Centre for Tropical Water and Aquatic Ecosystem Research

A synthesis of the changing sources, transport and delivery of sand to the Burdekin River Delta: implications for the stability of the Bowling Green spit

Stephen Lewis, Zoe Bainbridge and Scott Smithers

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This report was peer-reviewed in June 2022 by coastal geomorphologist Professor David M. Kennedy, the Director of the Office for Environmental Programs of The University of Melbourne. Professor Kennedy is also an Editor-in-Chief of the international journal *Geomorphology*.

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Executive Summary

This document synthesises the available science relevant to understanding sand transport through the Burdekin Basin, including through the sub-catchments, to the end-of-river Delta and along the beaches to Cape Bowling Green. The investigation was initiated by stakeholder concerns that the Burdekin Falls Dam (constructed in 1987) has potentially reduced sand delivery to the coast and, as a result, decreased sand supply to beaches and caused severe coastal erosion along the shorelines of the Burdekin Delta and Cape Bowling Green spit. These concerns are heightened by fears that Ramsar-listed wetlands within adjacent Bowling Green Bay are threatened by erosion of the Cape Bowling Green spit possibly related to a reduced sediment supply, which may be further exacerbated by newly proposed water infrastructure for the basin.

The brief for this synthesis identified three main areas of focus:

1. Sediment sources and dynamics through the Burdekin River catchment;
2. The geomorphological development of the Delta coast, morphodynamic changes, and the relationship between these and sediment supply from the catchment;
3. Additional science needs required to address critical gaps in understanding the above issues.

This synthesis will aid in the assessment of the Water Plan (Burdekin Basin) 2007 and help inform its next iteration. Here we present our key findings against the key questions identified from the Terms of Reference. It should be noted this report focuses on the role of hydrology on the transportation and delivery of sand to the Burdekin River Delta. The findings do not consider the implications of the extractive industry on sediment loads within the Burdekin Basin.

What is the grain size composition of the Burdekin Delta and beaches within Cape Upstart and what flow regime is necessary to deliver this material to the coast?

This section examined the potential changes in the supply of the sand fraction delivered from the Burdekin River and if such changes could potentially alter the geomorphology of the coastal zone. We initially reviewed the existing grain size measurements from the Burdekin River Delta, the beaches within Upstart Bay and the Cape Bowling Green spit. This review shows that **the beaches are predominately (>90%) composed of the fine and medium sand fraction (125 to 500 μm) and hence the riverine supply of this fraction is most important to replenish the coastal zone of this region**. A review of grain size studies of the Burdekin River show that **this sand fraction is predominantly transported in flood events as 'suspended bedload'** while bedload transport contributes a minor component of this total load (~ 10 to 15%). Indeed, <15% of the sediment in the Lower Burdekin River channel is composed of the fine and medium sand fraction. It would thus appear that the fine and medium sand fraction, the key component of beaches in the region, is effectively transported through the Burdekin River and to the end of catchment during flood events as suspended bedload (Figure i). Independent studies have shown that **substantial loads of fine and medium sand particles may be transported along the Burdekin River during flood events as low as 2,000 $m^3.s^{-1}$** (current annual return interval (ARI) = 1.38 years), although over 10,000 $m^3.s^{-1}$ flows (ARI = 4.3) are required for significant bedload transport (and >14,000 $m^3.s^{-1}$ (ARI = 7.5) to 'reset' the channel bed).

From where does most of the fine and medium sand delivered to the coast come from and has this delivery changed over time?

Our best estimate of the current ***annual average*** load of the fine and medium sand fraction exported from the Burdekin River is 200,000 tonnes per year, although given the high inter-annual flow variability, the annual range is estimated between 0 and 800,000 tonnes. The annual supply of this fraction increased following agricultural development in the catchment with the arrival of Europeans and then reduced with the construction of the Burdekin Falls Dam (captures 88% of the Burdekin basin), which measurements show traps ~95% of the fine and medium sand load supplied from the upstream catchment area (Figure ib). A first order approximation of how the fine and medium sand loads have changed over time can be made by assuming that this fraction would comprise an additional 10% of the fine (i.e. mud) sediment loads. Indeed, these finer sediment (mud) loads for the Burdekin River have been well constrained through catchment modelling exercises, accumulation rates in sediment cores, changing erosion rates in the catchment, coral core records and trapping efficiency measurements for the Burdekin Falls Dam. The application of the 10% factor of the mud load is supported by the findings of previous investigations and based on some measured data. These budgets indicate that **despite the limited sand transported past the Burdekin Falls Dam since construction, the increase in sediment loads from the catchment area below the dam have more than accounted for the reduced supply from the dam relative to the 'pre-development' (i.e. prior to the arrival of Europeans) period** (Figure ib). In fact, **the current fine and medium sand loads exported from the Burdekin River are estimated to be over 3-fold higher than the pre-development loads**. This result suggests that erosion of the shoreline at Cape Bowling Green spit is not related to reduced sediment supply to the coast by the Burdekin River since construction of the Burdekin Falls Dam. Please note extraction of sediment or quarry material is outside the scope of the investigation in this report. The Alluvium Consulting report (2019) quantified quarry extractions from different reaches of the lower Burdekin River at a reach scale.

How might proposed future water infrastructure (i.e. dams) affect fine and medium sand loads?

Based on the evidence presented above, **we conclude that the additional water infrastructure proposed (i.e. raising the Burdekin Falls Dam spillway; dams in the catchment area above the Burdekin Falls Dam; Urannah Dam) would have a negligible influence on the current coastal supply of fine and medium sand from the Burdekin River**. Since the construction of the Burdekin Falls Dam, a large load of the fine and medium sand fraction is now trapped before it reaches the reservoir (~450,000 tonnes a year on average). It is estimated that <5% of this load (i.e. ≤10,000 tonnes) is potentially transported through the dam which is, in turn, <5% of the current load (i.e. 200,000 tonnes) exported from the catchment. In that regard, any additional water infrastructure such as raising the Burdekin Falls Dam or construction of a new dam in the upper catchment area can only trap a proportion of the available load currently transported through the Burdekin Falls Dam, which in the context of the current export is negligible (especially when also taking into account the overall net increase in the catchment area below the dam since the arrival of Europeans) (Figure ic). Likewise, the very low total sediment loads transported through the section of the Broken River just downstream of the proposed Urannah Dam indicate that this dam will have limited influence on the total fine and medium sand exported from the Burdekin River. However, we do caution that potential changes in hydrology (i.e. peak and duration of flow) with the proposed water infrastructure may result in changes in the bedload transport and potentially influence the geomorphology of the channel. Such changes are difficult to assess and would require a more sophisticated modelling approach which is outside the scope of this desktop review. It is noted, there are several water infrastructure proposals currently undertaking Environmental Impact Statement (EIS) processes co-ordinated by the Office of the Coordinator-General. As part of the EIS process proponents are required to undertake both individual and cumulative assessments for changes to the delivery of fine and medium sand fraction to Cape Bowling Green and riverine morphology.

What is the geomorphological history of the Cape Bowling Green spit?

The Cape Bowling Green spit, the beaches and sand barrier bars within Upstart Bay are highly dynamic features and their progradation and erosion are influenced by ambient coastal processes (mostly wave-driven longshore drift), tropical cyclones (wave transport), large floods and, over the longer term, the avulsion history of the Burdekin River. The base of the Cape Bowling Green spit likely formed between 5,000 and 4,000 years before present (BP) as a result of sand supply from a former discharge point of the Burdekin River (i.e. the palaeo-channel from the 'Bowling Green Delta lobe' in Figure ii). More recent channel avulsions in this vicinity between 3,000 and 1,000 years BP continued to supply sand to the area (Figure iia). The most recent avulsion (after ~1000 years BP) has shifted the Burdekin River mouth to a position almost 30 km south of the base of Cape Bowling Green spit, greatly reducing the sediment supply to the spit. Longshore drift of shoreface sediments have supplied the continued growth/extension of the distal end of the spit to this day. However, transfer of these sediments at rates faster than they are now supplied from alongshore further south has resulted in sections of the spit shoreline actively eroding for some time. Indeed, the early geomorphological studies on the Cape Bowling Green spit from the late 1960s to 1970s documented this long history of erosion with estimates of up to a total of 2.5 km of coastal retreat occurring over the past 1,000 years. Exposed mangrove peat deposits on beaches (dated between 560 and 2,060 radiocarbon years BP) and the presence of dead trees along eroding sections of the shoreline (Figure iii) that were originally deposited/growing behind the spit provide evidence of these changes. Hence**, large sections of the Cape Bowling Green spit have been actively eroding for at least the past thousand years and historical studies have documented this eroding coastline prior to the construction of the Burdekin Falls Dam**. Importantly, the onset of the erosion significantly pre-dates the construction of the Burdekin Falls Dam and is most logically attributed to a reduced sand supply to the spit caused by the movement of the Burdekin River mouth to the southern part of the delta approximately 1,000 years ago. The sustained development of river mouth bars and continued progradation of the active delta lobe at the contemporary river mouth support our conclusion that sand supply to the coast has not reduced since construction of the dam. Coastal erosion on Cape Bowling Green spit may have recently accelerated due to higher sea levels and or climate conditions. However, the evidence clearly indicates that it is a long-active process largely driven by episodic shifts in the location of the river mouth and the redistribution alongshore of sands exported from the catchment.

Science needs

Some of the most critical science needs identified in this synthesis to support current and future water resource planning for the Burdekin Basin include:

- A sophisticated hydrodynamic model to quantify how the proposed dams will modify flow peaks and durations. The model should include consideration of dam type and operation protocols.

- Field measurements of the suspended bedload (and bedload) transported by the Lower Burdekin River channel under different flow conditions and with different source areas (i.e. above and below Burdekin Falls Dam sources). These data would help develop relationships between the loads of the fine and medium sand fractions with changing flows.
- A study to examine the dynamics of the fine and medium sand transported to (and potentially past) the Burdekin Delta under a range of flow conditions. Presently, the effectiveness of transport (i.e. where the fine and medium sand load is predominately deposited beyond the end-of-river) is unclear. Following deposition, the processes that govern the subsequent remobilization and transport of this sediment (i.e. floods, tides, waves, currents, storms) also need to be determined so that the final fate of this sediment can be determined.
- Systematic monitoring to quantify the coastal retreat of sections of the Cape Bowling Green spit and the assessment of the implications on the Ramsar site. This monitoring should utilise tools such as the DEA tool available through Geoscience Australia, augmented with geo-rectified historical imagery of the site captured prior to the DEA records, to establish mean rates of shoreline movement over the measurement intervals.

Please refer to Section 6 for the full list of recommendations.

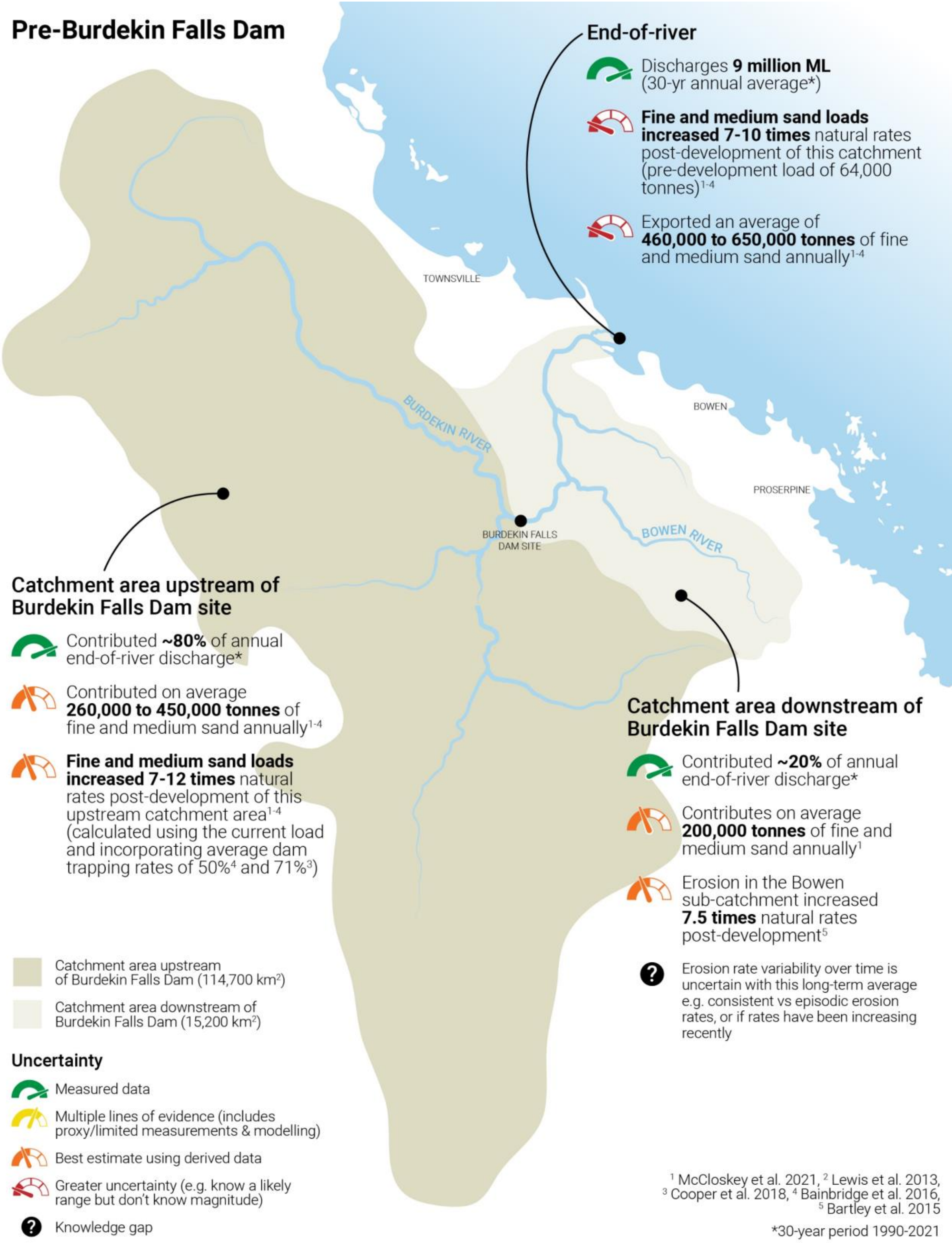


Figure i (a). Conceptual overview of the current understanding and knowledge gaps of Burdekin River hydrology and fine and medium sand sources and transport. Series include (a) pre-construction of the Burdekin Falls Dam (BFD); (b) present setting with Burdekin Falls Dam; and (c) future scenarios with proposed future water infrastructure (dam) developments.

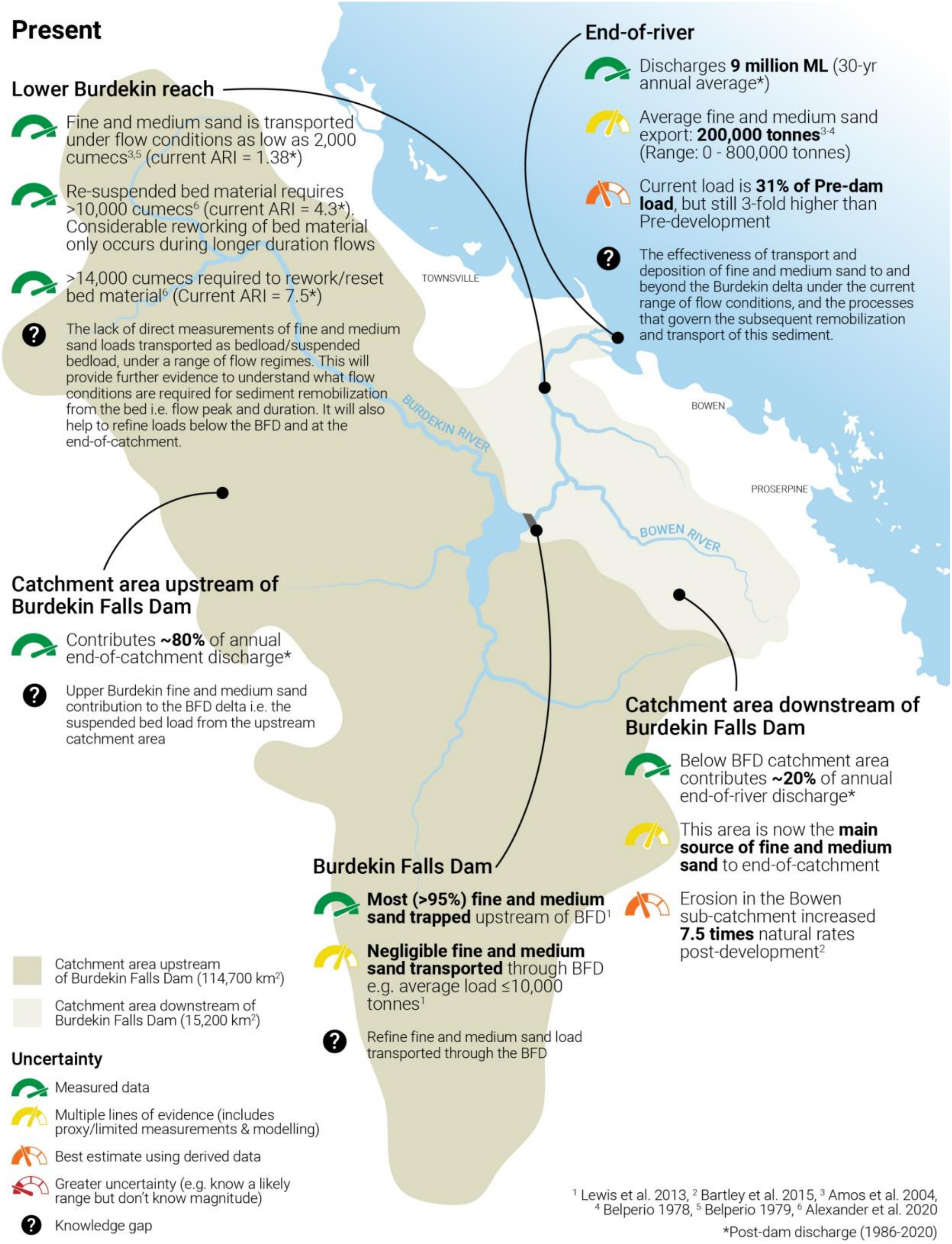
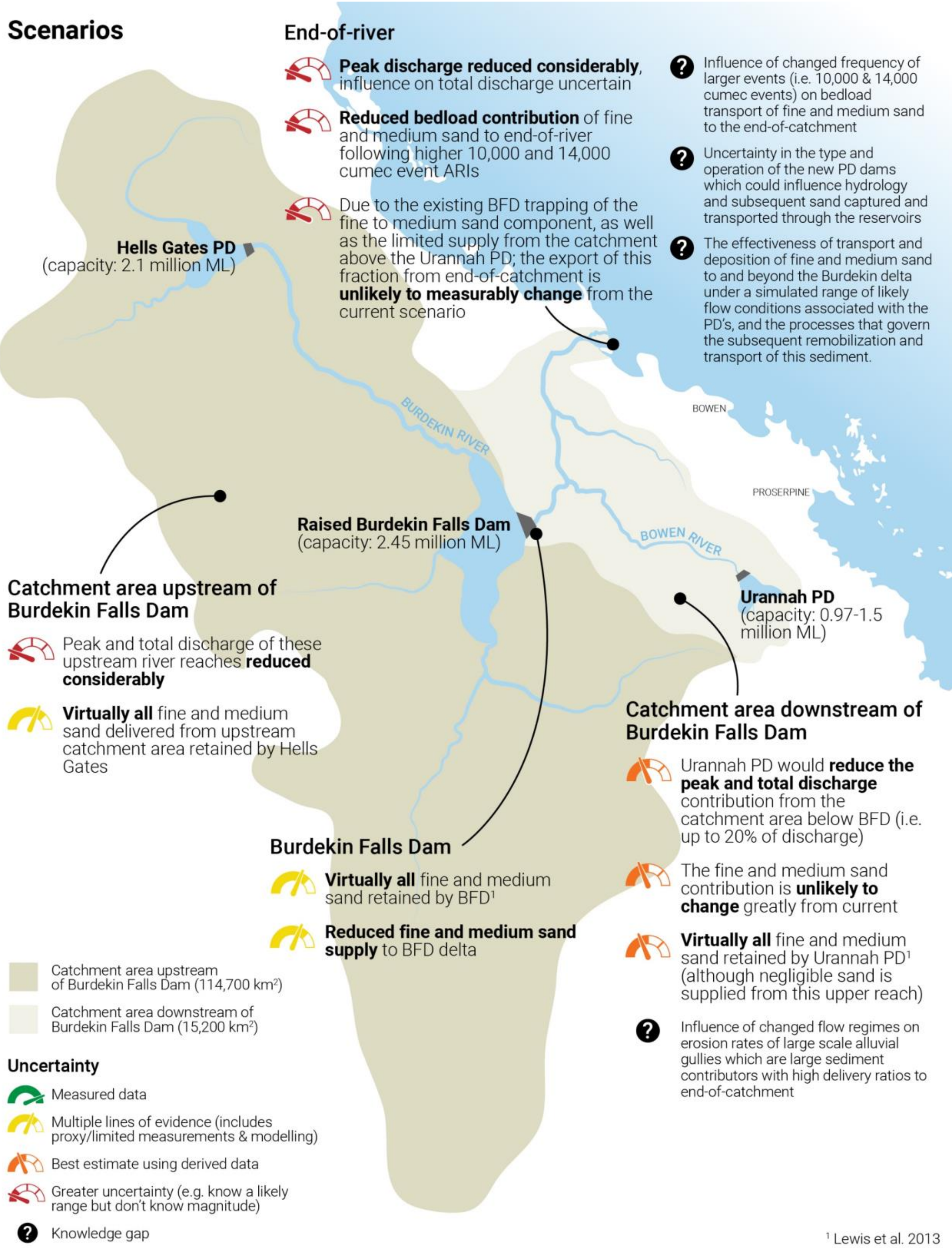


Figure i (b) (cont.). Conceptual overview of the current understanding and knowledge gaps of Burdekin River hydrology and fine and medium sand sources and transport. Series include (a) post-development of the catchment and pre-construction of the Burdekin Falls Dam (BFD); (b) present setting with Burdekin Falls Dam; and (c) future scenarios with proposed future water infrastructure (dam) developments.



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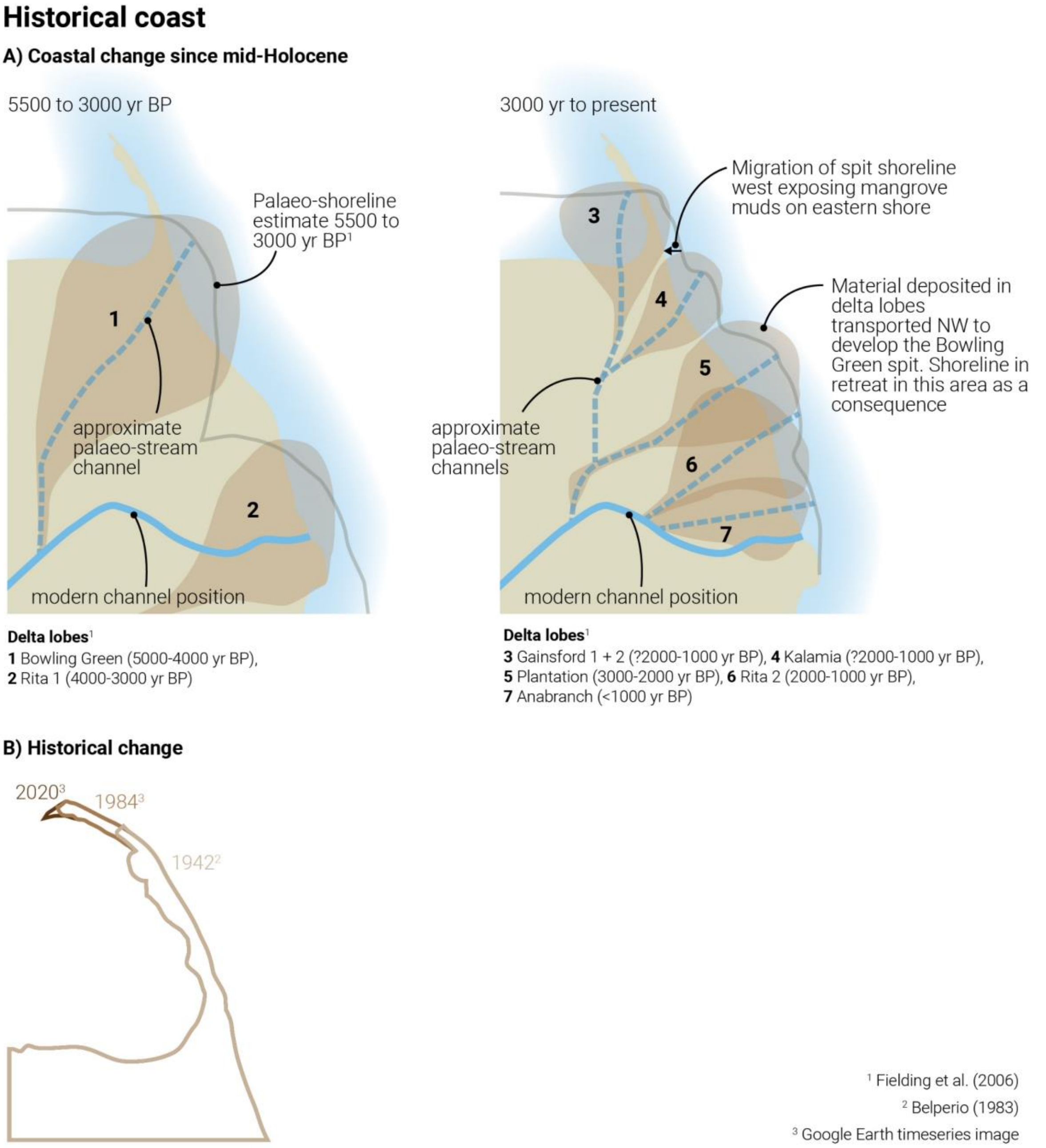

Figure ii. Long-term evolution of the Upstart and Bowling Green Bay coastline including (a) coastal change since the mid-Holocene (modified from Fielding et al. 2006) and (b) a more recent history of the Cape Bowling Green spit morphological changes.

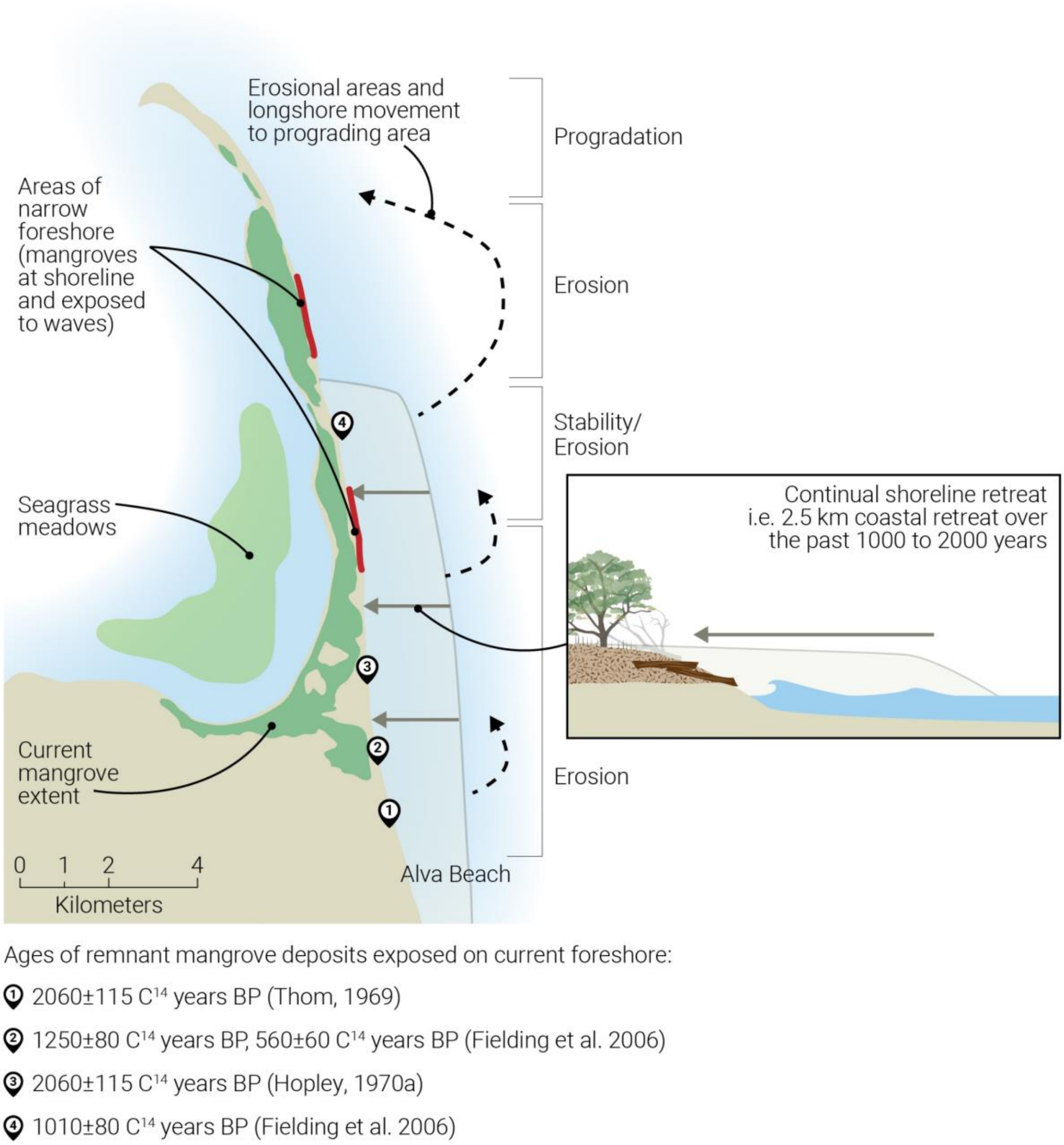

Figure iii. Sediment dynamics operating on the Bowling Green spit highlighting active areas of erosion and progradation deduced in the early 1990s by Goh (1992). Also shown are areas of exposed mangrove muds/peats on the current shoreline with their corresponding radiocarbon ages (labelled 1 to 4) which highlight extensive coastal retreat over the past millennia. Seagrass area from Davis et al. (2014).

1. Introduction

Water resource infrastructure and the associated management of flow regimes for water resource management can influence sediment transport through their modified catchments (Syvitski, 2003). Reduced fluvial supply to the north-east Queensland coastline through water infrastructure (i.e. weirs and dam structures) and natural channel avulsion processes has altered coastal dynamics, and in some cases, resulted in localised coastal erosion. This includes the Cairns northern beaches coastal zone which began to erode from the late 1930's due to an avulsion of the Barron River mouth (Pringle, 1991). In Townsville, a series of weirs constructed along the Ross River and a breakwater for the Port of Townsville starved the northern beaches including the 'Townsville Strand' of sand supply causing longstanding erosion issues that have been exacerbated by tropical cyclones (Muller et al. 2006). Hence coastal zone management of erosion issues is a fundamental consideration for local councils and state governments. In that regard, recent stakeholder concerns have emerged that the Burdekin Falls Dam (constructed in 1987) has potentially reduced sand delivery to the adjacent coast and, as a result, decreased sand supply to beaches and caused severe coastal erosion along the shorelines of the Burdekin Delta and Cape Bowling Green spit (hereafter referred to as 'Bowling Green spit').

The Burdekin Basin is one of the largest catchments in Queensland (133,600 km^2), with the Burdekin River producing an enormous discharge volume in wet years (>12,000 GL), including some of Australia's largest peak discharge volumes (Fielding et al. 1999, 2005a; Rustomji et al. 2009). Water resources within the basin are important for irrigation, mining and town supply purposes. Water Plans have been developed by the State Government to ensure that water resource management considers not only these uses and allocations, but also the impact they may have on other values, including both natural and cultural. The Water Plan (Burdekin Basin) 2007 (Burdekin Water Plan) came into effect in 2007 and is due to expire in September 2023. The Burdekin Water Plan has an outcome to manage water to maintain natural sedimentation processes to support the replenishment of beaches along the Burdekin Haughton floodplain and Cape Bowling Green.

This document synthesises the available science relevant to understanding sand transport through the Burdekin Basin, including through the sub-catchments, to the Delta and along the beaches north to Cape Bowling Green (Figure 1). In particular, the Bowling Green spit is a conspicuous feature along the coast of the lower Burdekin region of north Queensland and has been the subject of geomorphological studies since the late 1960s. The sand spit provides protection for parts of Bowling Green Bay from the prevailing south-easterly trade winds. Indeed the ecological importance of the coastal plain of Bowling Green Bay (including the sand spit) is recognised under the Ramsar convention of internationally important wetlands. There are stakeholder concerns that the Bowling Green spit has eroded since the construction of the Burdekin Falls Dam and this erosion may be further exacerbated by newly proposed infrastructure for the basin. Hence, this review also considers the longer geomorphological history of the Bowling Green spit and examines the key processes that governed its formation and evolution.

To assess whether the plan outcome is being achieved, it is important to understand the natural sedimentation processes. This synthesis identified three main areas of focus:

1. Sediment sources and dynamics through the Burdekin River catchment;
2. The geomorphological development of the Delta coast, morphodynamic changes, and the relationship between these and sand supply from the catchment;

3. Additional science needs required to address critical gaps in understanding the above issues.

The report is structured to address these key areas, following the Terms of Reference for this review. It should be noted this report focuses on the role of hydrology on the transportation and delivery of sand to the Burdekin River Delta. The findings do not consider the implications of the extractive industry on sediment loads within the Burdekin Basin.

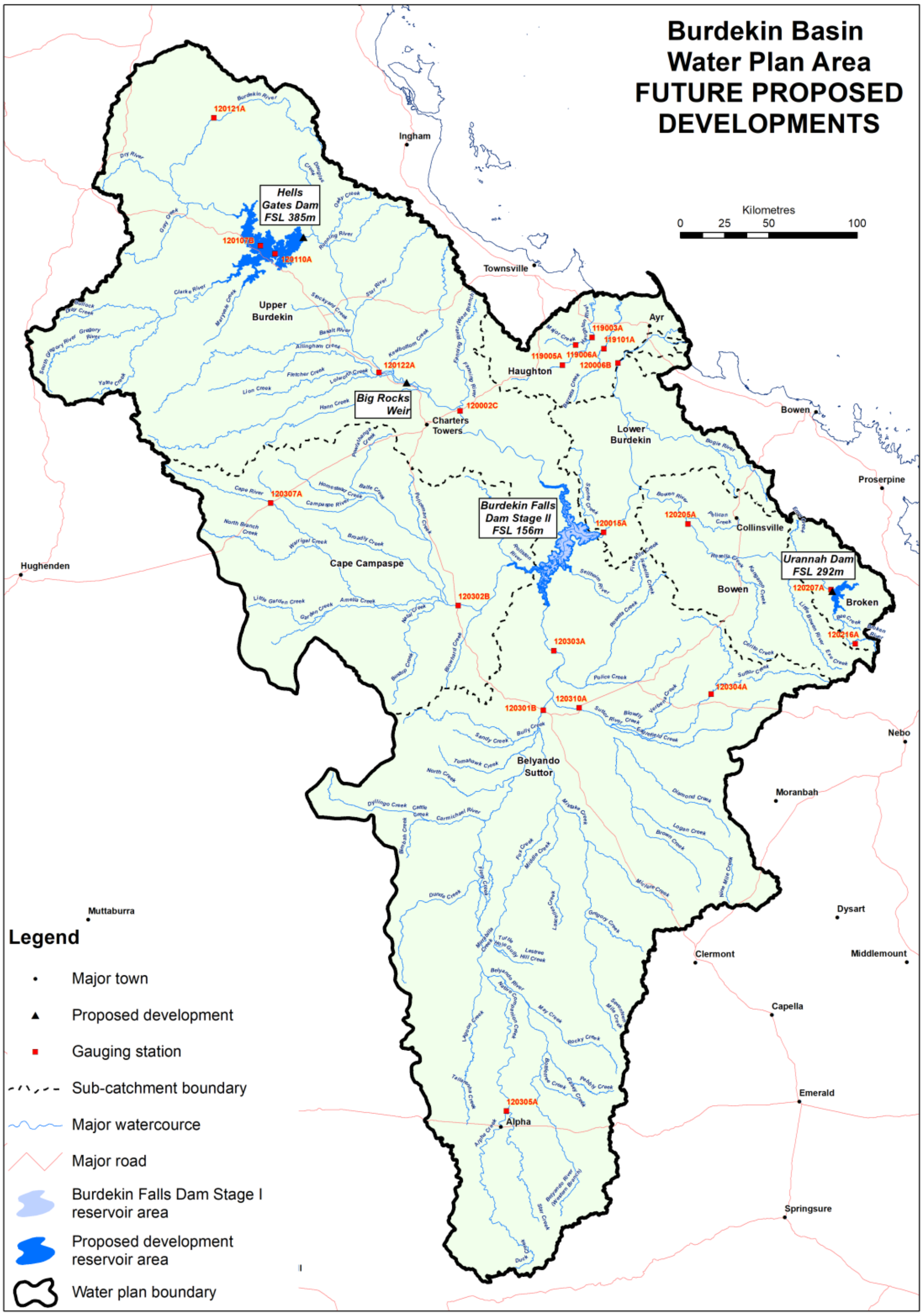

Figure 1. Burdekin Water Plan area and future proposed developments from Terms of Reference.

2. Sediments of the Burdekin Delta Coast – key grainsize fractions

A logical starting point for this investigation is to characterise the sediments naturally supplied to the coast, so that the potential impacts of water resource management on the supply of this fraction can be assessed. In the most comprehensive assessment available, Goh (1992) determined that sands sampled from the mid-beach of the Burdekin Delta and the Bowling Green spit are dominated by medium sand (250 to 500 µm) whereas those from the upper beach comprised mixtures of fine and medium sand particles (125 to 500 µm) (Figure 2). The slightly coarser mid-beach textures are likely to reflect the more active influence of waves on this part of the shoreface. Hopley (1970a,b) also reported that beach sands along the Burdekin Delta were dominated by fine and medium grainsize fractions (see also Belperio and Johnson, 1985). Orpin et al. (2004) examined the grain-size distribution of subtidal sand deposits within Upstart Bay, and concluded that the fine and medium sand fractions dominate sand transport along the coastal zone.

A review of the literature thus indicates that **the fine and medium sand fraction is the most important for beach replenishment on the Burdekin coast**. Accordingly, establishing the natural load of this fraction, and how it has changed through time is key to understanding whether modified sediment loads from the catchment are related to recent coastal changes on the Burdekin Delta, including along Cape Bowling Green.

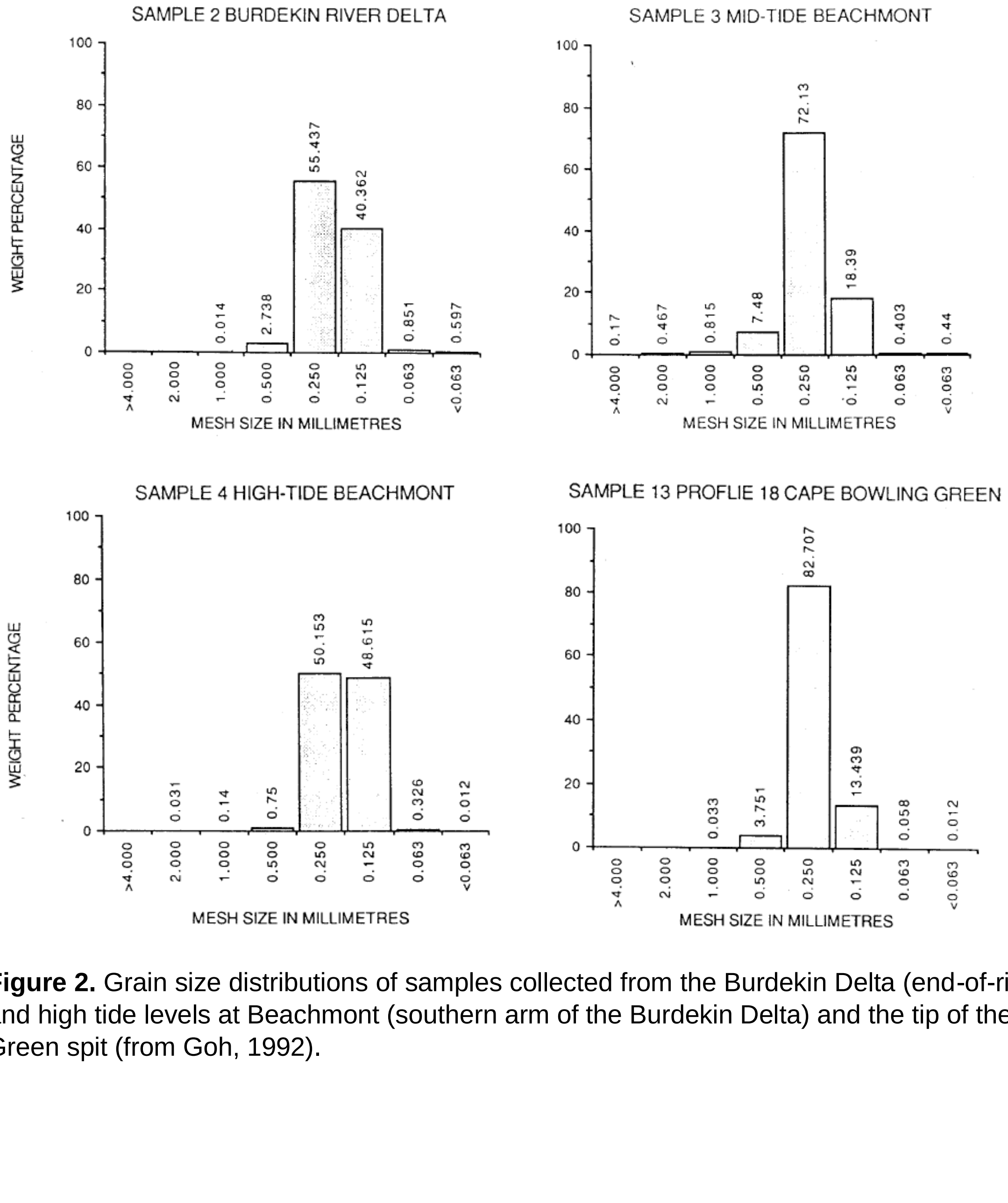

Figure 2. Grain size distributions of samples collected from the Burdekin Delta (end-of-river), mid and high tide levels at Beachmont (southern arm of the Burdekin Delta) and the tip of the Bowling Green spit (from Goh, 1992).

3. Burdekin catchment sediment transport dynamics and loads

To understand the export of the fine and medium sand load that dominates coastal deposits of the Burdekin coast, the Burdekin sub-catchment sources and sediment transport dynamics must also be understood.

Key questions to be addressed include:

- What flow regime is necessary to deliver this sediment to the coast?
- From where does most of the fine and medium sand delivered to the coast come from?

These questions are addressed in the following sections.

3.1. Sediment grain size and transport in the Lower Burdekin River channel

Sediment grain size is a fundamental parameter influencing sediment transport through stream networks. This report focuses on sand-size sediments (between 63 and 2000 µm in diameter in the Wentworth Classification). Important fractions within this range include the very fine sands (63 to 125 µm), fine sands (125 to 250 µm); medium sands (250 to 500 µm); and coarse and very coarse sands (500 to 2000 µm). Traditionally, sedimentologists consider that the clay (<4 µm) and silt (4 to 63 µm) fractions are transported in streams as 'washload' while coarser particles including the sand fractions are transported as either 'suspended bedload' or 'bedload' (e.g. Belperio, 1979).

Belperio (1979) and Amos et al. (2004) measured the concentrations of suspended sands, silts and clays at various depths through the water column of the Lower Burdekin River during flow events at the Clare gauging station and at Inkerman Bridge. The peak flow conditions during Belperio's measurements was 6,300 $m^3 s^{-1}$ (estimated ARI ~2.5 years) whereas a discharge peak of 11,155 $m^3 s^{-1}$ was recorded during Amos et al.'s measurements which had an ARI of ~5.0 years. Clearly discharges of these magnitudes are a fairly common occurrence for the Burdekin River. To place these data into context, the bankfull discharge for the Burdekin River (at the Clare gauge) has been calculated at 3,900 $m^3 s^{-1}$, which has an ARI of 1.8 years. Both the Belperio (1979) and Amos et al. (2004) studies report that the clay and silt particles were well mixed throughout and across the water column and confirm these fractions are exclusively transported as washload (Figure 3). In contrast, the concentration of sand particles increased from the stream surface toward the riverbed, indicating sand-sized sediments are transported as either suspended bedload or bedload (Belperio, 1979; Amos et al. 2004).

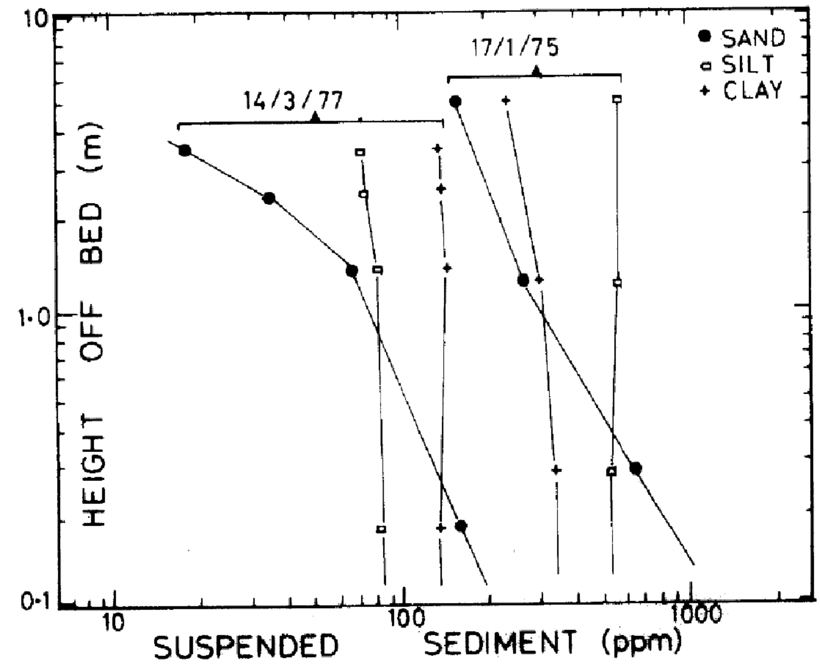

Figure 3. Grain size fractions of suspended sediments measured at different water depths of the Burdekin River during a flood event (from Belperio, 1979).

The only study that has directly measured Burdekin River bedload and associated grain size was conducted by Amos et al. (2004) over a 16-day period during a moderate flood event in the year 2000. The grain size distribution of the bedload (defined by Amos et al. (2004) as within 76 mm of the bed) was predominately (~ 85-90%) coarse to very coarse sand (>500 µm) with most samples comprising <15% of fine and medium sands (Figure 4). This distribution closely matches the sediment grain size composition reported for the Burdekin channel in many studies (Goh, 1992; Amos et al. 2004; Alluvium Consulting, 2019; Hebert et al. 2020). During the 2000 flood event, the grain size distribution of the suspended sediments differed between the near surface (top 20% of water column depth) and near bed (lower 20% of total depth) sections of the water column. The near surface samples were dominated by the clay and silt fractions (~ >90%) whereas the near bed samples contained a mix of clay, silt and fine and medium sand particles (Amos et al. 2004; Figure 5). Collectively, these results suggest that the **fine and medium sand fractions (125 to 500 µm) are mainly transported by the Burdekin River as suspended bedload and are mostly concentrated in the lower sections (bottom 20%) of the water column**. Coarse and very coarse sands (500 to 2000 µm) are predominately transported as bedload.

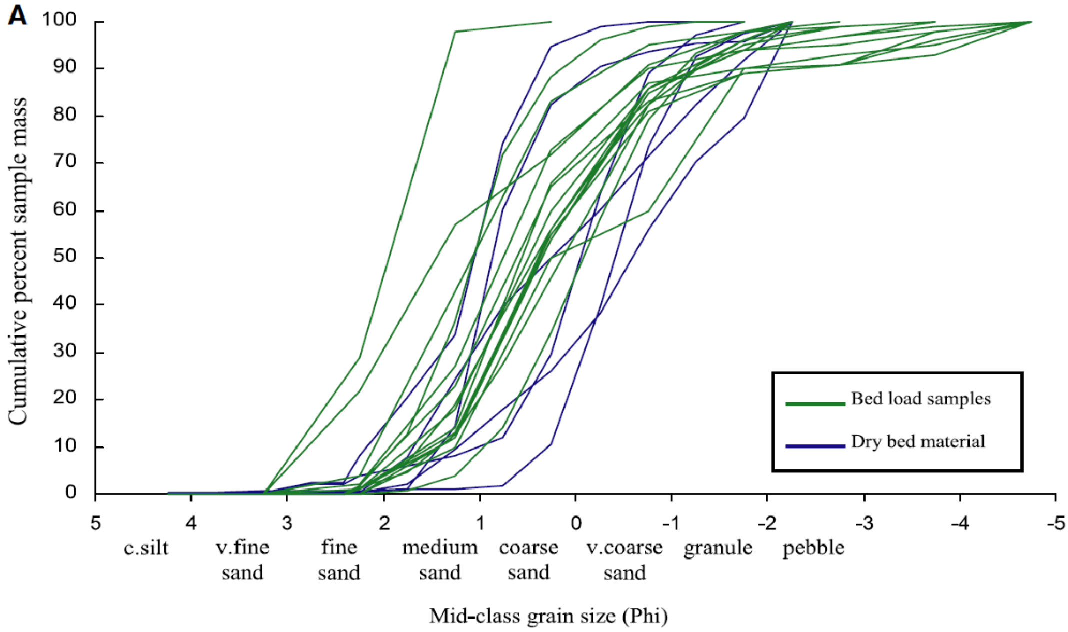

Figure 4. The variability of grain size distributions of bedload material transported during the 2000 Burdekin River flood (green lines) compared to the variability in the distributions of the sediments within the Burdekin channel during non-flood conditions (blue lines) (from Amos et al. 2004).

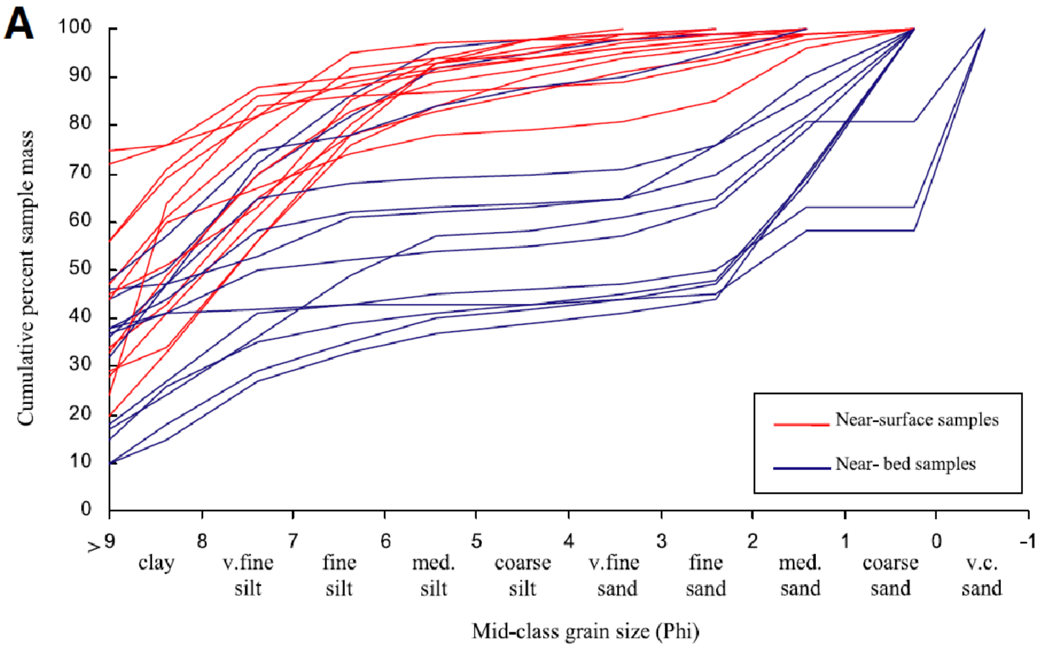

Figure 5. Grain size distributions of near surface (i.e. 20% of the surface depth: red line) and near bed (i.e. within 20% from the bed: blue line) samples (from Amos et al. 2004).

In summary, the sediment grain size and hydrological data available from the Lower Burdekin River channel suggest that:

- channel sediments which are transported as bedload are dominated by coarse and very coarse sands (>85%) (Amos et al. 2004);

- fine and medium sands are less abundant in channel sediments and are mostly transported as suspended bedload in the lower parts of the water column (Belperio, 1979; Amos et al. 2004).

The Burdekin Delta coast and the Bowling Green spit are dominated by medium sands (250 to 500 µm) (Goh, 1992; Figure 2) (see section 2). As indicated above, measurements by Amos et al. (2004) indicate that fine and medium sands (125 to 500 µm) are predominately transported as suspended bedload through the Lower Burdekin River channel, and that they can be transported in modest flows. It is assumed that at least some of this load must eventually make its way to the coast as sediments of this fraction dominate the delta shoreline (although the load of the material delivered to and past the delta, along with the processes (e.g. storms, waves, tides and floods) that distribute this material along the coastal fringe are unclear -refer to section 4). Belperio (1978) indicates that under contemporary sea level and hydraulic conditions, fluvially derived sand reaching the coast is confined to the nearshore (<5 m depth) and littoral zones. In contrast, the poor representation of coarse and very coarse sands in delta and other inshore deposits suggest limited net export of this fraction into the coastal zone (although this material is thought to form the 'base' of the prograding delta: see Fielding et al., 2005a, 2005b). Orpin et al. (2004) report that coarse sands in the marine environment offshore from the Burdekin River coast mostly occur in depths of >15m and are most likely relict quartz grains preserved beyond contemporary pro-delta deposits.

3.2. Estimated loads of the fine, medium and coarse sand fractions and how this delivery changed over time

Amos et al. (2004) provide the only direct measurements of the bedload of the Burdekin River during a flow event, achieved using a Helley-Smith bedload sampler. Bedload transport rates per metre channel width varied from 3×10^{-4} kg s^{-1} to >1.75 kg s^{-1}, with rapid fluctuations (several orders of magnitude between samples measured 5-10 minutes apart) interpreted as the influence of either pulsed bedload transport and/or of migrating bedforms. Other estimates of the average annual bedload for the Burdekin River have applied the Ackers and White (1973) equation and hence these calculations provide similar estimates ranging between 300,000 and 450,000 tonnes per year (e.g. Belperio, 1979; Brown and Root, 2001; Alluvium Consulting, 2019). Amos et al. (2004) caution the use of the Ackers and White equation as it is only suitable for streams where material transport is flow limited. They contend that the Burdekin River is 'supply limited' and thus bedload estimates derived using this equation may be unrealistic. However, recent evaluations of sediment transport through the Lower Burdekin River channel by Alluvium Consulting (2019) concluded that the channel downstream of the confluence with the Bogie River is transport (hydraulically) limited, improving confidence in the equation outputs for these lower reaches. We note that the parameters used to inform the Ackers and White (1973) equation are based on local bed and hydrological factors and do not consider changes in the upstream supply of bedload material. Hence the bedload estimates calculated using this method by Belperio (1979), Brown and Root (2001) and Alluvium Consulting (2019) are directly comparable but do not consider potential changes since Burdekin Falls Dam (BFD) construction (i.e. Belperio's bedload calculation should not be considered as a pre dam estimate compared to the more recent estimates).

Based on their bedload measurements, Amos et al. (2004) calculated 300,000 tonnes of bedload was transported over an 8.6 million ML flow event in 2000. We estimate that this event has an ARI of approximately 1.3 years. Amos et al. (2004) acknowledged that measurements varied significantly through the event thus potentially limiting both the precision and accuracy of their estimate, however it remains the most direct and reliable approximation of bedload available for the Burdekin. Applying the proportions of coarse sands (>500 µm; 90% of the material) and fine and medium sands (10% of the material) measured from the grain size distributions of bedload and channel deposits (Amos et al. 2004; Figure 4) indicates that roughly 270,000 tonnes of coarse sand and 30,000 tonnes of fine and medium sand were transported in this event as bedload. Amos et al. (2004) measured 3,700,000 tonnes of suspended load for this same event. Their suspended load total includes both the washload and suspended bedload components. Unfortunately, Amos et al. (2004) provide insufficient data for the suspended bedload to be discriminated. Our best estimates of the suspended bedload derived from the available data (Figure 8B and 8D in Amos et al. 2004) fall between 170,000 (event mean concentration: 20 $mg.L^{-1}$) and 430,000 (50 $mg.L^{-1}$) tonnes (i.e. equal to 5 to 12% of the total suspended load). Based on Amos et al.'s (2004) measurements, we consider that the fine and medium sand fractions typically comprise >80% of the total suspended bedload (Figure 5).

These calculations provide a rough estimate of the fine and medium sand load for this event (i.e. 10% of total bedload + ~80% of between 5-12% of the total suspended load) which ranges between 170,000 and 380,000 tonnes. This range is similar to Belperio's (1978) average longshore coastal sand transport rate of ~200,000 tonnes calculated for the Upstart Bay region, including along the Bowling Green spit. We note that the mean annual flow for the Burdekin River is 9.0 million ML and so the event Amos et al. (2004) sampled (8.6 million ML) reasonably approximates the annual average flow of this highly variable system (interannual COV = 119%; 1991-2020). The suspended sediment load exported from the Burdekin River has ranged from 0.009 to 15.7 million tonnes over the 1986/87 to 2009/10 period (Kuhnert et al. 2012). We estimate the loads of the fine and medium sand fractions have potentially ranged from essentially zero up to 800,000 tonnes by incorporating this variability from the total suspended loads (i.e. the mean total suspended sediment load from Kuhnert et al. (2012) is 4 Mt and the highest annual load (15.7 Mt) is ~ 4 times higher; hence applying this factor to the mean fine and medium sand load of 200,000 tonnes provides an upper range of ~ 800,000 tonnes). Belperio (1979) suggested the bedload transported from the Burdekin River could reach as high as 3,700,000 tonnes in a wet year, although the proportions of the different sand fractions in this total are unclear (applying the 10% factor from above provides a bedload contribution only: (i.e. does not consider suspended bedload) for the fine and medium sand fractions of 370,000 tonnes).

The load estimates above were calculated using the best available data, but a high degree of uncertainty persists regarding their accuracy due to the high variability observed across a limited number of measurements. To derive more accurate sediment budgets and loads more frequent and precise measurements of suspended bedloads (particularly the fine and medium sand fractions) during a range of measured Burdekin River flows are required. Nonetheless, for the purposes of this report, the calculations above deliver a 'best available' estimate of the suspended bedload fraction dominated by fine and medium sands that can be used to consider changes in these annual loads due to increased catchment erosion coinciding with the arrival of Europeans (c. 1860) and the construction of the Burdekin Falls Dam (1987) (Lewis et al. 2021). Although the data required to assess how these loads have changed with high certainty are not available, first order approximations can be derived from changes to the fine sediment (<20 µm) loads indicated by the Source Catchments model as described below.

The latest Source Catchments model indicates that the fine sediment (<20 µm) load exported from the Burdekin River has increased 5.2 fold since the arrival of Europeans (McCloskey et al. 2021; Table 1). This model incorporates the trapping efficiency equation for fine sediments retained within the Burdekin Falls Dam developed by Lewis et al. (2013). Sediment loads from different parts of the catchment and their contributions to the load exported at the coast vary as a consequence of factors including catchment physiography, climate and hydrology, land use and water resource infrastructure and management (Bainbridge et al., 2014). To explore the spatial contributions of sediment loads (average annual loads) currently delivered to the end-of-river, the loads indicated by the Source Catchments model for four key source areas (refer to Figure 1) are considered:

1. The load passing over the Burdekin Falls Dam (BFD);
2. The load at the Bowen River at Myuna gauge;
3. The load from the Bogie River; and
4. The cumulative loads of the remaining source areas below the dam (i.e. including the Bowen River catchment area downstream of the Myuna flow gauge as well as Landers and Expedition Pass Creeks) (Table 1).

To estimate the pre-development (i.e. prior to the arrival of Europeans) annual average fine sediment (<20 µm) loads the following procedures were applied.

1. The current Source Catchments model outputs (McCloskey et al., 2021) for the <20 µm sediment fraction for the four key source areas above were identified. The value for the area downstream of the first three (indicated as 'Remaining area' in Table 1) was calculated by summing the values for source areas along the remaining model reaches. The others were derived directly from the Source model outputs.
2. Pre-development fine sediment loads were determined by beginning with the Source Catchments model pre-development output for the end-of-river of 640,000 tonnes (McCloskey et al., 2021). For the source catchments below the Burdekin Falls Dam the pre-development loads were then derived by dividing the current Source Catchment model outputs by 7.5 to take account of the ~ 7.5 fold increase in erosion for these catchments calculated by Bartley et al. (2015). The sum of the source areas below the dam wall (270,000 tonnes) can then be subtracted from the total catchment load (640,000 tonnes) to derive the pre-development load from the areas above the dam wall (370,000 tonnes). The post-development increase factor for the area above the dam calculated here is 3.5 (e.g. 1,300,000 tonnes post development / 370,000 tonnes pre-development). This value closely matches the accelerated erosion (and delivery to coast) factor of 3.64 calculated for the Upper Burdekin by Bartley et al. (2015), providing confidence in the derived amounts.
3. To estimate the post development, pre-Burdekin Falls Dam fine sediment budget, the current Source Catchment model loads were used, but for the Burdekin Falls Dam overflow source the current trapping effected by the dam was removed. For this report two measures of trapping are considered. The first is the long-term mean sediment trapping efficiency of 71%, calculated over the period 1987/88 to 2014/15 by Cooper et al. (2018). However, sediment trapping is difficult to measure, and can vary depending on flows and the sediment grain size fractions of interest. Accordingly, we also consider the scenario whereby a smaller proportion in the order ~50% of the <20 µm fraction is trapped, as supported by measured data (Lewis et al. 2013; Bainbridge et al. 2016). The adjusted loads calculated for these two scenarios (correcting pre-dam values to account for 71% and 50% trapping efficiency of the Burdekin Falls Dam) are presented in Table 1, where loads at the Burdekin Falls Dam overflow source and for the total export significantly increase. In the case where the long-term trapping efficiency of the dam is 71%, the fine sediment loads exported by the Burdekin River

prior to dam construction were 10-fold greater than pre-development loads (Table 1). A change in load of this magnitude is supported by previous estimates of long-term sediment fluxes established using coral cores and marine sediment core accumulation rates (e.g. McCulloch et al. 2003; Lewis et al. 2014). In the case that long-term dam trapping efficiency is lower, around 50%, the pre-dam fine sediment load at the end-of-river becomes 7.2 times greater than the pre-development values.

The numbers calculated above are all for the fine sediment fraction (<20 µm) used in the Source Catchment model (RC2020 baseline model run as reported in McCloskey et al. 2021 with additional sub-catchment scale data retrieved by Cameron Dougall pers. comm. 2021). To calculate values for the fine and medium sand loads, the following procedures were followed:

1. To calculate the current annual average fine and medium sand load, we assumed that this sediment fraction typically comprises 10% of the fine sediment load from the catchment area downstream of the Burdekin Falls Dam (based on data from Amos et al. (2004) and estimates from Bartley et al. 2015), and that no fine and medium sand material passes over the dam (based on the data in Lewis et al. 2013). This approach generates an estimate for the current fine and medium sand load of 200,000 tonnes (sum of loads below dam wall), in accord with the loads calculated using data from Amos et al. (2004) for the 2000 flood event and Belperio's (1978) annual longshore coastal sand transport rate estimate for the adjacent coastal area. Water samples collected from the Burdekin Falls Dam overflow over four consecutive wet seasons (2005/06 and 2008/09) indicate that the assumption of no fine and medium sand by-passing the Burdekin Falls Dam is an oversimplification, with modest quantities (6,200 – 10,000 tonnes) estimated to have been transported over the dam during these events (Lewis et al. 2013). However, given that these quantities are relatively small in the context of the total load and it is unclear how they may vary under different flows and reservoir conditions (i.e. capacity of the receiving reservoir at the time of flooding), the assumption of nil flux is justified.
2. To calculate the pre-development fine and medium sand loads it was again assumed that these fractions comprise 10% of the total fine sediment (<20 µm) load at the end-of-river (see above for justification). Therefore, the pre-development fine and medium sand loads can be simply calculated by dividing the pre-development fine sediment loads by 10. Summing the loads for each of the source areas produced an estimated total average load of 64,000 tonnes of fine and medium sands within the Burdekin catchment for the pre-development period.
3. To calculate the post-development pre-dam fine and medium sediment loads the same two trapping efficiency rates (71% and 50%) were considered for the Burdekin Falls Dam overflow loads. These calculations reveal that if the dam trapping efficiency is 71% the fine and medium sand load exported from the Burdekin River before dam construction was approximately ten times larger than the pre-development load (650,000 tonnes compared to 64,000 tonnes). Where trapping efficiency was around 50% the fine and medium sand load exported from the Burdekin before dam construction was around 460,000 tonnes, 7.2 times larger than the pre-development load (Table 1).

Table 1. Estimated annual average sediment loads (in tonnes per year) for the Burdekin and key source areas for: a) the fine sediment (<20 µm) (top half of table); and b) the fine and medium sand fraction (63 – 500 µm) (lower half of table). Refer to Figure 1 for locations. (Note, numbers are reported to two significant figures).

Sediment loads		Burdekin Falls Dam overflow	Catchment area downstream of Burdekin Falls Dam			Total export (end-of-river)
			Bowen R (Myuna)	Bogie R	Remaining area	
Fine Sediment (<20 µm) Source Catchment model loads	Current fine sediment (Source Catchment model: McCloskey et al., 2021)	1,300,000	1,100,000	400,000	500,000	3,300,000
	Pre-development fine sediment (Source Catchment model with Bartley et al. 2015)	370,000	150,000	53,000	67,000	640,000
	Pre dam fine sediment[1]	4,500,000	1,100,000	400,000	500,000	6,500,000
	Pre dam fine sediment[2]	2,600,000	1,100,000	400,000	500,000	4,600,000
Derived fine and medium sand (63-500 µm) loads	Current fine and medium sand load	0	110,000	40,000	50,000	200,000
	Pre-development fine and medium sand load	37,000	15,000	5,300	6,700	64,000
	Pre dam fine and medium sand load[1]	450,000	110,000	40,000	50,000	650,000
	Pre dam fine and medium sand load[2]	260,000	110,000	40,000	50,000	460,000

[1]Assume 71% trapping (total of all particles from Cooper et al. 2018)
[2]Assume 50% trapping (for <20 µm fraction) from Bainbridge et al. (2016)

Importantly, the first order approximations above demonstrate that the estimated loads of fine and medium sand presently exported to the coast are ~3 times higher than the pre-development loads, even with the Burdekin Falls Dam in place. As previously stated, these estimates have a high degree of uncertainty. However, they do strongly suggest that increased sediment loads from catchments below the dam wall since the arrival of Europeans have more than offset the reductions associated with sediment trapping within the Burdekin Falls Dam.

3.3. How might proposed future water infrastructure (dams) affect Burdekin River fine and medium sand loads?

The particle size data for the Burdekin Falls Dam overflow samples collected in 2006, 2007, 2008 and 2009 show that particles >30 µm and up to ~ 700 µm pass through the dam during large flow events (see Figure 8 in Lewis et al. 2009; Lewis et al. 2013). However, Lewis et al. (2013) estimated that >95% of particles larger than 30 µm are trapped, with the implication very little sand passes through the dam. Indeed, using the data in Lewis et al. (2013) the fine and medium sand loads calculated in the Burdekin Falls Dam overflows for the 2005/06, 2006/07, 2007/08 and 2008/09 water years were just 9,300, 10,000, 7,900 and 6,200 tonnes, respectively. Interestingly, the lowest load measured (6,200 tonnes) over this four-year period coincided with the very large flow event in the 2008/09 water year. It is not clear if these variations reflect true changes in delivery or difficulties associated with measurement. Nonetheless, the measured sand fraction loads are all <5% of estimated end-of-river loads, supporting the conclusion that a very minor proportion of the fine and medium sand loads reaching the coast originates from the catchment above the dam.

Based on this finding, the conclusion must be that neither the proposed raising of the Burdekin Falls Dam nor the construction of the Hells Gates Dam on the upper Burdekin tributary would significantly alter sand delivery to the coast. While these proposed developments would likely further reduce the load of the sand fraction passing over the Burdekin Falls Dam, this additional reduction would be of an already insignificant load contribution. Interestingly, sediment cores from within the Burdekin Falls Dam reservoir show predominately mud size material deposited in the dam with only fine laminations of sand size material (M. Cooper, unpublished data). This sedimentation pattern suggests that sand transported from the upstream tributaries of the dam must be deposited before as it reaches the reservoir.

Review of available data also suggests that the proposed Urannah Dam on the Broken River arm of the Bowen catchment would also have negligible influence on the total sand loads exported from the Burdekin River. Suspended sediment monitoring of the Broken River arm just below the proposed Urannah Dam reveals very low sediment concentrations (average concentration ~ 20 $mg.L^{-1}$: Z. Bainbridge, unpublished data). A meagre annual average fine (<20 µm) suspended sediment load of ~15,000 tonnes calculated with these monitoring data (C. Dougall, pers comm) demonstrates that this section of the river transports very little sediment during flow events. Applying the same logic to estimate the fine and medium sand fraction loads in Table 1 (10% of the fine (<20 µm) sediment load) indicates 1,500 tonnes are transported from the Broken River arm. It should also be noted that this remarkably small load is derived from the upper reaches of the Bowen River catchment (Broken River section), and there is high likelihood that a large proportion of the 1,500 tonnes would be stored within downstream stream bench or overbank deposits rather than delivered directly to the Lower Burdekin channel (see Bartley et al. 2018). The contribution of fine and medium sands from the Broken River arm of the catchment (i.e the area above the proposed Urannah Dam) to the total load exported at the coast is thus considered negligible. Indeed, the key contributing catchments of the fine and medium sand fraction include the Bowen River (area below the Broken River junction) and the Bogie River, which collectively contributes ~ 70% of the total exported load (Table 1).

Although the focus here is the influence of the proposed dams on the transport of sand sediment fractions, the potential increase in turbidity (colloidal fraction <1 µm) that could develop due to reservoir construction requires some comment. The Burdekin Falls Dam is already a highly turbid system year round (Cooper et al. 2017), which results in elevated turbidity levels in the downstream receiving waters including the irrigation network through the Burdekin-Haughton Supply Scheme (e.g. Burrows, 1999 Perna and Burrows, 2005). In particular, the construction of the Hells Gates Dam in the upper Burdekin could result in turbid waters developing in the reaches between this dam and the Burdekin Falls Dam (Burrows, 1999). Particle size analysis of suspended sediments collected from contributing Burdekin tributaries (e.g. Clarke River and Grey Creek) above the proposed Hells Gates Dam reveal colloidal materials (i.e. particles <1 µm) (Bainbridge et al. 2007); particles of this size are the prime contributor to the persistent turbidity within the Burdekin Falls Dam (Cooper et al. 2017).

The potential modification of flow regimes on associated sand transport as a result of reservoir construction must also be considered. Studies have shown that peak discharges at the end of Burdekin River have reduced since the Burdekin Falls Dam was constructed (e.g. Alexander et al. 1999; Lewis et al. 2018) but the annual average discharge has not significantly changed. These changes may be explained by variations in rainfall/discharge since the Burdekin Falls Dam was constructed (see Lough et al. 2015), or by the dam and associated reservoir reducing peak discharges but increasing the duration of flows.

Alexander et al. (2020) demonstrated that both the peak and duration of discharge were key factors that mobilised the Burdekin channel bed sediments. They classified three types of events and their influence on the movement of the sediment on the Burdekin channel floor which included:

1. Events that peak between 10,000 and 14,000 $m^3.s^{-1}$ with short duration and rapid fall;
2. Events that peak between 10,000 and 14,000 $m^3.s^{-1}$ with more gradual flow decline and;
3. The ‘biggest events’ >14,000 $m^3.s^{-1}$.

The first of these events produce little overall movement or reworking of the large unit bars within the Burdekin channel. They may cause some change of the riverbed morphology and sedimentary features related to the high flows such as gravel anti-dune deposits are preserved. The second event type causes some reworking of the unit bars in the channel (it is argued that the bulk bed movement occurs 2-3 days following peak discharge as it takes time to erode the bed forms), and higher flow sedimentary deposits are not preserved. The third event type results in the large-scale reworking (or resetting) of the bedforms in the channel (Alexander et al. 2020). The frequency of these latter flows, which are the most important for bedload sediment transport, has been modified by the Burdekin Falls Dam; the ARI of 14,000 $m^3.s^{-1}$ flows in the Lower Burdekin channel prior to dam construction was calculated at 4.8 years, but is now 7.5 years post dam construction (i.e. calculating the ARI from peak daily flows for the pre dam period 1921/22 to 1986/87 and for the post dam period 1987/88 to 2019/20; refer Table 2). The complex relationship between flow parameters (peak, duration, rates of rise or fall, sequential events, etc.) and transport of the fine and medium sand fractions must be better understood to predict the influence of water resource infrastructure and management on sediment transport. Such an investigation would involve sophisticated modelling, beyond the scope of the present review.

Table 2. Annual return intervals (ARI) for various peak daily flows for pre (1921/22-1986/87) and post (1987/88 to 2019/20) Burdekin Falls Dam (dam) timeframes. Peak daily flows have been informed by bankfull discharge, transport of fine and medium sand particles and the flood classifications from Alexander et al. 2020 based on bedload movement (Source: © The State of Queensland, 2021).

Peak daily flows ($m^3.s^{-1}$)	Reference	Pre dam ARI (1921/22-1986/87)	Post dam ARI (1987/88 to 2019/20)
2,000	Belperio (1979) fine and medium sand transport	1.34	1.38
3,900	Bankfull discharge at Clare gauge	1.65	1.8
10,000	Alexander et al. (2020) bedload movement	3.1	4.3
14,000	Alexander et al. (2020) channel resetting	4.8	7.5

Ground penetrating radar analysis reveals that a large depth of the channel bed (~ 6 m) can be active during large (e.g. >10,000 $m^3.s^{-1}$) flow events (Fielding et al. 1999, 2005b; Alluvium Consulting, 2019) and surveys following flow events show that cobble size particles (>6 cm in diameter) can be transported at least 50 cm above the bed (Alexander et al. 2020). The coarser sand particles (i.e. >500 µm) are likely transported as bedload during very large flood events and provide the foundation for the initiation of new river mouth bars (Fielding et al., 2005a, 2005b).

In contrast, fine and medium size sand particles are transported in the Lower Burdekin River as suspended bedload even during much lower discharge events. Belperio (1979) showed that flows as low as 2,000 m^3 s^{-1} (ARI pre and post dam construction respectively of 1.34 and 1.38 years; Table 2) can transport reasonable loads of fine and medium sand (using the procedures outlined above loads in the order of 20,000 tonnes can be calculated). A detailed hydrological assessment would be required to model the change in the flow regimes that would occur under the raising of the Burdekin Falls Dam or the construction of a new dam. However, a review of existing information suggests the supply of the fine and medium sand fraction to the coast would not change greatly under any of the proposed changes (discussed above). Nevertheless, changes to the channel morphology and to the bedload movement of the coarse sediment fraction as a result of further water infrastructure cannot be ruled out. The analysis required to resolve this question is beyond the scope of this report but the reader is referred to the Alluvium Consulting (2019) report that describes the transport and budgets of the channel sand in the different reaches below the Burdekin Falls Dam.

Catchment – Summary of key findings (see also Figure i)

- The beaches of the Lower Burdekin coast (including Bowling Green spit) are predominately (>90%) composed of the fine and medium sand (125 to 500 µm) fraction;
- The load of the fine and medium sand fraction is predominately carried as suspended bedload in the lower sections of the water column, with a smaller contribution from bedload transport;
- Considerable fine and medium sand particles may be transported within the Lower Burdekin River channel during flood events as low as 2,000 m^3 s^{-1}
- The average annual load of fine and medium sand delivered to the end-of-river is 200,000 tonnes, with a range of 0 to 800,000 tonnes;
- Assuming 100% trapping of this fraction by the Burdekin Falls Dam and the contemporary erosion rates in the catchment area below the dam, the current fine and medium sand load is approximately 3-fold higher than the pre-development load;
- The additional water infrastructure proposed would have a negligible influence on the current supply of fine and medium sand from the Burdekin River delivered to the coast.

4. Sediment storage and movement in the coastal zone

As outlined above, a review of the literature indicates that the Lower Burdekin River channel near the Inkerman Bridge is predominantly composed of coarse sand whereas fine and medium sands dominate the delta beaches and coast (i.e. Hopley, 1970a,b; Goh, 1992; Orpin et al. 2004), indicating that the suspended bedload fraction is deposited either at the end of channel reaches in the delta or just offshore. The sandy upper delta front extends from river mouth bars to approximately 5 m below LAT at a distance generally within a few kilometres of the coast (Belperio, 1983). Fielding et al. (2005a, 2005b) documented the continued and relatively rapid accumulation of river mouth bars from the 1960s until 1996, and reference to later images indicates that this accumulation has continued to date (the seaward shoreline of the active river mouth bar prograded almost 1 km since 1996 based on the 2018 Google Earth image). Delta progradation through river mouth bar formation and consolidation is clearly ongoing at present, effectively forming a modern 'delta lobe'. Stratigraphic investigations show that river mouth bars are composed of medium to coarse sands (noting that they are generally less coarse than lower delta distributary channel sediments), confirming that these sands are transported to the river mouth. Fielding et al. (2005a, 2005b) suggest that these sediments may be delivered by only a small number of high magnitude events of short duration, with individual river mouth bars accumulating over several decades before they mature and another forms seaward of the dominant distributary channel. Maturation of the river mouth bars occurs as mostly fair-weather waves rework the seaward shoreline of the bars to form a linear 'barrier' beach mostly composed of fine and medium sands, behind which fine and medium sand fractions delivered by less extreme flows progressively accumulate. This accumulation also includes the infill and abandonment of one of the distributary channels flanking the active river mouth bar, concentrating flows and sedimentation as a consequence to a position where the new river mouth bar forms. This process has shifted the major focus of sedimentation at the mouth of the Burdekin from a position directly east of the main channel in the 1960s to a position further to the northeast at present (see Figure 3 in Fielding et al. 2005a). Direct measurement of surficial suspended sediments collected in flood plumes just offshore of the Burdekin River mouth did not detect sand size particles (Bainbridge et al. 2012, 2021), suggesting that most if not all sand is at least initially deposited within the delta reaches, although in higher discharge events it is possible that sands may be moved offshore as bedload or in the lower water column as suspended bedload.

The fate of the fine and medium sand fraction once delivered to the coastal zone is less well established. River mouth bars and associated beaches and shoals store significant quantities of these sand fractions, and their formation demonstrates the importance of waves in sorting these fractions into accummulations for redistribution. The position of the active river mouth and the morphology of shoals and bars will also influence the supply of these sediments to the delta coast. Clearly longshore drift processes redistribute some of this material alongshore to the north. Evidence includes the development of spits such as Bowling Green spit, the migration of sand bars reported by various authors (e.g. Pringle, 1984, 2000), and coastal changes depicted in satellite image time series accessible through Google Earth. However, the lower reaches of the delta are tidal, and it is also possible that tidal currents and waves also redistribute some of the fine and medium sand fraction exported from the catchment in this zone. This may include the import of some sand back into the delta mouth estuary. Recurved ends on the seaward beaches on the active river mouth bar provide some support for this process. Investigations from the Normanby River and the Haughton River demonstrate a net landward transport of fine sands into the river mouth by flood tide currents (Bryce et al. 1998; Dalla Pozza, 2005), but whether tides or waves play a role in the Burdekin is yet to be determined.

Earlier in this review it was concluded that pre-dam loads of fine and medium sand (between 460,000 and 650,000 tonnes) were probably around 7 to 10 times higher than the pre-development loads (64,000 tonnes) due to land use changes. It has also been established that current average annual loads are around 200,000 tonnes, around three times the pre-development load, despite the construction of the Burdekin Falls Dam and the trapping of sand within its reservoir (see Table 1). This increase is attributed to the increased loads of fine and medium sand from the catchment areas downstream of the dam associated with European land use changes. Thus, the net result is that despite the Burdekin Falls Dam trapping essentially all of the fine and medium sand delivered above the reservoir, average loads of these estimated sediment fractions delivered to the coast are still three times higher than they were before European modifications to the catchment. If this were true it may be reasonably expected that the delta would be continuing to prograde offshore. Although at the timescales required it is difficult to definitively confirm this, the evidence available certainly suggests that progradation is ongoing. The active formation and progradation of river mouth bars documented between the 1960s and late 1990s (Fielding et al. 2005a, 2005b) that continues to present (discussed above) supports this interpretation, as does a sediment core collected approximately 1 km offshore of the Burdekin mouth by Lewis et al. (2014). The upper 1 m of the core is comprised of fine and medium sands, with a terrestrial organic matter unit at the surface. The OSL depositional ages indicate this is a relatively young deposit (<50 years). It is, however, unclear whether this material was delivered from a recent flood (or a series of recent floods) or comprised of older reworked previously deposited sediments. Nevertheless, mercury contamination associated with gold mining in the upper Burdekin catchment detected in a lower section of this core provides strong evidence for rapid (and recent) net accretion and the continued export of substantive fine and medium sand loads. Earlier efforts to trace the source sediments deposited offshore using magnetic fingerprinting of sand particles was not successful, despite early indications of promise (Maher et al. 2009).

'Negative' evidence to support the conclusion that fine and medium sand delivery to the coast has not reduced below natural levels since the Burdekin Falls Dam was constructed can also be presented. Logically, if the fine and medium sand load had reduced considerably from the Burdekin River, erosion would first be evident and most severe at or close to the river mouth. It would not be expected first at the updrift end of the system (i.e. along the shores of the Bowling Green spit). Although the locations where the relevant sand fractions are deposited, temporarily stored, transported and sorted have changed as would be expected in such a dynamic system, we contend that there is no evidence to suggest that the coastal delta is in sand deficit, or that it has markedly changed since early historical accounts. Indeed, reference to the first written accounts of the Burdekin River mouth by Jukes (1848), compiled as he attempted to enter the Burdekin River in the dry season of 1843, match the appearance of the contemporary delta. Notably, his accounts emphasise the shallowness of the channel and waves breaking over wide areas of sand bars, familiar hazards to those navigating the entrances today. The development of a contemporary delta lobe through river mouth bar accumulation appears to be active at the present river mouth, and at a larger scale the delta still maintains a protruding deltaic form, typically indicative of systems which actively export sediments. Retreat of the shoreline along sections of the Delta coast over historical timescales has certainly occurred, and it is understandable that this erosion has been cause for concern by many stakeholders. However, it is our view that this is not related to a reduced fluvial sediment supply. In the main it can generally be attributed to the redistribution of sands alongshore from temporally varying delivery points associated with river mouth avulsions, or associated with spatial and temporal variations in the movement of sands onto the beach driven by inshore bathymetry and coastal processes.

5. Geomorphological history and morphological changes on Cape Bowling Green

The Bowling Green spit is an approximately 15-20 km long recurved sand spit that extends from the northern end of the Burdekin Delta (Figure ii). Bowling Green spit forms the eastern boundary of Bowling Green Bay. The spit strongly structures habitats within Bowling Green Bay by providing protected waters in its lee in which muds are deposited, allowing seagrasses and mangroves to thrive (Goh, 1992; Orpin et al. 2004; Fielding et al. 2006; Davis et al. 2014; Figure iii).

Radiocarbon ages of coastal deposits at the base of the Bowling Green spit suggest it has formed since ~3000 years ago (Paine et al. 1966; Hopley, 1970a,b; Belperio, 1978; Belperio and Johnson, 1985), as obliquely approaching coastal waves and associated currents generated by prevailing onshore south-easterly trade winds transported fluvially-derived sediments northwards (Coleman and Wright, 1975). Dated mangrove muds exposed on the seaward shore approximately halfway along the spit are approximately 1000 years old (Fielding et al. 2006), providing a minimum age for the spit at that location (Figure iii). Belperio (1978) estimated that wind and wave conditions capable of transporting sediments toward Cape Bowling Green occur on average around 20% of the year.

The impressive dimensions of the spit reflect the availability of a large sediment supply from the Burdekin River (e.g. Belperio, 1978; Amos et al. 2004; Fentie et al. 2006; see Table 1) and sufficient energy to rapidly transport sand alongshore (Pringle, 1984, 2000). However, the position of the Burdekin River mouth has varied significantly since the mid-Holocene (Hopley, 1970a,b, Fielding et al. 2005a, 2005b, 2006), with episodic avulsions of the main distributary channel producing at least ten different delta lobes over the past 7000 years (since sea level reached its approximate present position) (Fielding et al. 2006). Three projected into what is now Bowling Green Bay, but seven extended from the eastern shoreline, including several (Gainsford 1 + 2 and Kalamia) very close to the base of the Bowling Green spit (refer to Figure ii). Sediments deposited within these delta lobes are believed to have 'formed' the more substantive base of Bowling Green spit (Hopley, 1970a,b; Fielding et al. 2006, see Figure 8 therein).

Hopley (1970a,b) argued that the Bowling Green spit is largely composed of sediments originally deposited in the abandoned Kalamia Delta (and probably the Gainsford Delta lobes identified by Fielding et al. 2006 but not discriminated by Hopley), with only minor contributions from the active Burdekin mouth. Hopley (1970a,b) offered four lines of evidence to support his interpretation:

1) visible truncation of Kalamia Creek levees on the seaward side of the spit (indicating the delta previously extended further seaward);

2) exposed mangrove peats on the foreshore north of Alva around 2000 years age, deposited behind the spit when it was located further to the east;

3) the concave alignment of the coast near the Alva township, in contrast to the convex shoreline at the present actively prograding delta; and

4) the narrow westerly migrating dune belt near Alva which suggests foreshore erosion dominates this section of the delta coast.

Taken overall, Hopley (1970a,b) estimated that the reworking of earlier deposited delta lobes near the base of the Bowling Green spit may have produced as much as 2.5 km of coastal retreat as the coastline naturally straightened under the influence of its changed sediment supply and the prevailing southeasterly wind and wave regime. Based on the ages provided by Fielding et al. (2006) this would equate to a long-term average rate of shoreline retreat at the base of the Bowling Green spit of around 1 m yr^{-1}, or about half that if an earlier Bowling Green Bay delta lobe contributed most sediment to the spit. Sediments reworked during this coastal retreat have in part been transported westward (as indicated by the sands deposited over the mangrove peats and muds originally deposited in the lee of the spit but now exposed on the seaward shore). They are also transported alongshore to contribute to the distal sections of the spit, which continues to extend to the northwest at rates averaging around 10 m yr^{-1} (Belperio and Johnson, 1985). The large-scale geomorphology of the Bowling Green spit has undoubtedly been influenced by the history of Burdekin channel avulsions, including both shifts in stream mouth position and the intervals between events, over the past few thousand years.

At shorter timescales the contemporary morphology of the Bowling Green spit is influenced by the tempo of climatic conditions that influence sediment supply and transport along the coast. These dynamics and their geomorphological outcomes have been well researched (e.g. Belperio, 1978; Hopley, 1979; Pringle, 1984, 1991, 2000; Goh, 1992; Fielding et al., 2005a, 2005b). All noted that the shoreline along the Burdekin Delta coastline, including towards the base of the Bowling Green spit was dynamic and strongly controlled by pulsed movement of sediment offshore to form shoals during flood events – often associated with tropical cyclones - when abandoned Burdekin channels such as Plantation and Kalamia Creeks become active. These sediments are subsequently transported shoreward to form supratidal bars or 'barrier spits' that become elongate under the influence of the dominant northwesterly littoral drift. These barrier spits may form and prograde rapidly following major floods and then eroded and modified during drier intervals (Hopley, 1979). Pringle (1984, 2000) provides detailed analysis of the formation and influence of these features. Pringle (1984, 2000) suggests that these dynamic features may act as barriers and protect leeward shorelines that then become vulnerable to erosion once they migrate northward or are breached. These spits may lengthen at remarkable rates of up to 375 m/yr (Pringle, 2000; see also Google Earth link in section 4), and commonly become shore-attached at their southern ends over time. Once anchored to the coast, tidal creeks may rapidly infill the protected lagoon. This process is interpreted to be the dominant mechanism for coastal progradation on this coast (Belperio and Johnson, 1985; Pringle, 2000). Critically, the sediments moved offshore to form these spits that characterise the Burdekin Delta coast are largely composed of sediments moved offshore from the foreshore and existing barrier spits during major flood events in the former distributary channels and creeks – there is no evidence that sediments discharged by contemporary floods from the main Burdekin channel mouth contribute significantly, especially over the short term (Hopley, 1979; Pringle 1984, 2000; Goh, 1992). Goh (1992) reports the observations of local residents who similarly contend that large sub-tidal bars were formed between Alva and Cape Bowling Green when sediment eroded from the foreshore was moved into the sea during Tropical Cyclones Charlie (1/3/1988) and Aivu (4/4/1989) which occurred just prior to his study. However, in contrast to sediments eroded along the main delta coast which mostly move back onshore over time, Goh (1992) reported that sediments eroded from the Bowling Green Spit were quickly dispersed northward towards the Cape. Direct hydrodynamic measurements are not available to assess the differences in physical processes likely to drive these different observations.

The geomorphological evidence thus suggests that the Bowling Green spit is now largely in an erosionary state (see Figure iii), mainly as a consequence of the effective exhaustion of the sand depocentres near the base of the spit that fed its construction through the mid to late-Holocene (see Figure ii; Hopley, 1970a,b; Fielding et al. 2006), combined with a trend along the spit of localised erosion during cyclones and limited recovery between events (Goh, 1992). The erosionary impacts of tropical cyclones, which may also breach spits along the Burdekin Delta coast, have clearly significantly influenced the geomorphology of the foreshore (Figure

6) in the past (Hopley, 1979; Pringle, 1984, 1991, 2000; Goh, 1992), and will undoubtedly be a major driver of coastal change into the future. Interestingly, despite these changes, Goh (1992) concluded that outside of a few isolated areas of erosion, the morphology of the Bowling Green Spit in 1990-1991 was remarkably similar to that initially described by Hopley (1970a, 1970b) more than two decades earlier. A comparison of the shoreline at the area near the top of the spit most commonly argued to be at risk of a breach captured in an oblique aerial photograph taken by Goh in 1990 with the most recent image captured in Google Earth (December 2019) also shows relatively little supratidal change at the same location, although the distal end of the spit has markedly grown and changed shape (Figure 7). We note, however, that shoreline estimations from satellite imagery over the period since 1988 suggest rates of shoreline retreat of as much as 5.3 +/-1.6 m per year over this period (https://maps.dea.ga.gov.au/), noting that these rates are derived from estimated changes in the inferred median mean sea level position (not the supratidal, and thus very sensitive to changes in shoreface/intertidal morphology). The same resource also documents marked accretion on the distal seaward (mostly above 7 m/yr) and distal point (up to 27.4 +/- 1.2m) of the spit. It also shows patchy areas of stability, accretion and erosion on the west-facing shoreline of the cape.

Figure 6. Collection of images (taken c. 1991) from Goh (1992) showing the erosional nature of large sections of the Bowling Green spit. The top left and bottom right photos were from the 'southern end of Cape Bowling Green' and the top right and bottom left photos were from the 'central section of Cape Bowling Green'.

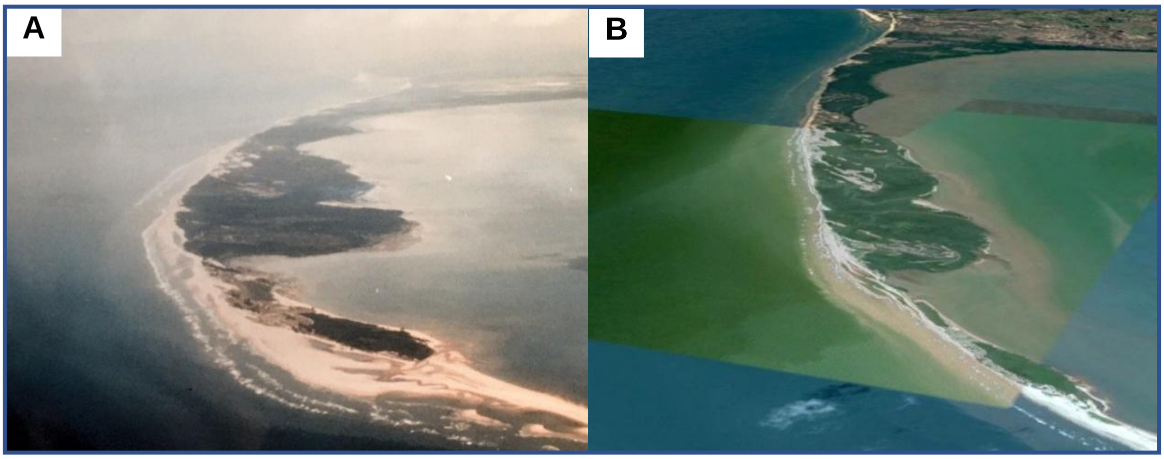

Figure 7. Oblique views of Bowling Green spit in area speculated to be vulnerable to breaching a) in 1990 from Goh (1992), and b) in December 2019 taken from Google Earth. Note that the tide was higher in December 2019 at the time the photograph was taken.

There is no question that the Bowling Green Bay spit shoreline is dynamic and in the main is in an erosionary state (as discussed above, some areas are stable or accreting). However, the weight of evidence suggest that contemporary changes to the shoreline and stability of the Bowling Green spit are not directly related to sediment supply disruptions developed since the construction of the Burdekin Falls Dam. Combined with the geomorphological evidence described above, the evidence supporting this conclusion includes:

- the persistence (and recent growth) of a prominent delta protuberance at the coast near the contemporary Burdekin River mouth;
- the general shallowness of the delta and its similarity to the form described by Jukes more than 170 years ago;
- the lack of conspicuous accelerated or locally severe shoreline erosion near the Burdekin mouth itself;
- the history of delta avulsions and spatial variations in sediment supply to the coast established by Fielding et al. (2006);
- the evidence provided by Hopley (1970a,b) documenting the retreat of a delta lobe developed several thousand years ago closer to the base of Bowling Green spit; and
- the evidence presented by Goh (1992) showing erosion on the spit well prior to Burdekin Falls Dam construction.

In summary, the Bowling Green spit is a naturally dynamic coastal feature that has undergone significant erosion and also extension over the past few thousand years. The evidence indicates that these changes have largely been the result of two natural processes:

1. the exhaustion of earlier delta deposits produced when the Burdekin River discharged at locations closer to the base of the Bowling Green spit before switching to its present location further south; and
2. littoral drift driven by the prevailing south-easterly wind and wave regime that typically transports this material toward the northwest.

If present trends continue it is likely that the spit will eventually breach, most likely toward its northern end and most likely during cyclonic wave conditions. It is also possible that both the rates of sediment transport north and the rates of shoreline retreat have accelerated in recent decades due to various influences including higher sea levels and disturbances associated with vehicular damage to littoral vegetation on the spit, but these are unquantified. The influence of these factors must also be discriminated from the periodic influence of storms, which Goh (1992) noted can produce significant localised erosion to the spit shoreline. Although only basic modelling has so far been undertaken (Goh, 1992), it would seem that the longer-term integrity of the Bowling Green spit, and the protection it offers to the Ramsar listed wetlands in Bowling Green Bay, are more at risk of changes in coastal geomorphology driven by natural processes and possibly the impacts of sea-level rise than contemporary sand supply to the coast from the Burdekin River. Science to understand the nature of future changes and planning to scope potential management options is important and necessary to prioritise the key pressures and to design the optimal responses.

Coast – Summary of key findings (see also Figures ii and iii)

- Sand movement within the Burdekin Delta coastal zone, including the Bowling Green spit is naturally dynamic and influenced by tropical cyclones, large floods and, over the longer term, the avulsion history of the Burdekin River;
- Large sections of the Bowling Green spit have been actively eroding for at least the past thousand years and studies prior to the construction of the Burdekin Falls Dam have well documented this eroding coastline;
- The tip of the Bowling Green spit is actively prograding due to supply from the erosional areas towards the base of the sand spit;
- The longer-term integrity of the Bowling Green spit (and protection to the Ramsar listed wetlands within Bowling Green Bay), are more at risk of changes in coastal geomorphology driven by natural erosional processes, and possibly the impacts of sea-level rise than reduced contemporary sand supply to the coast from the Burdekin River;
- The evidence suggests that the construction of the Burdekin Falls Dam has had negligible influence on sediment dynamics operating in the adjacent coastal zone.

6. Science needs

Some of the most critical science needs identified in this synthesis to support current and future water resource planning for the Burdekin Basin include:

- A sophisticated hydrodynamic model to quantify how the proposed dams will modify flow peaks and durations. The model should include consideration of dam type and operation protocols.
- Field measurements of the suspended bedload (and bedload) transported by the Lower Burdekin River channel under different flow conditions and with different source areas (i.e. above and below Burdekin Falls Dam sources). These data would help develop relationships between the loads of the fine and medium sand fractions with changing flows (i.e. this would address critical questions like how do the fine and medium sand loads change when there is a 10,000 $m^3.s^{-1}$ flow over 1 day compared to five days of 2,000 $m^3.s^{-1}$ flows – that is, the same flow volume but change in peak and duration).
- The modelling and monitoring data collected in points 1 and 2 above can be used to quantify the potential changes in loads of the fine and medium sand fractions with the changed hydrological conditions under the proposed dams.
- Field measurement and quantification of the fine and medium sand load (i.e. suspended bedload) contributions from the key tributaries below the Burdekin Falls Dam to complement the Lower Burdekin monitoring (above). A more accurate fine and medium sand budget could then be developed, reducing uncertainty in a number of current assumptions.
- Better knowledge of the potential changes in erosion rates of large-scale alluvial gullies resulting from changed flow regimes (i.e. lower peak discharges, increased flow duration) following dam construction.
- An improved understanding of how erosion rates have changed over time (i.e. have the erosion rates stabilised, increased, decreased since catchment development?) to evaluate whether the long-term mean increase in loads, particularly below the dam source, is applicable.
- A study to examine the dynamics of the fine and medium sand transported to (and potentially past) the Burdekin Delta under a range of flow conditions. Presently, the effectiveness of transport (i.e. where the fine and medium sand load is predominately deposited beyond the end-of-river) is unclear. Following deposition, the processes that govern the subsequent remobilization and transport of this sediment (i.e. floods, tides, waves, currents, storms) also need to be determined so that the final fate of this sediment can be determined. To begin with, quantification of the volumes of fine and medium sands stored in river mouth bars over time need to be compared/balanced against the estimated deficits along the Burdekin Delta shoreline. Furthermore, an understanding of other possible sediment sources to the region (such as delivered by smaller coastal streams in the area or from the offshore Upstart Bay) and how these are influenced by changing coastal processes such as sea-level transgression and storm/cyclone frequency.
- Systematic monitoring to quantify the coastal retreat of sections of the Cape Bowling Green spit and the assessment of the implications on the Ramsar site. This monitoring should utilise tools such as the DEA tool available through Geoscience Australia, augmented with geo-rectified historical imagery of the site captured prior to the DEA

records, to establish mean rates of shoreline movement over the measurement intervals.

- A study on the effects of the current and future sea-level rise on the morphology and sediment dynamics of the Bowling Green spit and an assessment of the implications on the Ramsar site.
- Should a decision be made to help protect sections of the Bowling Green Bay Ramsar site from the natural coastal retreat of the spit (and potential enhanced retreat with future sea-level rise) then the potential restoration options to stabilise the split can be explored (i.e. plant mangroves in the lee of the existing spit).
- A model of the future avulsion potential of the Burdekin River channel.

7. Management responses

A review of available research suggests the proposed new water infrastructure will not significantly modify the present volumes of fine and medium sand delivered to the end of the Burdekin River. Accordingly, there is no pressing management response required to ensure the continued export of this material. However, should the hydrodynamic modelling and monitoring of the fine and medium sand loads under different flow conditions (i.e. identified as science needs) show that changes in flow dynamics may influence sand export, then potential modifications of the dam type and operation should be explored to minimise these effects.

Once the future implications of the natural (and enhanced with sea-level rise) coastal retreat of the Cape Bowling Green spit on the Ramsar site are better understood (i.e. identified science need) a decision can be made on whether or not to protect this spit through restoration efforts.

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