights that material should not be extracted from the nearshore / beach environment, as removal of this material can accelerate coastal erosion. Extraction should be sited far enough offshore to avoid any link between the extraction site and the coastal sediment supply. This typically requires that offshore extraction is sited over 1 km (or often considerably greater distances) from the coast.

Currently, there is offshore extraction of marine sands in The Gambia. The sand is pumped from several hundred meters offshore near Denton Bridge, 5 km west of Banjul, via a fixed pipeline. This extraction close to shore is justified based on a survey into the hydrodynamics (Royal HaskoningDHV 2000) of the area. This highlights that a sand spit (the target of extraction) is causing strong currents and is adding to coastal erosion nearby. Sand from this operation is known to contain competent clay layers that are being disturbed by the dredging. This results in the occurrence of 10–20 cm lumps of clay in the sand product. Without processing (washing and screening) this material, which is fine to medium grained, is not suitable for concreting applications.

There has also been some investigation into sand deposition, predominantly for beach nourishment and coastal defence between 2000–2010 in relation to a beach nourishment project at Kololi Beach (Royal HaskoningDHV 2000, Bijl 2011). This project was judged to be unsuccessful as much of the sand was removed from the beach within seven years. This highlights some of the difficulties associated with the extraction of offshore resources. In this case, it is suggested that the sand was eroded faster than originally modelled due to a high shell content, which skewed the grain size distribution of sand to make it appear coarser. The action of waves preferentially moved easily eroded shells. The sand used for this scheme is reported to have a shell content between 10–20% with a maximum of 30% (Bijl 2011). Standards for fine aggregate specify a maximum shell content of 5%. During the planning stages of this project numerous samples were taken to locate suitable sand resources. Such studies highlight that data may already be available for the preliminary delineation of marine sand resources in The Gambia. These marine deposits are typically fine sands with clay and a thin veneer of shell sand and silt, as well as areas with several metres of medium and coarse sand. The results of these studies have not been analysed in detail or reproduced here but they may form the basis of future geological investigations.

It should be noted that deposits of sand suitable for beach nourishment may not be suitable for use as construction aggregate. Where sand is used for beach nourishment the sediment budget of the nearshore environment is not affected as the sand deposited on the beach is subsequently transported back into the offshore area. However, if the sand is removed for use in construction, the overall sediment budget is reduced leading to a greater risk of coastal erosion.

3.5.1 Sample Analysis

Two samples were collected from the SMJ Denton Bridge sand dredging operation, consisting of material extracted from marine sand deposits. One sample was collected before the processing stage, ‘as dug’ and one sample was collected that was processed (i.e. washed).

<u>SMJ Denton Bridge ‘as dug’ sample</u>: This sand was classified as a moderately sorted medium sand. The size fractions coarser than 1 mm are mostly composed of shell fragments and rock clasts that are rounded with a low sphericity. The size fractions finer than 1 mm and coarser

than 125 µm generally contain a high proportion of quartz grains, and minor proportions of shell fragments and lithic clasts. The grains are rounded with medium sphericity.

<u>SMJ Denton Bridge processed (washed) sample</u>: This sand was classified as a poorly sorted medium sand. The size fractions coarser than 1 mm are mostly composed of shell fragments and rock clasts that are rounded with a low sphericity. The washed and processed sand has a lower proportion of shell compositions, and more quartz and rock clasts than the 'as dug' sample for fractions coarser than 1mm. The size fractions between 1mm and 125 µm generally contain a high proportion of quartz grains, and minor proportions of shell fragments and lithic clasts. However, the retained -1mm to +500 µm and -250 µm to 125 µm fraction contain less quartz grains than the respective 'as dug' sample fractions. The retained -2mm to +1mm and -500 µm to +250 µm fractions contain higher quartz grain compositions than the respective 'as dug' fractions. The grains are rounded with medium sphericity.

The PSD of the Denton Bridge samples in Figure 6 shows most of the sand is between 125 µm and 1 mm in diameter. The PSD of the Denton Bridge samples are plotted in comparison to Garside Sharp Sand, a construction aggregate that conforms to European standards BS EN 12620 for use in concrete, BS EN 13043 for use in bituminous mixtures and surface treatments for tarmac surfaces, and BS EN 13139 for use in mortar. Only the weight percent of sand samples retained in the -1 mm to +500 µm fraction is greater than the upper limit of the Garside Sharp Sand. The weight percent difference between the Denton Bridge samples and the Garside Sharp Sand upper limit is small, approximately seven percent, therefore the sample material would not meet the European Standards for construction aggregates. Further processing is required to remove shell fragments to forma potential aggregate product.

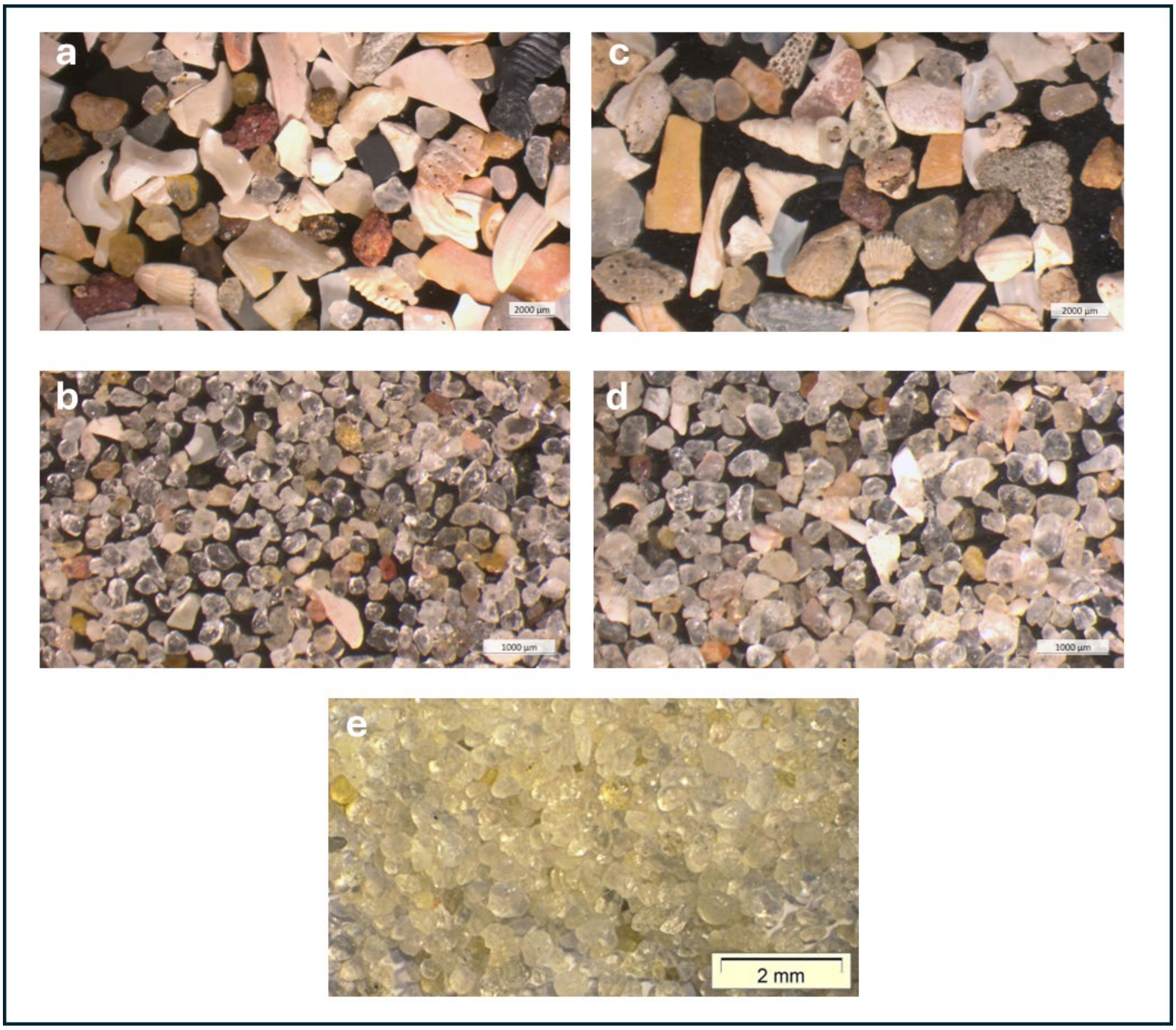

Figure 8. Photomicrographs of the marine sand samples.

These illustrate: a) the retained -2 to +1 mm SMJ Denton Bridge (as dug) sample size fraction; b) the -500 to +250 µm SMJ Denton Bridge (as dug) size fraction; c) the -2 to +1 mm ' SMJ Denton Bridge (washed and processed) size fraction; d) the -500 to +250 µm ' SMJ Denton Bridge (washed and processed) size fraction; e) photomicrograph of the quartz grains of the Woburn Sands Formation quarried for the Garside Sharp Sand aggregate product.

4 Alternatives and new sources of supply

4.1 MANUFACTURED SAND

Manufactured sand is the result of crushing hard rocks to produce sand sized particles. It forms good quality construction sands and is a well-established industrial process forming a significant proportion of supply in many countries. It has the advantage that extraction is constrained to discrete sites, located away from active sedimentary systems and can utilise the waste products of other hard rock extraction in some cases. However, it has two significant constraints reducing its potential in The Gambia. Firstly, hard rocks are scarce in The Gambia. The only rocks with potential are the hard iron-cemented laterites (which are already crushed for gravel). Secondly, the process is capital and energy intensive, requiring heavy plant, such as that on offer from manufacturers like CDE or Metso, that can cost more than £1 million and is expensive to run due to the fuel costs required for crushing and screening. It also requires a level of technical expertise in plant operation to achieve optimal results. Such costly and technically difficult solutions may not be an appropriate solution in The Gambia, especially considering, as far as the authors are aware, there is no production of manufactured sand from laterites anywhere else in the world.

4.2 ONSHORE DEPOSITS

It is possible that detailed geological mapping and improved geological knowledge and models for The Gambia may identify further onshore deposits. Such studies may also be beneficial for other applications such as engineering, groundwater and agriculture. However, onshore deposits are generally fine-grained with a high clay and silt content that are not suitable to supply the concrete market. Also, there are significant issues regarding land access for mineral extraction.

4.3 RECYCLED MATERIAL

In many western counties, the future supply of construction materials is focused on recycling demolition waste. Whilst this is undoubtedly an important part of future supply in some countries, it is not a realistic near-term solution for The Gambia as most buildings are comparatively young and there is very little demolition waste available.

4.4 MARINE SAND

Marine sand was discussed numerous times during the visit by the BGS as a potential source of future supply for The Gambia. Sand is currently being extracted at a large-scale from the Denton Bridge sites, although strictly speaking the deposits, located only a few hundred metres from the coast are a continuation of the nearshore beach deposits. This working is based on a detailed study into the local environment by Royal Haskoning DHV which stated that removal of a specific sand feature would decrease coastal erosion nearby. In most other settings globally, extraction so close to the coast would have consequences, such as coastal erosion and environmental degradation, and is best avoided.

Identification of marine sand deposits suitable for extraction requires detailed offshore mapping and sampling to confirm that there is no link to nearshore sedimentary processes. Evaluation of marine sand deposits can be very capital intensive and requires significant expertise in working with offshore geological and environmental studies as detailed by the British Marine Aggregates Association (2017).

There are also concerns regarding the chloride content of marine dredged sands (due to the high salt content in sea water). However, this can be easily mitigated for by ensuring marine sands have some degree of washing prior to use.

5 Improving supply for the future.

It is recognised that the supply of sand for construction applications has reached a critical point in The Gambia and is severely limiting major construction projects. Coastal dune deposits, that were historic sources of sand, have now been almost entirely removed. It is accepted that such practices are damaging to coastal resilience, severely impact the tourism sector and sterilise potentially valuable real estate. In addition, there are limited volumes of suitable alternatives identified onshore. These deposits are generally too fine grained for use in high strength concrete and can only serve the mortar and block markets. The Ministry of Petroleum and Energy and the Geological Department have recognised these issues and have initiated positive steps towards their resolution, such as setting up an interdisciplinary technical committee on sand. However, significant barriers remain regarding the identification of new suitable sand resource and access to land. There are significant risks related to the potential for environmental damage caused by sand extraction, especially in coastal / nearshore areas.

Further understanding around geological information and sands resources, could help increase supply security and sustainability going forward. The recommendations below relate to issues around geological information and sand resources. This is, however, a complex issue that has social, environmental and land use planning considerations which are outside the scope of this work. Before such considerations can be properly assessed, baseline data on the physical availability of materials needs to be understood.

1: Increased geological understanding of onshore sand resources in The Gambia including:

- Basic geological characterisation (such as particle size analysis and mineralogy) of potential geological formations that have the potential to produce construction sand (for concrete, mortar and foundation applications).
- Regional reconnaissance to identify sand deposits in both green and brownfield sites and creation of regional sand potential maps. An example of such regional studies which may provide useful background are located here: https://www2.bgs.ac.uk/mineralsuk/mines/IMAU.html

Increased geological understanding will provide information for policymakers on the constraints and restricted availability of onshore sand resources in The Gambia. It will provide information for the quarrying industry looking to invest and for those with responsibility for spatial planning to understand where sand extraction needs to be considered alongside other land uses.

This recommendation will require increased laboratory capacity of the Geological Department including basic equipment for geological characterisation and training of staff. For assessment of sand resources, the laboratory equipment required include sieves and weighing balances for particle size analysis. The use of Geographic Information systems (GIS) would be required to enable easy access to geological map data (both geological and licensing) and would require training. A review of the current geological maps and stratigraphy of The Gambia would be a useful exercise to ensure it is sufficient for the country's current and future needs.

2: Increased geological understanding of offshore sand resources in The Gambia including:

- Creation of a standard procedure for Coastal Impact Studies for any new marine dredging areas to provide the dredging industry with information on what they will be required to report on. As a priority this needs to focus on: coastal erosion; beach draw down and biodiversity. It is recommended that such procedures can be adapted from existing reports such as: https://bmapa.org/documents/BMAPA_TCE_Good_Practice_Guidance_04.2017.pdf
- Such studies cover both geological and environmental considerations. This will require cooperation with other relevant Ministries, as such this needs to be recognised as a

multidisciplinary process and stakeholders in the relevant government agencies need to be informed and / or involved.

- There is currently very little (or no) data for offshore geology and the location of offshore sand resources, away from environmentally unsuitable locations for extraction in the nearshore beach environment. An understanding of the seabed sediments, topography, and geology is required. Although it is expensive and difficult to carry out offshore geological mapping, there may be useful data produced by port surveys, oil and gas exploration, environmental studies, past beach replenishment schemes, coastal resilience studies and hydrographic surveys. A literature review of all available offshore geodata should be considered as a first step in this process.
- Using all available data (both geological and environmental), suitable or acceptable areas for marine aggregate extraction need to be defined, as well as possible areas of exclusion in consultation with industry and other regulatory bodies and stakeholders.
- Set up processes for incorporation of data from new offshore activities such as mineral prospecting into the Department's geological models and understanding. Ultimately, as a long-term goal, move towards extending existing onshore geological maps to include the geology offshore.

3: Improvement of industry practices

There is almost no processing (washing and / or screening) of sands in The Gambia. This is an essential step in producing material suitable for some applications (e.g. concreting sand) and is a way of maximising value from sand production. All sand operations that were visited sold sand 'as dug' i.e. unprocessed. The only exception being by-product material from the heavy mineral 'black sands' which received some degree of washing and screening as part of heavy mineral separation process. It is notable that this was the only sand that the BGS encountered that met the required standards for government infrastructure projects. There was also an unused pilot plant at Denton Bridge which had been used for pilot processing trials (as detailed in section 3.5). Due to the high chloride, mud and shell content in the sand worked here such processing is essential for most end uses apart from bulk fill and foundation material. The processing plant was inactive due to the high cost of fuel and a lack of access to water for washing the sand.

As a result of the lack of processing, sand sold into the market is often of poor quality and not suitable for many applications, such as fine aggregate for concrete. Investment in basic washing plant (regarded as essential for most sand operations in many parts of the world) is recommended to process sand and produce higher quality construction materials. This may also enable the production of sand from resources that have otherwise be deemed to be unsuitable for use in construction. This would help to reduce supply bottlenecks by broadening the end-uses that sand can be used for. This may be especially relevant for marine sand due to the capital intensive nature of this industry making investment in plant less challenging.

4: Research into alternative materials

Although sand will remain the primary building material of choice, research should also be undertaken to understand if other local construction materials could form alternatives, such as clay or earth blocks, crushed gravel from iron-cemented lateritic rocks etc. Such interdisciplinary research needs to be undertaken by collaboration between academic institutions, the construction sector and the Geological Department.

6 Conclusions

The supply of sand is of critical importance to the construction industry in the Gambia. With currently few options for alternative materials and a rising consumption, addressing supply issues is vital to ensure future demand is met.

Coastal sand resources, which were historically the main source of sand in The Gambia, are now virtually depleted, and the potentially negative environmental effects of exploiting such deposits are now widely recognised. Alternative sources include inland and offshore deposits of sand. The inland sand deposits can be of variable quality, are often too fine grained for use in many aggregate applications (with average gain sizes about 0.2 mm). These deposits also face considerable opposition to their development from local communities.

The marine sand deposits are largely unknown offshore but operations in coastal marine environments indicate these would provide good quality sand, with suitable grain size profiles (i.e. coarser than those found onshore) although with a typically high shell content. The quality of these sands could be greatly enhanced via simple screening to remove large shell fragments. Extraction from the marine environment must be carefully managed to avoid coastal erosion and environmental damage, considering current predictions for shoreline retreat and the country's reliance on tourism linked to coastal areas.

This preliminary study recommends development of a better understanding of both onshore and offshore sand deposits, consideration of how the supply chain can be made more efficient via processing to improve the quality of sand and consideration of how demand may be reduced via the use of less sand intensive building practices.

Appendix 1 BGS activities report

BGS sand mining project team (Tom Bide, project leader and construction minerals geologist; and Clive Mitchell, industrial minerals geologist) travelled from the UK to The Gambia for an 11-day mission to support the sand mining activities of the Geological Department of the Ministry of Petroleum and Energy (MoPE). The mission was facilitated by The Geological Department and MoPE who provided a high level of logistical support without which the successful output of the mission would not have been possible.

All sites visited are shown in Figure 9.

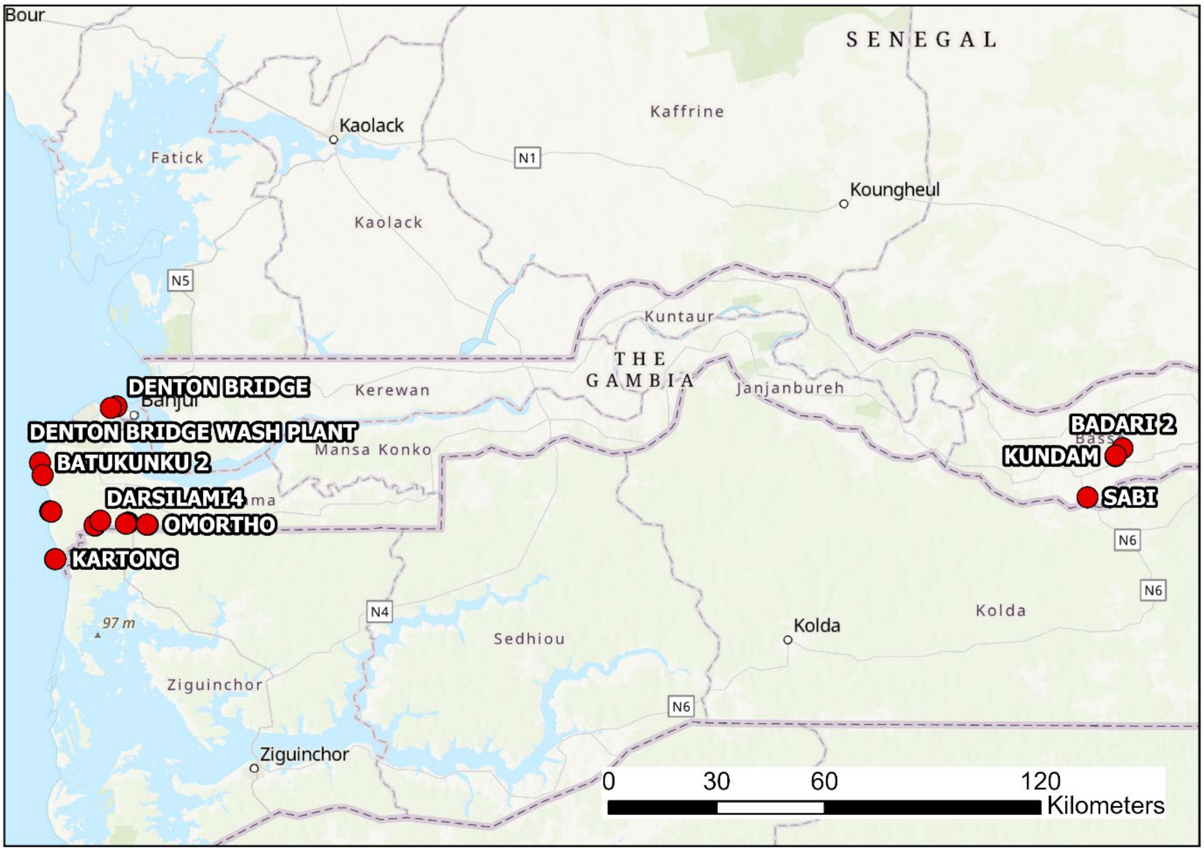

Figure 9 sites visited by BGS. Map data © OpenStreetMap contributors (2024).

<u>Wednesday 8th November</u>

The day started by meeting the Acting Director of the Geological Department, Alieu Jawo to discuss the scope of the BGS mission to The Gambia and work out a schedule of activities. The BGS team were supported by Muhaed Karaga who provided transport and practical assistance. A full day of meetings at the following organisations followed:

- MoPE where the BGS team met the Permanent Secretary, Amie Njie and selected senior officers of MoPE. In addition, the BGS team met the Director General of the Petroleum Commission, Jerrah Barrow (formerly of the Geological Department).
- National Roads Authority (NRA) where the BGS team met the Deputy Managing Director.
- National Environment Agency (NEA) where the BGS team met the Executive Director, Dr Dawda Badgie and selected senior officers of NEA.
- Ministry of Environment, Climate Change and Natural Resources (MECCNAR) where the BGS team met Principal Assistant Secretary, Momodou Kanyi.

Thursday 9th November

The BGS team spent the morning with Alieu Jawo and the Geological Department field team discussing the construction sand survey programme, sand sampling and size analysis. In the afternoon, the BGS team accompanied the Geological Department to the sand mining areas of Giboro and Omortho in Kombo East, Western Region. The BGS team provided guidance on auger sampling and sub-splitting of sand samples. Also in attendance was the MoPE communications officer, Anna Marie Valentine (who also participated in most of the field work carried out during the BGS mission to The Gambia).

Friday 10th November

In the morning, the BGS team met with Deputy High Commissioner, Martin Norman at the British High Commission to discuss sand mining in Gambia. Also present at the meeting were Tanja Roy (Deputy Head of Mission, Embassy of the Federal Republic of Germany) and Raphael Brigandi (Deputy Head of Delegation, Delegation of the European Union to The Gambia). In the afternoon, the BGS team accompanied the Geological Department field team to the sand deposit in Darsilami where auger sampling was carried out.

Saturday 11th November

The BGS team accompanied the Geological Department to a series of worked out construction and heavy mineral sand mining sites along the Gambian coastline. The first site was at Batukunku, a former heavy mineral sand operation. The field group progressed further south to worked out construction sand sites, the first at Sambuyang and then to Kartong, the most southerly site visited which is close to the border with Senegal. This stretch of coastline is close to the area offshore that is proposed for the licencing of marine sand extraction by dredging.

Sunday 12th November

Day off.

Monday 13th November

The BGS team met with Alba Energies at the Geological Department to learn about their plans for marine sand dredging in the area offshore of Sambuyang. This was followed by a visit to the heavy mineral sand mining site at Tujereng operated by Gach Mining. The by-product tailing is quartz sand, part of which is used for site restoration and the remainder is sold for construction. The BGS team then travelled across country with the field team from the Geological Department to a guest house in Basse, Upper River Region.

Tuesday 14th November

The BGS and Geological Department teams visited three alluvial sand mining sites (Kundam, Badari and Sabi) in the area around Basse. The last site at Sabi has a recorded occurrence of alluvial gold. There are several artisanal miners (“Galamsey”) that are conducting gold prospecting. The BGS team set off back west and arrived at their hotel in the evening.

Wednesday 15th November

In the morning the BGS team visited the Geological Department then went back to work at their hotel. In the afternoon the BGS team attended a meeting of the ‘Technical Committee on Sand and Gravel Quarries’ which was held at MoPE. Afterwards the BGS team had a brief meeting with a consultant, Mohammed Leroy, working for the West Africa Coastal Area Management Programme on a World Bank funded project focused on the Kotu stream catchment area.

Thursday 16th November

In the morning, the BGS and MoPE (including Alieu Jawo; Mansata Darboe, Deputy P.S., Yira Jammeh, P.A.S. and Anna Marie Valentine), attended meetings at the Ministry of Lands, Regional Government and Religious Affairs (MOLRG), and the Ministry of Foreign Affairs (MoFA). Present at the MOLRG meeting were Famin Tooray (Director of Physical Planning, MOLRG), Alieu Badjie (Deputy P.S., MOLRG), and Mummudu Nanjang (APSID/ MOLRG). The meeting at the MoFA was with Ambassador Lang Yabou (Principal Secretary). This was followed by a visit to the sand dredging operation of Sino Majilac Jalbak (SMJ) at Denton Bridge where the BGS and MoPE visited the sand stocking area and the washing plant.

Friday 17th November

In the morning, the BGS took part in some filming on the beach near Kotu stream. At lunchtime the BGS met with Martin Norman (Deputy High Commissioner, British High Commission) and Eric Mehler (Deputy Chief of Mission, United States Embassy). The BGS team held some final meetings with Alieu Jawo over the afternoon. The BGS team departed Gambia in the evening.

Saturday 18th November

The BGS team arrived back in the UK.

Appendix 2 Sand sampling sheet

<table>
<tr><td colspan="2">Location:</td><td colspan="7">Formation (if known)</td><td colspan="2">Co-ordinates
E: | W:</td><td colspan="2">Staff:</td></tr>
<tr><td rowspan="2">Depth below surface</td><td rowspan="2">Thickness</td><td colspan="7">Sand grain size</td><td rowspan="2">Colour</td><td rowspan="2">Sorting</td><td rowspan="2">Description</td><td rowspan="2">Samples</td><td rowspan="2">Photos</td></tr>
<tr><td>Mud</td><td>VF</td><td>F</td><td>M</td><td>C</td><td>VC</td><td>G</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Appendix 3 Useful links

BGS good practice guidance: https://www2.bgs.ac.uk/mineralsuk/download/mines/Illustrative-good-practice-for-sand-mining.pdf

UNEP report: 10 Strategic Recommendations to Avert a Crisis
https://www.unep.org/resources/report/sand-and-sustainability-10-strategic-recommendations-avert-crisis

Marine dredging good practice guidance:
https://bmapa.org/documents/BMAPA_TCE_Good_Practice_Guidance_04.2017.pdf

Marine aggregate dredging and the coastline: a guidance note
https://bmapa.org/documents/Coastal_Impact_Study_Best_Practice_Guidance.pdf

Appendix 4 Sand Sample Analysis

The samples collected from the Darsilami Formation and the Essau Formation were dried and sieved for particle size analysis. Samples were sieved through the following sieve mesh sizes: 2 mm, 1 mm , 500 µm , 250 µm , 12 µm , and 63 µm . The remaining sample particles less than 63 µm in diameter were collected and retained. The following grain size fractions were obtained from the particle size analysis: +2 mm, -2 to + 1 mm, -1 mm to +500 µm, -500 to +125 µm, - 125 to +63 µm, and -63 µm. The measured mass of each grain size fraction of each sample is reported in Table 1. Following particle size analysis, the size fractions collected, except for -125 to +63 µm and -63 µm size fractions, were qualitatively analysed for quartz, shell and lithic clasts content, as well as grain morphological information. A summary of the qualitative analysis of the sample sieved fractions are given in Table 4. Results from the particle size analyses were processed in the GRADISTAT Excel program (Version 9.1) developed by Blott and Pye (2001).

In addition to the data included in this report the results generated from the GRADISTAT software report various statistical parameters calculated by Methods of Moments, arithmetically, geometrically (µm), and logarithmically (Φ), including grain size diameter percentiles (D_n), mean, mode(s), sorting (σ), skewness (Sk) and kurtosis (K) (Blott and Pye 2001). The software also outputs physical descriptions of the sediments analysed applying the Folk & Ward Method, such as ‘medium sand’ and ‘well sorted’ which inputs into the sediment name of samples as well as calculating the percentage of grains of each grain size fraction, based on a modified Wentworth grain size scale. Further information on the GRADISTAT software is available in the work published by Blott and Pye (2001).

APPENDIX 4A GAMBIAN SAND SAMPLE STATISTICS

Table 1. Particle size analysis results of the sand samples collected from The Gambia.

Sample Information					Sieve fraction (µm) retained mass (g)						
Sample Name	Sample No.	Initial Sample Mass (g)	Total Mass After Analysis (g)	Sample Loss (g)	2000	1000	500	250	125	63	Pan
Tujereng tailings	1	543.65	543.28	0.37	0.34	0.44	17.33	451.25	73.45	0.27	0.2
DS2 WP54 Darsilami	2	421.6	420.61	0.99	0.62	0.78	18.69	194.66	177.61	15.89	12.36
Batukunku 2 heavy mineral beach sand	3	477.37	476.23	1.14	0.2	0.11	6.5	199.65	264.36	5.34	0.07
SMJ Denton Bridge (as dug)	4	453.55	453.08	0.47	14.27	13.59	75.5	227.36	110.8	11.4	0.16
Omortho	5	458.14	455.8	2.34	0	0.91	22.74	147.93	208.32	38.93	36.97
SMJ Denton Bridge (Washed & Processed)	6	517.42	516.45	0.97	28.03	16.88	74.62	232.31	145.07	18.23	1.31

Table 2. Selected output of the GRADISTAT software of the sand samples collected from The Gambia.

GRADISTAT software developed by Blott and Pye (2001). Abbreviations used: heavy mineral

Method	Statistic	Tujbreng tailings	DS2 WP54 Darsilami	Batukunku 2 HM beach sand	SMJ Denton Bridge as dug	Omortho	SMJ Denton Bridge W + P
SIEVING ERROR:		0.1%	0.2%	0.2%	0.1%	0.5%	0.2%
SAMPLE TYPE:		Unimodal, Well Sorted	Unimodal, Moderately Sorted	Unimodal, Moderately Well Sorted	Unimodal, Moderately Sorted	Unimodal, Poorly Sorted	Unimodal, Poorly Sorted
TEXTURAL GROUP:		Sand	Sand	Sand	Sand	Sand	Sand
SEDIMENT NAME:		Well Sorted Medium Sand	Moderately Sorted Medium Sand	Moderately Well Sorted Fine Sand	Moderately Sorted Medium Sand	Poorly Sorted Fine Sand	Poorly Sorted Medium Sand

(HM); washed and processed (W + P).

Statistic	Tujbreng tailings	DS2 WP54 Darsilami	Batukunku 2 HM beach sand	SMJ Denton Bridge as dug	Omortho	SMJ Denton Bridge W + P
MODE 1 (μm):	375.0	375.0	187.5	375.0	187.5	375.0
D_{10} (μm):	207.8	131.9	139.6	154.4	73.31	145.7
D_{50} (μm):	338.7	254.0	230.1	343.5	207.3	330.6
D_{90} (μm):	472.9	462.4	433.9	852.0	451.2	939.4
(D_{90} / D_{10}) (μm):	2.276	3.505	3.108	5.519	6.154	6.446
(D_{90} - D_{10}) (μm):	265.1	330.5	294.3	697.6	377.9	793.6
(D_{75} / D_{25}) (μm):	1.518	2.189	2.011	2.054	2.308	2.303
(D_{75} - D_{25}) (μm):	142.4	200.6	170.2	248.9	185.6	274.9
% GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
% SAND:	100.0%	97.1%	100.0%	100.0%	91.9%	99.7%
% MUD:	0.0%	2.9%	0.0%	0.0%	8.1%	0.3%
% V COARSE GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
% COARSE GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
% MEDIUM GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
% FINE GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
% V FINE GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
% V COARSE SAND:	0.1%	0.3%	0.1%	6.1%	0.2%	8.7%

% COARSE SAND:	3.2%	4.4%	1.4%	16.7%	5.0%	14.4%
% MEDIUM SAND:	83.1%	46.3%	41.9%	50.2%	32.5%	45.0%
% FINE SAND:	13.5%	42.2%	55.5%	24.5%	45.7%	28.1%
% V FINE SAND:	0.0%	3.8%	1.1%	2.5%	8.6%	3.5%
% V COARSE SILT:	0.0%	0.5%	0.0%	0.0%	1.3%	0.0%
% COARSE SILT:	0.0%	0.5%	0.0%	0.0%	1.3%	0.0%
% MEDIUM SILT:	0.0%	0.5%	0.0%	0.0%	1.3%	0.0%
% FINE SILT:	0.0%	0.5%	0.0%	0.0%	1.3%	0.0%
% V FINE SILT:	0.0%	0.5%	0.0%	0.0%	1.3%	0.0%
% CLAY:	0.0%	0.5%	0.0%	0.0%	1.3%	0.0%

APPENDIX 4B GAMBIAN SAND SAMPLE COMPOSITION

Table 3. Composition of sample size fractions.

Summarising the estimated proportions of quartz grains, shell fragments, and lithic grains within each fraction as well as the average particle angularity and sphericity. Sample numbers correspond to Table 1. *This sieve fraction is composed of two shell fragments. **This sieve fraction had no mass retained resulting from the particle size analysis.

Sample	Sieve Fraction Retained (µm)	Average Angularity	Average Sphericity	Composition (%)		
				Quartz	Shell	Lithic
1	2000	Poorly Rounded	Low	33.3	0	66.7
1	1000	Poorly Rounded	Medium	70	0	30
1	500	Rounded	Medium	95	0	5
1	250	Rounded	Medium	95	0	5
1	125	Rounded	Medium	60	0	40
2	2000	Poorly Rounded	Low	12.5	0	87.5
2	1000	Poorly Rounded	Medium	97	<1	2
2	500	Poorly Rounded	Medium	98	<1	1
2	250	Rounded	Medium	99	0	1
2	125	Rounded	Medium	99	0	1
3	2000	*	*	0	100	0
3	1000	Rounded	Low	16	81	<3
3	500	Well Rounded	High	90	5	5
3	250	Rounded	Medium	96	<2	<2
3	125	Rounded	Medium	94	<1	5
4	2000	Poorly Rounded	Low	1	89	10

4	1000	Poorly Rounded	Low	10	80	10
4	500	Rounded	Medium	94	5	1
4	250	Rounded	Medium	94	5	1
4	125	Rounded	Medium	97	2	1
5	2000	**	**	0	0	0
5	1000	Rounded	Medium	98	0	<2
5	500	Rounded	High	98	0	<2
5	250	Rounded	Medium	99	0	<1
5	125	Rounded	Medium	99	0	<1
6	2000	Poorly Rounded	Low	2	80	18
6	1000	Poorly Rounded	Medium	40	40	20
6	500	Rounded	Medium	80	18	2
6	250	Rounded	Medium	95	3	2
6	125	Rounded	Medium	93	2	5

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