Estimated sediment infilling rates for dams in northern Australia based on a review of previous literature

A technical report to the Australian Government from the CSIRO Flinders and Gilbert Agricultural Resource Assessment, part of the North Queensland Irrigated Agriculture Strategy

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The Strategy was guided by two committees:

(i) the **Program Governance Committee**, which included the individuals David Crombie (GRM International), Scott Spencer (SunWater, during the first part of the Strategy) and Paul Woodhouse (Regional Development Australia) as well as representatives from the following organisations: Australian Government Department of Infrastructure and Regional Development; CSIRO; and the Queensland Government.

(ii) the **Program Steering Committee**, which included the individual Jack Lake (Independent Expert) as well as representatives from the following organisations: Australian Government Department of Infrastructure and Regional Development; CSIRO; the Etheridge, Flinders and McKinlay shire councils; Gulf Savannah Development; Mount Isa to Townsville Economic Development Zone; and the Queensland Government.

This report was reviewed by Dr Scott Wilkinson (CSIRO), Dr Cuan Petheram (CSIRO) and Dr Peter Stone (CSIRO).

Director's foreword

Northern Australia comprises approximately 20% of Australia's land mass but remains relatively undeveloped. It contributes about 2% to the nation's gross domestic product (GDP) and accommodates around 1% of the total Australian population.

Recent focus on the shortage of water and on climate-based threats to food and fibre production in the nation's south have re-directed attention towards the possible use of northern water resources and the development of the agricultural potential in northern Australia. Broad analyses of northern Australia as a whole have indicated that it is capable of supporting significant additional agricultural and pastoral production, based on more intensive use of its land and water resources.

The same analyses also identified that land and water resources across northern Australia were already being used to support a wide range of highly valued cultural, environmental and economic activities. As a consequence, pursuit of new agricultural development opportunities would inevitably affect existing uses and users of land and water resources.

The Flinders and Gilbert catchments in north Queensland have been identified as potential areas for further agricultural development. The Flinders and Gilbert Agricultural Resource Assessment (the Assessment), of which this report is a part, provides a comprehensive and integrated evaluation of the feasibility, economic viability and sustainability of agricultural development in these two catchments as part of the North Queensland Irrigated Agricultural Strategy. The Assessment seeks to:

- identify and evaluate water capture and storage options
- identify and test the commercial viability of irrigated agricultural opportunities
- assess potential environmental, social and economic impacts and risks.

By this means it seeks to support deliberation and decisions concerning sustainable regional development.

The Assessment differs from previous assessments of agricultural development or resources in two main ways:

- It has sought to 'join the dots'. Where previous assessments have focused on single development activities or assets – without analysing the interactions between them – this Assessment considers the opportunities presented by the simultaneous pursuit of multiple development activities and assets. By this means, the Assessment uses a whole-of-region (rather than an asset-by-asset) approach to consider development.
- The novel methods developed for the Assessment provide a blueprint for rapidly assessing future land and water developments in northern Australia.

Importantly, the Assessment has been designed to lower the barriers to investment in regional development by:

- explicitly addressing local needs and aspirations
- meeting the needs of governments as they regulate the sustainable and equitable management of public resources with due consideration of environmental and cultural issues
- meeting the due diligence requirements of private investors, by addressing questions of profitability and income reliability at a broad scale.

Most importantly, the Assessment does not recommend one development over another. It provides the reader with a range of possibilities and the information to interpret them, consistent with the reader's values and their aspirations for themselves and the region.

Peter Stone

Dr Peter Stone, Deputy Director, CSIRO Sustainable Agriculture Flagship

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Shortened forms

APE	areal potential evaporation
APSIM	Agricultural Production Systems Simulator
CMIP	Coupled Model Intercomparison Project
CSIRO	Commonwealth Scientific and Industrial Research Organisation
Cv	coefficient of variation
DEM	digital elevation model
EEMD	Ensemble empirical mode decomposition
ENSO	El Niño Southern Oscillation
GCMs	global climate models
GCM-ES	global climate model output empirically scaled to provide catchment-scale variables
IMF	Intrinsic Mode Functions
IPCC AR4	the Fourth Assessment Report of the Intergovernmental Panel on Climate Change
IPO	Inter-decadal Pacific Oscillation
ITCZ	Inter-tropical Convergence Zone
MJO	Madden-Julian Oscillation
NASA	National Aeronautics and Space Administration
NQIAS	North Queensland Irrigated Agriculture Strategy
ONA	the Australian Government Office of Northern Australia
PE	potential evaporation
SOI	Southern Oscillation Index
SRES	Special Report on Emissions Scenarios

Units

MEASUREMENT UNITS	DESCRIPTION
GL	gigalitres, 1,000,000,000 litres
keV	kilo-electronvolts
kL	kilolitres, 1000 litres
km	kilometres, 1000 metres
L	Litres
m	Metres
mAHD	metres above Australian Height Datum
MeV	mega-electronvolts
mg	milligrams
MJ/m^2	megajoules per metre square
ML	megalitres, 1,000,000 litres

Preface

The Flinders and Gilbert Agricultural Resource Assessment (the Assessment) aims to provide information so that people can answer questions such as the following in the context of their particular circumstances in the Flinders and Gilbert catchments:

- What soil and water resources are available for irrigated agriculture?
- What are the existing ecological systems, industries, infrastructure and values?
- What are the opportunities for irrigation?
- Is irrigated agriculture economically viable?
- How can the sustainability of irrigated agriculture be maximised?

The questions – and the responses to the questions – are highly interdependent and, consequently, so is the research undertaken through this Assessment. While each report may be read as a stand-alone document, the suite of reports must be read as a whole if they are to reliably inform discussion and decision making on regional development.

The Assessment is producing a series of reports:

- Technical reports present scientific work at a level of detail sufficient for technical and scientific experts to reproduce the work. Each of the 12 research activities (outlined below) has a corresponding technical report.
- Each of the two catchment reports (one for each catchment) synthesises key material from the technical reports, providing well-informed but non-scientific readers with the information required to make decisions about the opportunities, costs and benefits associated with irrigated agriculture.
- Two overview reports – one for each catchment – are provided for a general public audience.
- A factsheet provides key findings for both the Flinders and Gilbert catchments for a general public audience.

All of these reports are available online at <http://www.csiro.au/FGARA>. The website provides readers with a communications suite including factsheets, multimedia content, FAQs, reports and links to other related sites, particularly about other research in northern Australia.

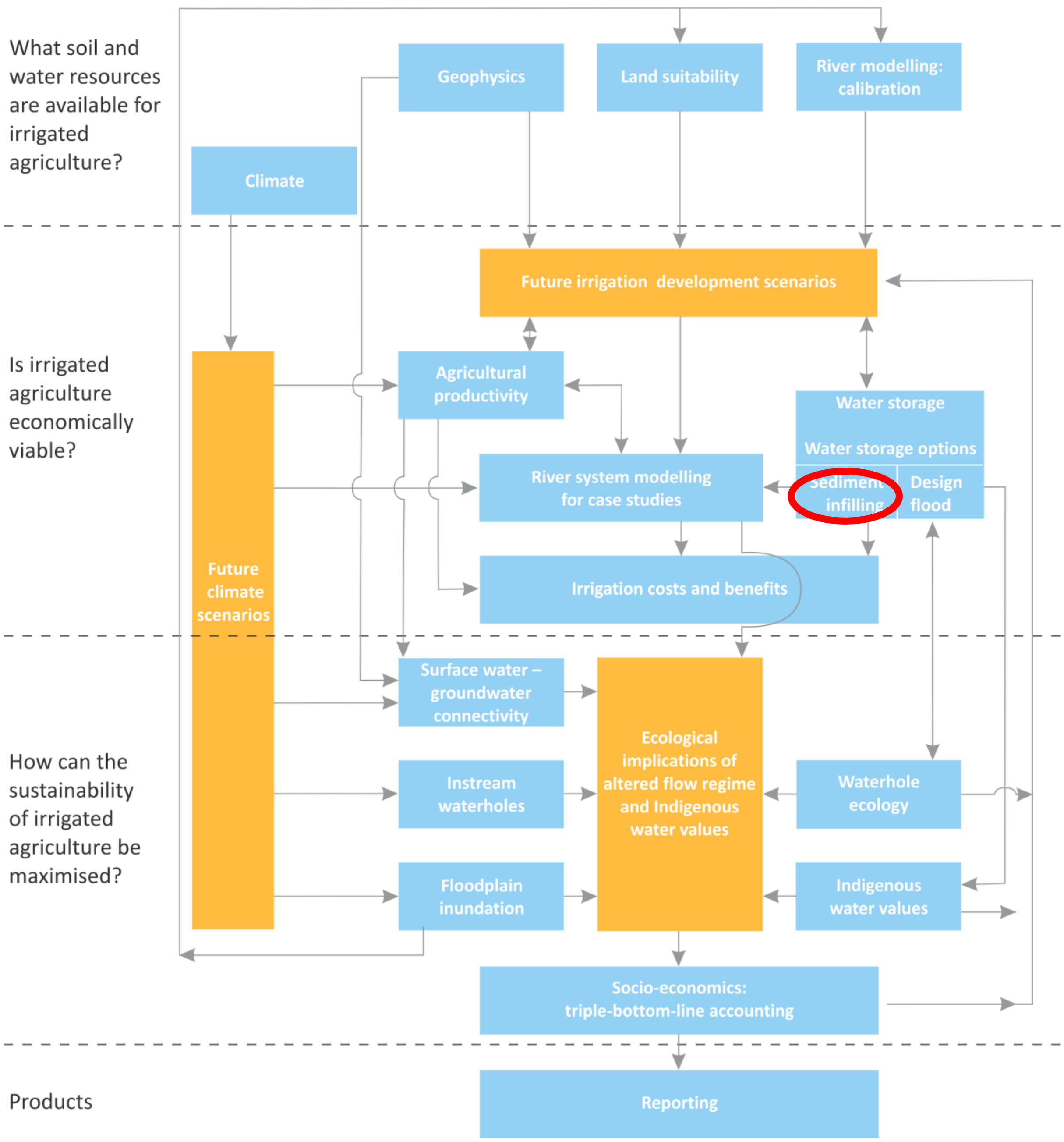
The Assessment is divided into 12 scientific activities, each contributing to a cohesive picture of regional development opportunities, costs and benefits. Preface Figure 1 illustrates the high-level linkages between the 12 activities and the general flow of information in the Assessment. Clicking on an 'activity box' links to the relevant technical report.

The Assessment is designed to inform consideration of development, not to enable particular development activities. As such, the Assessment informs – but does not seek to replace – existing planning processes. Importantly, the Assessment does not assume a given regulatory environment. As regulations can change, this will enable the results to be applied to the widest range of uses for the longest possible time frame. Similarly, the Assessment does not assume a static future, but evaluates three distinct scenarios:

- Scenario A – historical climate and current development
- Scenario B – historical climate and future irrigation development
- Scenario C – future climate and current development.

As the primary interest was in evaluating the scale of the opportunity for irrigated agriculture development under the current climate, the future climate scenario (Scenario C) was secondary in importance to scenarios A and B. This balance is reflected in the allocation of resources throughout the Assessment.

The approaches and techniques used in the Assessment have been designed to enable application elsewhere in northern Australia.



Preface Figure 1 Schematic diagram illustrating high-level linkages between the 12 activities (blue boxes)

This report is a technical report. The red oval in Preface Figure 1 indicates the activity (or activities) that contributed to this report.

The orange boxes indicate information used or produced by several activities. The red oval indicates the activity (or activities) that contributed to this technical report. Click on a box associated with an activity for a link to its technical report (or click on 'Technical reports' on <http://www.csiro.au/FGARA> for a list of links to all technical reports). Note that the Water storage activity has multiple technical reports – in this case the separate reports are listed under the activity title. Note also that these reports will be published throughout 2013, and hyperlinks to currently unpublished reports will produce an 'invalid publication' error in the CSIRO Publication Repository.

Executive summary

The objective of this study was to provide preliminary estimates of the rates of sediment infilling in 22 potential dam sites in the Flinders and Gilbert catchments. There are a number of different methods for estimating sediment yields, loads and reservoir trap efficiency in catchments. These are based on one or more of: field measurement, desktop assessment using other data, establishment of empirical relationships from data, and mathematical modelling. Because of the limited existing field data from the Flinders and Gilbert catchments and limitations in existing sediment models, deriving an empirical relationship between sediment yield and catchment area was deemed to be the best method available to meet the core objective within the project timeframe. The method was commensurate with the spatial extent of the Assessment area, the number of potential dam sites to evaluate and the available resources.

Initially, a review of the sediment generation, sediment transport and reservoir trapping efficiency literature from across northern Australia was undertaken. This review provided the majority of the data and information used to derive the sediment yield-catchment area relationship, as well as provide context for sediment processes in rivers in the Flinders and Gilbert catchments where potential dam sites are being examined. The location and size of the dams had been determined by previous modelling of topography and irrigation potential undertaken as part of the Assessment, as well as previous geotechnical investigations and specifications of existing infrastructure.

Historical sediment yield data were collated from 10 studies across northern Australia, including a study from the Flinders River at Glendower. A non-linear (power) function was fitted to the data to derive the relationship between sediment yield and catchment area. Minimum and maximum uncertainty bounds were also calculated based on the mean error between the observed and predicted sediment yields. The predicted historical yields for each dam site were determined using the dam catchment area. These were then subjectively adjusted to reflect the upstream geology, likely sediment supply and field observations from the sites. For some dams, the predicted yields were considered an over-estimate, while others were considered a good estimate or an under-estimate. The manner in which this was done is documented within the report.

The rates of sediment infilling for the potential dam sites were determined for 30, 100 and 1000 years using linear scaling. The number of years to 100% sedimentation were also determined to indicate the maximum life of each dam. A dam trapping efficiency of 90% was assumed to be the most likely value, based on the literature. Infilling rates were also calculated for trap efficiencies of 60% using the minimum predicted sediment yields, and 100% using the maximum predicted sediment yields for each site to indicate the best (minimum) and worst (maximum) case scenarios, respectively. A ~60% trap efficiency would apply only in rare instances to very small dams with a large overflow or where sediment management controls were incorporated into the dam infrastructure. A 100% trap efficiency would apply where a dam never spills.

Eighty-two percent of the potential dams examined in the Assessment are estimated to have between 0.3% and 7% sediment infilling after 30 years and between 1% and 24% sediment infilling after 100 years. These are predicted to be the most likely percentages, although infilling under the worst case scenario could be as high as 0.9 to 22% after 30 years and 3 to 72% after 100 years for 82% of dams, with four dams at or close to 100% after 100 years. The most likely median time to complete sediment infilling (100%) is estimated at around 780 years. Under the worst case, the median time is around 375 years.

There is a strong relationship between the capacity of the dams and the infilling rates. Small dams with a large catchment area and large sediment yield infill much more rapidly than large dams with a small catchment area and small sediment yield. These trends were very evident from the results for the 22 potential dam sites examined here. Hence, sites with a relatively high sediment yield will not infill more rapidly relative to others if the volume of the proposed dams at those sites is also high.

The results presented in this report are considered to be reasonable estimates based on limited existing historical data, results from previous studies, field observations and expert judgement. However, there are a number of assumptions in the analysis and a large uncertainty in the predicted sediment yields.

There are also a number of issues that have not been explicitly investigated in this study. For example, the estimates average out variations in yields between wet and dry years, as well as the impacts of extreme flood events. These could significantly increase the percentage of infilling within a short period of time, which would affect the sediment infilling rates over ~1 to 10 year time-scales. The estimates do not consider long-term changes in sediment yields under future climates. If there is a strong change in the climate signal, it is likely that sediment yields would be biased above (or below) the historical mean yield under conditions of more (or less) effective rainfall and discharge. Changes to the frequency and/or magnitude of inter- and intra- annual climate variability including the frequency of extreme events will increase the uncertainty in sediment yields.

The impacts of sediment trapping in triggering a sediment starved response downstream of the dams were not considered, nor were the patterns of deposition within the reservoirs. Deposition within a reservoir can have an impact on the trap efficiency of the dam and the effective storage volume over time. It can also affect the extent of back-flooding in streams draining into the reservoir.

If any of the potential dams examined in the Assessment were to be constructed in the future, sediment yields would need to be re-computed by undertaking a detailed field measurement and modelling program.

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1 Introduction

This study investigates the potential rates of sedimentation in 22 potential dams in the Flinders and Gilbert catchments (Figure 1.1). The impacts of dams on sediment transport in rivers are widely reported across the globe (e.g. Vorosmarty et al., 2003; Syvitski et al., 2005). Dam walls act as barriers to sediment transport, trapping around 100% of bed load material (i.e. sand and gravel) and large proportions, sometimes as high as 100%, of suspended sediment (i.e. clay, silt and fine sand). Downstream impacts can occur as well, including sediment starvation, which can trigger channel bed incision and bank erosion.

Sedimentation within dams is a major problem for water storage capacity since infilling progressively reduces the volume available for active water storage. Vorosmarty et al. (2003) estimates that most dams trap > 50% of the sediment load and on average this results in the trapping of 25 to 30% of the global sediment flux. Some dams have a predicted lifespan of only decades before completely infilling. For example, the World Commission on Dams (2000) shows data where 5 of the 47 dams surveyed had a loss of active storage capacity of > 60%, and one of these had lost 80% of capacity in just over 25 years. Extreme sedimentation has also been shown to have affected some smaller dams in Australia, resulting in complete infilling of the storage capacity (Chanson, 1998).

Other impacts of sediments in dams include abrasion of outlets and turbines, and poor water quality, especially where sediment re-suspension occurs and/or where sediments are carrying considerable nutrients. In some instances, the pattern of dam sedimentation is also problematic. The majority of sediments, particularly coarse bed load sediments, are deposited in the backwater (upstream) areas of reservoirs due to a rapid decline in flow velocity from riverine to lake conditions (Outhet, 1991). Depending on dam levels during flow events, the build-up of sediments in the back-water can cause back-flooding beyond the flood limit originally determined for the reservoir.

The approach used in this study was to develop a regional picture of sediment yields for the large monsoonal rivers of northern Australia, based on a review of literature. These yields were used to estimate the sediment infilling rates in 22 potential dams in the Flinders and Gilbert catchments. This report is organised into the following sections:

- Brief overview of the dominant controls on sediment yields in catchments.
- Brief overview of the common methods for estimating sediment yields, loads and dam trap efficiency.
- Review of literature from the Flinders, Gilbert and other northern Australian rivers to identify current knowledge and gaps.
- Estimation of sediment yields and rates of infilling in potential dams in the Flinders and Gilbert catchments.
- Summary comments.

1.1 Dominant controls on sediment yields in catchments:

The volume of sediment, or mean sediment load that is exported from a catchment is termed the end of system sediment yield. Sediment yields are governed by a number of controls relating to i) sediment supply from hillslopes to the stream network, ii) transport through the stream network, and iii) storage within the stream network. Sediment supply is largely a function of the catchment sediment supply potential, dominant erosion processes and connectivity between hillslopes and streams. Sediment transport in rivers is largely a function of discharge regime, stream power and sediment size, while storage within the channel bed and floodplains depends on depositional processes, sediment residence times and valley/floodplain width.

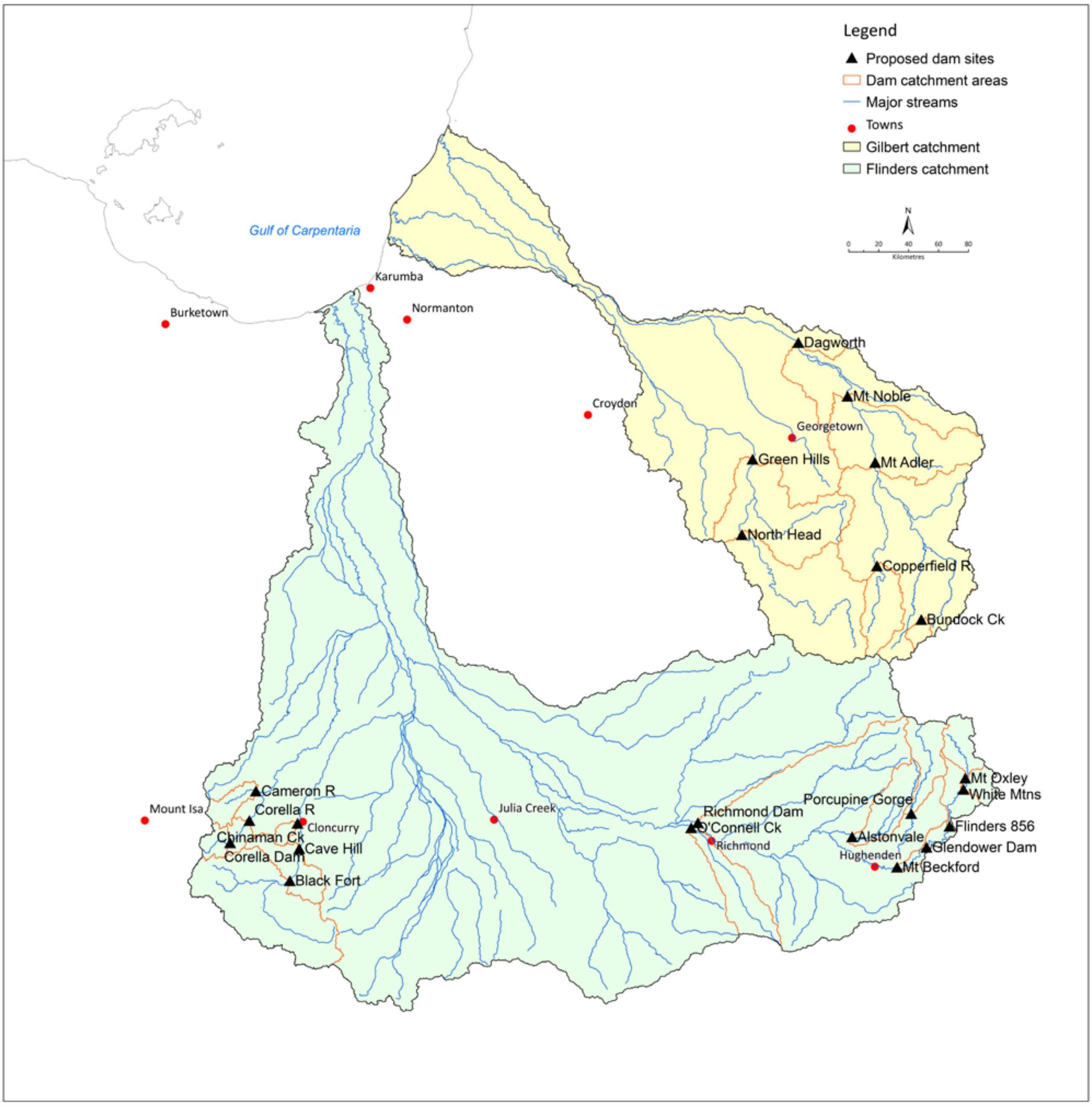

Figure 1.1 Flinders and Gilbert catchments in northern Australia, showing the location of 22 potential dam sites. The Flinders River at Glendower is indicated by Glendower Dam.

1.1.1 SEDIMENT SUPPLY FROM CATCHMENTS

The sediment supply potential (or sediment production potential) of a catchment is governed by three factors:

1. Bedrock lithology – the characteristics of the rock including grain size and mineralogy.
2. Rates of weathering – the extent and rate of breakdown of the rock surface by chemical and physical processes, depending on lithology, climate and biota.
3. Erosional susceptibility – the ease or resistance of weathered material to erosion and transport by overland flow.

Hence, the volume and size fraction of sediments in channels are inherited from the bedrock from which they are derived. Catchments that drain a single rock type with a uniform lithology will generate sediments with a consistent range of grain sizes. Catchments that feature variability in rock types will generate multiple grain size distributions characteristic of those different lithologies.

Weathering governs the rate of conversion of rock to soil, and hence the availability of erodible sediment. Where catchments are comprised of resistant rocks with low weathering rates, bedrock outcrop will form a large area of the surface and soils may be thin and sporadic. Erosional susceptibility will be low and potential erosion rates will be limited by the amount of sediment available for erosion (i.e. weathering-limited). Conversely, where the bedrock is highly weathered and soil formation is non-limiting, the erosional susceptibility will be high. Potential erosion rates can also be high depending on climate (hydrology), topography (relief), biota (primarily vegetation cover) and the dominant erosion processes. It is common for catchments to drain a mix of lithologies with varying degrees of resistance and weatherability. This applies to the Flinders and Gilbert catchments, which are described later in this report.

The key sediment generating processes in catchments include, but are not limited to:

- Sheetwash (surface erosion).
- Rilling and gullying (concentrated erosion in small depressions and channels formed in alluvium or colluvium).
- Landslides, debris flows and rock falls (slope failure by mass movement; not common in Australia).
- Channel incision and bank erosion (Prosser et al*.,* 2001).

Not all processes are active in all catchments since these also depend on climate, hydrology (rainfall, runoff), topography, lithology and vegetation cover. Additionally, some processes may be spatially and temporally variable or event-based, e.g. landslides.

The proportion of sediment eroded from hillslopes that is delivered to the stream network is known as the hillslope sediment delivery ratio. This ratio is rarely equal to one since sediment delivery to streams is rarely direct or continuous. More often a ratio of less than one occurs because sediment delivery is limited by the transport capacity of surface runoff (Kinnell, 2004). Another key factor is the spatial and temporal connectivity, or dis-connectivity, between hillslopes, tributaries and trunk streams (Prosser et al., 2001; Fryirs et al., 2007). Often sediment is only transported short distances on hillslopes depending on slope angle and the intensity and duration of rainfall-runoff events. As a result, sediment can accumulate at the base of hillslopes forming a colluvial mantle, and in headwater streams as valley fills. These sediment accumulation zones can create positive feedbacks, trapping further sediments until a threshold is reached and the sediments are released through erosion. The net result is discontinuous sediment conveyance through upper catchments.

1.1.2 SEDIMENT TRANSPORT IN RIVERS

There are a number of factors relating to discharge and sediment character that control sediment transport in rivers. One of these is discharge regime, which is a function of the frequency and duration of flows. In ephemeral rivers, flow is strongly seasonal and intermittent, with several months of no flow (and no sediment transport), often punctuated by large streamflow events. In perennial rivers, streamflow and sediment transport are generally continuous all year round with only occasional periods of cease-to-flow, and seasonally higher flows or infrequent large flood events.

In perennial streams, bankfull flows which occur on average every ~1 to 2 years have been shown to have the greatest capacity to transport the largest proportion of the total sediment load (Wolman and Miller, 1960). This is in comparison to the more frequent (intra-annual), but smaller flow events that are less effective at doing 'geomorphic work', and the larger, less frequent flood events that occur only rarely. In ephemeral streams and highly variable streams, the largest percentage of sediment is transported by large streamflow events since these dominate the flow regime (Wolman and Miller, 1960).

The ability of a river to transport sediment during streamflow events is determined by stream power relative to critical power. Stream power is the power per unit length of stream, or the rate of energy supply

at the stream bed which is available to overcome friction and transport sediment (i.e. 'do geomorphic work') (Bagnold, 1966). Critical power is the energy condition which is needed to transport the mean sediment load (Bull, 1979). Unit stream power or specific stream power is the energy available to do work per unit area of the channel bed. High energy streams with steep gradients and/or high runoff typically have a unit stream power of between 100 - 1000 W m^{-2}. Low energy streams with low gradients and/or low runoff have a unit stream power of < 100 W m^{-2} (Summerfield, 1991).

The dominant terms in the stream power equations are discharge and slope. In channels, stream power varies temporally through changes in discharge during flow events associated with the rise and fall of the hydrograph, as well as between flow events. Stream power also varies spatially along channels through changes in the bed long profile, particularly where the bed slope ranges from very low gradients associated with open floodplains to vertical knickpoints (waterfalls) in gorges and confined valleys.

Sediment size is also a major control on sediment entrainment, transport, deposition and sorting in rivers. A key relationship exists between sediment size and flow velocity, which is described by the Hjulstrom (1935) curve (Figure 1.2). The curve defines the competence of different mean flow velocities that are required to entrain, transport and deposit sediment in channels where sediments are well sorted and no armouring occurs. Sediment transport occurs through rolling or sliding on the bed (bed load), saltation or in suspension (suspended load) and is a function of particle size and density.

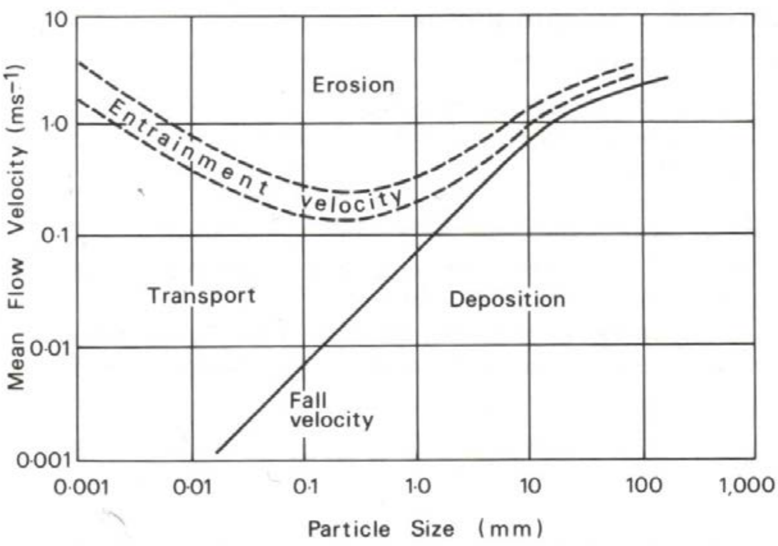

Figure 1.2 Hjilstrom curve showing the relationship between sediment particle size and mean flow velocity in rivers (Source: Summerfield, 1991; after Hjulstrom, 1935)

For example, the Hjulstrom curve (Figure 1.2) shows that medium sand particles (0.25 - 0.5 mm) are entrained and transported at the lowest flow velocities (~0.2 ms^{-1}). Fine clay particles (< 2 um) require much greater flow velocities for entrainment (> 2 m s^{-1}) due to strong cohesion but remain in suspension and have the greatest transport potential even under very low flows. Large, heavy pebbles and gravels (> 10 mm) require the greatest flow velocities for entrainment and transport along the bed and if these high velocities are not maintained in the channel, deposition occurs. Hence, bed load sediment has the lowest transport potential, especially where the bed slope is low and/or where discharge declines with distance downstream due to evaporation and seepage into groundwater. Depending on catchment lithology and distance downstream, the typical sediment composition of most streams includes both bed and suspended load. With respect to sediment trapping in dams, the amount of bed material is particularly important since most dams are located in headwater areas.

Another key relationship is sediment size and shear stress. Transport of bed load and suspended load occurs when the average bed shear stress and turbulence exceeds the critical bed shear stress. Average bed shear stress is calculated as unit stream power divided by the mean flow velocity. Critical shear stress values for bed load are provided in Garde and Ranga Ranju (2000).

1.1.3 SEDIMENT STORAGE

A fundamental part of sediment transport through stream networks is storage, since in large channels that flow over long distances, sediment conveyance is rarely continuous and input does not equal output on a daily, monthly or even longer timescale. In most systems, a large component of the total sediment load is temporarily stored in within-channel units, such as the channel bed, sediment bars, benches, islands or floodouts, and/or in long-term depositional features like floodplains and alluvial fans.

Sediment deposition is governed by the fall velocity of particles which is a function of particle size, roundness, fluid viscosity and the extent of the wetted channel and/or floodplain area. The mean fall velocity threshold for different particle sizes is shown by the Hjulstrom curve (Figure 1.2) which defines the minimum mean channel flow velocity required to maintain sediment transport, below which deposition occurs. For gravel the threshold is > 0.1 m s^{-1}; sand is 0.05 – 0.1 m s^{-1}, while silt and clay is < 0.01 ms^{-1}. For bed load, the velocity of flow immediately above the bed is also critical.

1.1.4 SEDIMENT TRANSPORT-LIMITED VERSUS SUPPLY-LIMITED STREAMS

Streams are often described as being transport-limited or supply/detachment/weathering-limited (Arhnert, 1974). Transport-limited streams have a relatively high catchment sediment supply, but sediment yield is limited by the frequency of flows and stream power to transport sediment through to the end of system. Ephemeral streams are a good example of transport-limited conditions. Conversely, supply-limited streams have adequate flows and stream power, but yield is limited by adequate catchment sediment supply. An example is a bedrock stream or gorge formed in resistant rock. Many streams fall in between supply- and transport-limited, particularly alluvial streams which have the capacity to adjust their boundaries through erosion and deposition, and are said to be in a state of equilibrium or quasi-equilibrium where sediment transport approximately equals the rate of upstream sediment supply. Individual streams can also be supply-limited in the headwaters and transport-limited in low gradient floodplain reaches.

Supply or transport-limited conditions can also apply to sediment size fractions. For example, fine sediment is usually supply-limited in catchments since the transport potential is very high even under low stream power, whereas bed load sediment is both supply- and transport-limited.

1.2 Common methods to estimate sediment yields, loads and dam trap efficiency

There are a number of different methods for estimating sediment yields, loads and dam trap efficiency in catchments (Table 1.1). Note: sediment load is the volume of sediment that is actively being *transported* through the channel(s) at local-, reach- or catchment-scale and is expressed in units of mass such as tonnes (t); sediment yield is the mean sediment load that is *supplied* by the catchment and is expressed as mass per year (t yr^{-1}), or mass per unit area per year (t km^{-2} yr^{-1}, specific sediment yield); and dam trap efficiency is the proportion of sediment trapped and *stored* behind a dam wall or in a reservoir, relative to the in-coming sediment load.

These methods are based on one or more of: field measurement, desktop assessment using other data, establishment of empirical relationships from data, and mathematical modelling. However, there are significant differences between the methods. For example, methods that are largely based on field measurement are generally accurate and reliable, but are site specific, time consuming and labour intensive. Methods that are largely based on desktop assessments and modelling are often time and cost effective, and suitable for large areas, but usually have a large uncertainty due to the need for assumptions and simplification of processes. A more common approach is to derive estimates of sediment yields, loads and trap efficiency using a combination or average of methods where available.

Table 1.1 Methods for estimating sediment yields, loads and trap efficiency (Source: Stigter et al., 1989)

METHOD	DESCRIPTION
Estimate catchment sediment yields	Undertake a field and desktop assessment of catchment variables including: rainfall amount and intensity, soil type, ground cover (percentage vegetation vs bare ground and rock), land use, topography, erosion sources, runoff and drainage density, sediment characteristics, channel hydraulics. Use gross erosion rate equations based on measured or estimated data/variables e.g Revised Universal Soil Loss Equation. Establish empirical relationships between variables using sediment estimates from similar catchments, e.g. sediment yield vs discharge or sediment yield vs drainage area. Use numerical sediment models e.g. SedNet.
Estimate sediment loads in channels and at reservoir sites	Measure discharge, sediment size distributions and concentrations using field samplers. Use sediment transport equations and sediment rating curves. Undertake bathymetry surveys of existing reservoirs to determine sediment accumulation volumes and rates.
Estimate dam/reservoir trap efficiency	Estimate the suspended sediment trap efficiency based on the capacity of the dam and the ratio of outflow (e.g. spillway discharge) to inflow, and assume 100% trapping of bed material. Calculate trap efficiency based on the total sediment deposited divided by the total sediment inflow, adjusted for particle size and discharge (and operational level for short-term estimates).

1.3 Gilbert, Flinders and other northern Australian Rivers: current knowledge and gaps

1.3.1 DOMINANT SOURCES OF SEDIMENT

Much of the information on the sediment supply potential of the Flinders and Gilbert catchments is derived from a detailed survey of the geomorphology of the Leichhardt-Gilbert Area by Twidale (1966). Twidale identified 28 physiographic regions, which were grouped into four divisions: the Isa Highlands (A) in the west; the Carpentaria Plains (B) in the centre which drain northwards to the Gulf of Carpentaria; the Inland Plains (C) in the south which drain to Lake Eyre; and, the Einasleigh Uplands (D) in the east.

Across the area, relief and drainage is strongly determined by structural controls relating to uplift, warping, doming, faulting and subsidence. For example, most of the major rivers follow a north-west to south-east alignment consistent with regional lineaments and many of the ranges and plateaux like the Gregory and Newcastle Ranges are upwarped features. Lithological control is also a major factor governing weathering and erosion and the degree of dissection of the upland surfaces. Much of the region is formed on erosion-resistant Palaeozoic and older metamorphic and igneous rocks, which are unconformably overlain by sub-horizontal sedimentary rocks that are in places laterized (cemented by iron and aluminium oxides). In the eastern part of the region, large areas of the plateaux are covered by basalts that flowed across the surface during the Late Tertiary-Quaternary, infilling valleys and streams including parts of the Einasleigh River.

The physiographic regions that occur within the Flinders and Gilbert catchments are shown in Table 1.2 and Table 1.3, respectively. Also shown is an estimate of the sediment supply potential of each region based on the description of geology, landforms and drainage by Twidale (1966) and the approximate proportion of each region in the catchments of the dam sites based on Twidales map. The resistance of the rocks to erosion was subjectively assessed based on strength and structure. For example, siltstones and shales are

generally weak with a high sediment supply potential of fine sediment, whereas metamorphic rocks such as porphyry and quartzite are typically strong with a low sediment supply potential of mixed grain size.

Previous studies, such as Wasson et al. (2002), have shown that even small areas of catchments (~10%) formed on highly erodible sedimentary rocks can generate significant proportions of the catchment sediment yield (> 90%). In the Flinders and Gilbert catchments, the most erodible regions that include large areas of siltstones, shales, slate, phyllite and granites are the Uplands and Ranges of the Divide, Georgetown Uplands, Gilbert Plain, Devoncourt Upland and the Baronta Plateau. The more resistant regions that are predominantly porphyry or basalt, include the Newcastle and Gregory Ranges, the Nulla, Chudleigh and McBride Plateaux, and the Isa Highlands. Most of the potential dam site catchments include more than one region and the number tends to increase with catchment area. It is expected that catchments draining the more erodible regions would have a relatively high sediment supply, even where those regions comprise only a small part of the total catchment area. In contrast, the existing Copperfield River Gorge Dam, Chinamans Creek Dam and Corella River Dam and the potential Cameron River dam site, appear to have to the lowest potential sediment yields since the majority of their catchments drain resistant geology.

There is good agreement in the scientific literature on the key sediment generating processes in northern Australian catchments. Alluvial gully erosion has been identified as a major source of fine sediment in some rivers draining into the Gulf of Carpentaria (Brooks et al., 2007). The gullies are formed on mid-catchment and lowland floodplains and fan alluvium adjacent to channels, and are most extensive in larger, steeper gradient rivers such as the Mitchell River, where there is a large local relief between the thalweg and floodplain surface. The likelihood of gully formation is controlled by a number of factors namely, ground cover, soil dispersibility, groundwater concentration and seepage (facilitating piping and tunnelling), overland flow and backwater flooding (Brooks et al., 2009; Shellberg et al., 2012). Alluvial gullies have been shown to affect only a small area of the gulf catchments (<1%), but their high connectivity with the major river channels enables direct transfer of significant quantities of fine sediment to downstream (Brooks et al., 2009).

On hillslopes, colluvial gully erosion has been shown to be locally important especially in the headwaters of some of the eastern draining catchments such as the Fitzroy (Hughes et al., 2009) and Burdekin (Bartley et al., 2007). Colluvial gully erosion appears to be less widespread in the gulf catchments, potentially due to different geology and/or lower land-use pressure. However, the rates and distribution of alluvial and colluvial gully erosion have been found to have increased through post-European disturbance. In the Fitzroy catchment, gully erosion from cultivated land on granite and metasedimentary rocks is now one the largest contributors of fine sediment in the catchment (Hughes et al., 2009). In the Mitchell River, alluvial gully initiation and/or acceleration was triggered by prolonged intense grazing of cattle in the riparian zones (Shellberg et al., 2010).

Another key potential sediment source is the sandy bed load sediment stored in channels across the region. In many channels (small to large) these sediments exceed 10 m thickness (see Table 1.4 and Table 1.5). In the Mitchell catchment, Brooks et al. (2008) estimate that only the upper metre or few metres of sediment in the channel bed is being actively scoured and reworked during flow events. This results in a total net turnover over of sediment of > 5 Mt yr^{-1}, which is equivalent to the average contribution of sediment estimated to be derived from alluvial gully erosion in the catchment. Reworking of sediments stored in channels has also been shown to be a significant component of the sediment yield in several other catchments in northern Australia including the Burdekin, Fitzroy, Daly and Ord Rivers (Wasson et al., 2002; Bartley et al., 2007; Wasson et al., 2010; Hughes and Croke, 2011).

Channel bank erosion appears to be less widespread across the region. In the Daly River, significant channel widening through slumping and scour is estimated to account for 57% of the fine sediment input (Rustomji and Caitcheon, 2010; Wasson et al., 2010; Wilkinson et al., 2012). Wasson et al (2010) propose that the widening is a response to regional hydrological changes to wetter conditions post-1990. It is likely that similar hydrological changes occurred in other rivers in the region but may not have been reported.

Modelling results presented in the 2001 National Land and Water Resources Audit (NLWRA, 2001) had previously indicated that surface hillslope erosion was an important component of sediment budgets in

northern Australian Rivers. However several field studies using sediment tracers such as ^{137}Cs have shown that surface erosion by sheet wash is a relatively minor source of sediment (< 10%) (Wasson et al., 2002; Caitcheon et al., 2012) leading to a revision of these earlier conclusions.

1.3.2 HYDROLOGICAL REGIME AND ABILITY TO TRANSPORT SEDIMENT

The hydrological regime of rivers in northern Australia has a major influence on the timing and extent of sediment transport. The rivers are strongly ephemeral with an annual wet and dry which limits potential sediment transport to only a few months of the year. The region also experiences large inter- and intra-annual variability of streamflow (Petheram et al. 2008) and sediment transport (Table 1.6 and Table 1.7).

There are few previous estimates of stream power from rivers in northern Australia that can be used to evaluate the effectiveness of streamflow in transporting sediment. Unit stream power in the lower Daly River (Northern Territory) at Mount Namcar (which is described as a low sinuosity sand bed channel with outcropping rock bars and a bed slope of 0.0002) is estimated as ~15 W m^{-2}, consistent with suspended load transport (Wasson et al., 2010). Poplawski et al. (1989) provide streamflow data for the Flinders River at Glendower. At this site unit stream power is also low (<< 100 W m^{-2}) for a range of flows up to 850 $m^3 s^{-1}$. However, because of higher flow velocities and a steeper bed slope (0.0009), channel bed shear stress appears to be sufficient to transport coarse sandy bed load sediment and finer sediment with a discharge of around 120 $m^3 s^{-1}$ or greater, or a mean depth of ≥ 1.2 m (Table 1.8).

The limited data on stream power from rivers in the Gulf region was supplemented by field observations from the potential dam sites and around the region (Table 1.4 and Table 1.5) to evaluate sediment transport. Much of the sediment in the channels is coarse, ranging from sands to small gravels and occasionally large boulders in rivers like the Einasleigh at Mt Adler and Mt Noble. In all of the streams, bed load transport appears to be active in the upper and mid-catchments, evidenced through imbrication of gravels and the formation of bed forms such as at Green Hills. Suspended sediment is transported further during flow events or deposited overbank, with very little fine sediment stored in the channel bed, at least in the upper-mid catchments (see Table 1.9 showing data from Rockfields downstream of Green Hills, as an example).

However, it is possible that some, or most, of the bed load sediment within the channels is a much older lag and was more actively transported during previous enhanced flow conditions. Dating of sandy channelised sediments on the Gilbert Fan showed that there have been several periods during the Pleistocene when stream power and potential sediment transport were much greater than present due to more hydrologically effective climates associated with the glacial/inter-glacial cycles (Nanson et al., 2005). In contrast, current hydrological conditions appear to favour transport of only suspended sediment to the end of system in most rivers across northern Australia.

Although there is little sediment dating evidence at present, it is probable that much of the sandy sediment infilling the channels in the mid-upper catchments of the Flinders and Gilbert rivers is an older lag (i.e. it may be a similar age to the sandy sediments on the Gilbert Fan dated by Nanson), and only some of the surface sediment is being actively reworked and transported a distance downstream at present, with the remainder stored in the channel bed. To test this, calculations were made using the drilling results from Rockfields (Table 1.9). These suggest that reworking of the upper 25 – 50 cms of bed material could produce feasible sediment loads in the Gilbert River (see Table 1.10 and Table 1.11). Reworking of the upper 25 - 50 cms of sediment also matches observations from the site including the presence of bedrock outcrop in the bed, which undoubtedly plays a role in determining bed slope and limiting the depth of bed scour. However, further studies based on field measurements, sediment dating and determination of sediment residence times would be needed to verify this hypothesis.

1.3.3 PREVIOUS ESTIMATES OF SEDIMENT YIELDS AND DAM TRAP EFFICIENCY

Previous estimates of sediment yields from eight catchments in northern Australia are shown in Table 1.12. An estimate of the sediment yield for the Flinders River at Glendower is also included based on the data

from Poplawski (1985), which is summarised in Table 1.6. The sediment yields are based on a variety of methods including field measurements, mapping, sediment tracing and sediment modelling. The yields range from 85 t yr^{-1} for a small catchment draining into the East Alligator River, Northern Territory (4.8 km^2) (Duggan, 1994), to > 10 Mt yr^{-1} for the Mitchell, Daly and Ord river catchments (> 50,000 km^2).

The SedNet modelling yield results for the Mitchell and Daly Rivers appear to be substantially lower than those derived from field-based measurements for the same catchment. It is likely that the SedNet yields are under-estimates since previous evaluations of SedNet have shown that the model has a number of limitations in its application to northern Australian rivers. Namely, the model tends to over-estimate the contribution of hillslope erosion, under-estimate the contribution of gully erosion and does not simulate the contribution from channel reworking (Brooks et al., 2007; Rustomji et al., 2010). Conversely, the field-based measurements also have a degree of uncertainty and some may be over- or under-estimates. For instance, Poplawski (1985) states that his estimates are based on only limited field data and mathematical calculations, so should be considered as a minimum approximation only.

A number of the modelled and measured estimates are also based only on suspended load and do not include any of the bed load fraction. These are likely to be significant under-estimates of the total yield. In this review it is assumed that all of the yield values shown in Table 1.12 preliminary estimates rather than absolute determinations of yield.

Information on dam trapping efficiency was sourced from two studies: Poplawski (1985) for the Flinders River at Glendower and Lewis et al. (2009; 2013) for the Burdekin Falls Dam. Poplawski estimates that a potential 200,000 ML dam at Glendower would have a sediment trapping efficiency of 95% of wash load (clays) and 100% of bed load (silt, sand and gravels) equating to an estimated volume of 135,000 m^3 yr^{-1} in an average year, or 0.07% per annum of the total dam capacity. Poplawski states that the sediment would be deposited at the upstream end of the dam, significantly impacting on the active storage volume over time.

For the Burdekin Falls dam (1,860,000 ML), Lewis et al. showed that the trapping efficiency of suspended sediments is ~60 ± 10% and 95% for coarser sediment (> 30 ųm). However, the trapping efficiency of suspended sediment during low flows could be greater if the dam levels are low. Trapping efficiency was also strongly dependent on particle size with 100% of the sediment < 0.5 ųm (i.e. very fine clay) passing through the dam since it remains continuously in suspension. Overall, the residence times of suspended sediment in the dam are short due to the seasonal fill and spill, while the residence times of bed load sediment are indefinite due to effective trapping. It is expected that similar dam trapping efficiencies and patterns of deposition would apply at the potential dam sites in the Flinders and Gilbert catchments.

Table 1.2 Summary of the geology, landforms and drainage in the Flinders Catchment (Source: Twidale, 1966). The erosion and sediment supply potential of each region is indicated based on geology and landforms, along with the approximate distribution of each region within the catchment of each potential dam

	PHYSIOGRAPHIC REGION	GEOLOGY	LANDFORMS AND DRAINAGE	EROSION AND SEDIMENT SUPPLY POTENTIAL, AND DOMINANT GRAIN SIZE	DAM (APPROX% DISTRIBUTION)								
					Mt Oxley	White Mtns	Flinders 856	Glendower Dam	Mt Beckford	Porcupine Gorge	Alstonvale	Richmond	O'Connell Ck
Upper and Mid Flinders (to d/s Richmond)	Uplands and ranges of the divide (D8)	Strongly folded Palaeozoic rocks dominated by siltstone, greywacke and limestone, some weakly metamorphosed. Granite and basalt is common.	High plain with broad low interfluves dissected by deep structurally controlled v-shaped valleys.	High. Mixed grain size.	-	-	-	-	-	25	-	3	-
	Cape Upland (D14)	Igneous and metamorphic rocks of the Etheridge Complex comprising gneiss, granite and amphibolite. Strong structural trends.	Irregular erosional plain with parallel ridges and hills and low relief valleys. Higher density drainage in hills, low density in valley floors.	Moderate. Mixed grain size.	80	85	60	55	45	-	-	5	-
	Nulla Plateau (D11)	Sheets of olivine basalt flows, some weathered (similar to McBride plateau).	Undulating basalt surface, deeply dissected at the margins with drainage diversion.	Low. Fine sediment.	10	5	5	5	3	15	-	2	-
	Sturgeon Plateau (D13)	Siltstones and shales of the Cretaceous Rolling Downs Group, overlain by successive basalt lava flows (similar to McBride Province).	Dissected basalt plateau with radial drainage due to doming and drainage diversion. Deep valleys and gorges formed where incision has reached the softer underlying shales.	Mod-high. Fine sediment.	10	10	15	20	27	60	100	30	-
	Baronta Plateau (D15)	Cretaceous sandstones and shales overlain by sub-horizontal, laterized sandstones and conglomerates of the Glendower Formation in the west. Deeply weathered Late Tertiary olivine basalt occurs south of Glendower Homestead.	Very low relief plain forming the divide with few streams except at the margins where the plateau is dissected by deep valleys.	High. Considerable fine sediment.	-	-	20	20	20	-	-	5	-

	Gilberton Plateau (D3)	Continuous, sub-horizontal sandstones and siltstones (weathered & laterised) overlying near-vertical metasedimentary and igneous rocks. Many east-west faults and upwarping.	Narrowly dissected plateau, dominated by weathering. Few small streams, mainly with radial drainage controlled by warps. Deeply incised larger streams controlled by faults.	Moderate. Mixed grain size.	-	-	-	-	-	-	-	10	-
	Red Plateau (B4)	Sandstones and siltstones.	Narrowly dissected plateau with moderate drainage density forming deep gorges and mesas.	Moderate. Mixed grain size.	-	-	-	-	5	-	-	45	100

	PHYSIOGRAPHIC REGION	GEOLOGY	LANDFORMS AND DRAINAGE		DAM (APPROX DISTRIBUTION)					
					Black Fort	Cave Hill	Chinamans Ck	Corella Dam	Corella R	Cameron R
Cloncurry Area	Devoncourt Upland (C3)	Sub-horizontal, gently warped, sedimentary rocks dominated by limestone, and including sandstone, siltstone and silicified breccias.	Erosional plain with low hills and plateaux. Few surface streams where limestone. Radial drainage from mesas.	High. Mixed grain size.	25	15	-	-	-	-
	Burke Plain (C4)	Igneous and metamorphic rocks of the Cloncurry complex with mesas formed of Mesozoic siltstones with large iron concretions and Pre-Cambrian rocks.	Irregular erosion plain with low hills and ridges. Drainage is joint controlled.	Moderate. Mixed grain size.	30	20	-	-	-	-
	Isa Highlands (A)	Jurassic/Cretaceous conglomerate and arkose (laterized) forming mesas, overlying metamorphic and igneous rocks of the Cloncurry Complex comprising granite, quartzite, gneiss, schist, amphibolite, phyllite, limestone and shale.	Dissected plateau with strong structural control. Highly dissected areas are characterised by entrenched meanders and deep gorges through resistant rocks, small streams with high drainage density on granite and very low density drainage on resistant quartzite. Advanced dissected areas are characterised by larger streams.	Low. Mixed grain size.	45	60	30	100	100	80
	Cloncurry Plain (B1)	Igneous and metamorphic rocks of the Cloncurry Complex in the west. Cretaceous sandstones and conglomerates in the east.	Undulating plain with granite piedmonts and widely spaced streams in broad shallow valleys.	Low. Mixed grain size.	-	5	70	-	-	20

Table 1.3 Summary of the geology, landforms and drainage in the Gilbert Catchment (Source: Twidale, 1966). The erosion and sediment supply potential of each region is indicated based on geology and landforms, along with the approximate distribution of each region within the catchment of each potential dam

	PHYSIOGRAPHIC REGION	GEOLOGY	LANDFORMS AND DRAINAGE	EROSION AND SEDIMENT SUPPLY POTENTIAL, AND DOMINANT GRAIN SIZE	DAM (APPROX% DISTRIBUTION)						
					Bundock Ck	Copperfield R	Mt Adler	Mt Noble	Dagworth	North Head	Green Hills
Upper Einasleigh catchment (above Einasleigh)	Chudleigh Plateau (D12)	Palaeozoic igneous and metamorphic rocks with valley-filling basalt flows.	Some drainage impedance from basalts.	Low. Mostly fine sediment.	60	-	5	5	4	-	-
	Uplands and ranges of the divide (D8)	Strongly folded Palaeozoic rocks dominated by siltstone, greywacke and limestone, some weakly metamorphosed and laterized. Granite and basalts are common.	High plain with broad low interfluves dissected by deep structurally controlled v-shaped valleys.	High. Mixed grain size.	40	-	20	10	12.5	-	-
	McBride Plateau (D10)	Sheets of olivine basalt flows, some weathered.	Undulating basalt plains with radial drainage due to doming and drainage diversion due to basalt flows.	Low. Fine sediment.	-	-	5	10	12.5	-	-
	Einasleigh-Copperfield Plain (D7)	Valley-filling basalts, metamorphic and igneous rocks dominated by granite and amphibolite.	Undulating hills on granite and low hills, ridges and mesas formed of basalts, sandstones, siltstones and porphyry dykes. Low drainage density in shallow valleys until the basalt flows at Einasleigh where valleys become more gorge-like.	Moderate. Mixed grain size.	-	50	50	60	45	-	-
	Newcastle Range (D2)	Sub-horizontal sandstone and siltstone caps underlain by porphyry, granite and Pre-Cambrian strata of the Georgetown Massif. Strongly jointed, faulted and upwarped (similar to Gregory Range).	Dissected range with considerable outcrop of resistant porphyry forming a high erosion plain with bare, rounded slopes. N/NE elongate radial drainage due to strong structural control with falls and rapids at faults.	Low. Mixed grain size.	-	50	20	15	15	-	-
	Burdekin Upland (D9)	Flat-lying sandstones overlying sedimentary, igneous and metamorphic rocks.	Narrowly dissected, rolling sandstone plateaux, increasingly dissected at the margins and forming extensive plains with isolated ridges and hills where the sandstones have been removed.	Moderate. Mixed grain size.	-	-	-	-	3	-	-
Mid Einasleig	Georgetown Upland (D6)	Mostly granites with outliers of thin sub-horizontal sandstones and, metamorphic rocks such as amphibolite in the east (Einasleigh).	Rolling irregular high plain, separating the narrow v-shaped valleys of the Gilbert and Einasleigh Rivers. Strong structural control on stream direction.	High, Significant coarse sediment.	-	-	-	-	4	-	-

Upper Gilbert catchment (above Rockfields)	Red Plateau (D4)	Sandstones and siltstones.	Narrowly dissected plateau with moderate drainage density controlled by jointing forming deep gorges and mesas.	Moderate. Mixed grain size.	-	-	-	-	4	-	-
	Newcastle Range (D2)	Sub-horizontal sandstone and siltstone caps underlain by porphyry, granite and Pre-Cambrian strata of the Georgetown Massif. Strongly jointed, faulted and upwarped (similar to Gregory Range).	Dissected range with considerable outcrop of resistant porphyry forming a high erosion plain with bare, rounded slopes. N/NE elongate radial drainage due to strong structural control with falls and rapids at faults.	Low. Mixed grain size.	-	-	-	-	-	60	50
	Gilberton Plateau (D3)	Continuous, sub-horizontal sandstones and siltstones (weathered and laterized) overlying near-vertical metasedimentary and igneous rocks. Many east-west faults and upwarping.	Narrowly dissected plateau, dominated by weathering. Few small streams, mainly with radial drainage controlled by warps. Deeply incised larger streams controlled by faults.	Moderate. Mixed grain size.	-	-	-	-	-	20	10
	Gregory Range (D1)	Sub-horizontal sandstone and siltstone caps underlain by porphyry, granite and Pre-Cambrian strata of the Georgetown Massif. Strongly jointed, faulted and upwarped (similar to Newcastle Range).	Dissected range with considerable outcrop of resistant porphyry forming a high erosion plain with bare, rounded slopes. North/north-east elongate radial drainage due to strong structural control with falls and rapids at faults.	Low. Mixed grain size.	-	-	-	-	-	20	15
	Georgetown Upland (D6)	Mostly granites with outliers of thin sub-horizontal sandstones and, metamorphic rocks such as amphibolite in the east (Einasleigh).	Rolling irregular high plain, separating the narrow v-shaped valleys of the Gilbert and Einasleigh Rivers. Strong structural control on stream direction.	High. Significant coarse sediment.	-	-	-	-	-	-	15
	Gilbert Plain (D5)	Sub-horizontal sandstones overlying slate, phyllite and other metasedimentary rocks of the Georgetown massif. Intrusive quartz veins and porphyry outcrop.	Irregular, low relief plain with sparse stream channels. Higher density drainage in other areas e.g. sandstone mesas and low rugged hills. Considerable alluviation in the Gilbert River and tributaries due to porphyry rock bars, backponding and levee-damming of tributaries.	High, Mixed grain size.	-	-	-	-	-	-	10

Table 1.4 Description of the stream sediment characteristics at potential dam sites in the Flinders catchment based on field observations and published data/information

DAM SITE	CATCHMENT AREA (km^2)	SEDIMENT CHARACTERISTICS AND OTHER HYDROLOGICAL INFORMATION
Alstonvale	1,132	• Narrow valley with basalt capped ridges overlying mudstones. Small sand bed stream, 22 m wide, with adjacent floodplains. Occasional basalt gravels and other mixed lithologies exposed in the bed. • Volume of sand overlying gravels determined from a sediment probe investigation = 10.6 m^2
Black Fort	4,249	• Unknown
Cameron River	494	• Unknown
Cave Hill	5,264	• Reports of a previous seismic refraction survey revealed up to 15 m of alluvium and locally deeper (source unknown).
Chinamans Creek	166.5	• Small dam near Cloncurry. Channel upstream is sand-filled with localised areas of deposition similar to floodouts (transport-limited), probably reflecting the small catchment area and small discharge.
Corella Dam	334.5	• No mention of alluvium. Mostly bedrock outcrop visible in the channel upstream.
Corella River	642	• Unknown
Flinders 856	1,694	• Unknown
Glendower Dam	1,912	• Results from a previous study estimating sediment yields at this site (Poplawski, 1985): Estimated average sediment load = 177 kt a^{-1} and sediment volume = 134,847 m^3 a^{-1} (see Table 1.6 and Table 1.7). Proportion of wash to bedload is 54:46. For a 200,000 ML dam, the predicted infill rate is on average 0.067% (134.8 ML) per year or 2% (4045 ML) in 30 years or 6.8% (13,485 ML) in 100 years. • Sediment transport estimates: flows of > ~10 m s^{-1} are required to transport sand; > ~14 m s^{-1} for very coarse sand; > ~200 m s^{-1} for small pebbles and >> 850 m s^{-1} for large pebbles (see Table 1.8).
Mt Beckford	2,065	• Wide sand bed stream (~ 90 m), scoured to bedrock (mudstones) on the outside bend. Ridge and swale floodplain on inside. Alluvial gullies and active erosion of the mudstones. • Estimated area of sand in the channel is about 900 m^2 and depth is assumed to be about 8 to 12 m.
Mt Oxley	690	• Unknown
O'Connell Creek	1,508	• Small channel, 10 to 15 m wide, inset within a larger macro-channel, 40 to 50 m wide. No sandy bed load evident at the site. • No investigations of sediments. Assume that the thickness of alluvium is similar to Richmond Dam (~13 m).
Porcupine Gorge	1,051	• Wide (~100 m) channel filled with coarse sand and small gravels. Larger rounded gravels and boulders deposited on the bed and on a point bar ~3 m above the bed indicating high velocities. Finer sand and silt deposited on the adjacent floodplain. Unknown thickness of bed load – probably > 2 m (up to ~4 m). • In the catchment upstream there is no visible sediment in the bed and few gravels. The river is actively downcutting through the sedimentary rocks below the basalts.
Richmond	17,724	• Multi-channelled anabranching stream with small sand bars. • Relict higher gravel terrace between the Flinders R and O'Connell Creek and exposed limestone to the north of the site. • Five cores from the potential dam site revealed 10 to 13 m alluvium comprised of soft to hard clays, interbedded sands (at ~4 to 5 m) and sands (10 to 13m) overlying shale and mudstone (Maunsell McIntyre, 1999).
White Mountains	1085	• Unknown

Table 1.5 Description of the stream sediment characteristics at potential dam sites in the Gilbert catchment based on field observations and published data/information

DAM SITE	CATCHMENT AREA (km^2)	SEDIMENT CHARACTERISTICS AND OTHER HYDROLOGICAL INFORMATION
Bundock Creek	204.5	• Small (~25 m) creek, with bars of sandy gravel to maximum 20 mm diameter. A seismic refraction survey showed a unit comprised of saturated loose sand or gravel, consolidated alluvium or weathered granite up to 14 m deep, overlying bedrock (Irwin, 1999).
Copperfield River	1,244	• Channel ~50 to 100 m wide with alternating bedrock outcrop and sand and gravel bars upstream and downstream of the dam. • Reports of a 1980 to 1983 seismic survey that included trenching and boreholes, only found weathered bedrock (Source unknown).
Dagworth	15,351	• Extremely wide (up to 1000 m) sand-filled channel set within a relatively narrow floodplain. In-channel braiding and formation of vegetated islands reflecting seasonally high discharge and sediment loads.
Green Hills	8,310	• Wide (~215 m), continuous sand sheet with large bed forms comprising point bars and bank attached bars indicating active transport downstream. Small gravels also present. Bedrock outcropping at the channel margins acting as thalweg control. Vegetation only present at the margins. • Seismic survey showed 2 to 3 m of loose dry sand overlying 7 to 8 m of saturated sand and gravel (Irwin, 1999). • Drilling downstream at Rockfields (Benjamin, 1998) indicates that the bed load sediment yield is ~190 kt km^{-1}, assuming 1/16th of the sediment is mobile which equates to the upper ~25 cm of sediment at this site (see Table 1.10).
Mt Adler	8,641	• Bedrock constriction and bar formed downstream of basalt flows in the Einasleigh R. • High energy, sediment throughput zone with very efficient transport of sediment through the system, minor storage in small sand deposits at the channel margins and imbricated small pebbles to boulders in the channel bed. Sediment yield rates probably depend on catchment supply (i.e. supply-limited) and local bed slope.
Mt Noble	12,382	• Alternating steeper bedrock cascades and flatter sand accumulation zones. • Sediment accumulation zones are composed of coarse sands and gravels to ~20 cm diameter, and well rounded granite boulders with some other lithologies.
North Head	4,680	• Thin pockets of sand and gravel in the bed with exposed bedrock. • Seismic survey showed low and intermediate velocity layers > 12 m to ~20 m in the channel bed, possibly representing weathered metamorphosed basalt (Irwin, 1999).
Rockfields (downstream of Green Hills)	10,940	• Very wide (~400 m) sand-filled channel with vegetated islands and some bedrock outcrop in channel. Alluvial banks and floodplain on either site. Prominent sand-filled low flow and high flow channels. The largest floods were in 1974 and reached several meters about floodplain and 10's of meters above the low flow channel. • Drilling program at 8 locations upstream and downstream of Rockfields Bridge (Benjamin, 1998) showed that the total sediment stored in the 60 km reach is 98,192,483 m^3 (see Table 1.9, Table 1.10 and Table 1.11) and the bed load sediment yield is ~190 kt km^{-1}, assuming 1/16th or ~the upper 25 cm of sediment at this site is mobile.

Table 1.6 Estimated sediment loads for the Flinders River at Glendower based on suspended sediment sampling in 1983/84, development of rating curves and mathematical calculations of bed material load. (Source: Poplawski, 1985, Table 5-12)

	WASH LOAD (T)	BED MATERIAL LOAD (T)	TOTAL (T)
	Sediment < 0.25 mm (clay, silt and fine sand)	Sediment > 0.25 mm (medium sand and coarser)	
Dry year (1977/78)	320 (45%)	390 (55%)	710
Flood year (1973/74)	284,706 (54%)	243,840 (46%)	528,546
Average year	95,673 (54%)	81,541 (46%)	177,214

Table 1.7 Volume of sediment predicted to be trapped in Glendower dam, assuming a 95% trap efficiency of wash load and 100% TE of bed material (Source: Poplawski, 1985)

	WASH VOLUME (m^3 yr^{-1})	BED MATERIAL VOLUME (m^3 yr^{-1})	TOTAL VOLUME (m^3 yr^{-1})
Dry year (1977/78)	304	210	514
Flood year (1973/74)	270,471	131,450	401,921
Average year	90,889	43,957	134,847

Note: Poplawski uses specific weights of 1 t m^{-3} for the wash fraction and 1.855 t m^{-3} for bed material (calculated as the specific weight of quartz, 2.65 t m^{-3} adjusted to allow a void ratio of 30%).

Table 1.8 Hydrological and sediment transport characteristics for the Flinders River at Glendower (Source: Poplawski et al., 1989)

DISCHARGE (m^3 s^{-1})	MEAN VELOCITY (m s^{-1})	MEAN DEPTH (m)	WIDTH (m)	STREAM POWER (WATTS)[A]	UNIT STREAM POWER (W m^{-2})	CHANNEL BED SHEAR STRESS (N m^{-2})	SEDIMENT TRANSPORT[B]
14	0.64	0.35	63.31	127.0	2.006	3.135	Medium sand and finer
52	0.77	0.67	100.29	464.4	4.630	6.014	Very coarse sand and finer
117	0.99	1.16	102.12	1044.5	10.228	10.331	Very coarse sand and finer
214	1.26	1.61	105.38	1910.4	18.129	14.388	Small pebbles and finer
345	1.54	2.03	110.13	3079.8	27.966	18.159	Small pebbles and finer
488	1.75	2.46	113.49	4356.4	38.386	21.935	Small pebbles and finer
655	1.94	2.92	115.54	5847.3	50.608	26.087	Small pebbles and finer
850	2.15	3.37	117.32	7588.0	64.678	30.083	Small pebbles and finer

[a]Using a bed slope of 0.00091, from Poplawski et al. (1989).
[b]Based on critical shear stress values for bed load from Garde and Ranga Raju (2000).

Table 1.9 Drilling results from the Gilbert River upstream and downstream of Rockfields Bridge (AMTD 261 km to 321 km) (Source: Benjamin, 1998)

LOCATION	CHANNEL WIDTH (M)	AREA OF CLEAN SAND AND GRAVEL (M^2)	PARTICLE SIZE DISTRIBUTION: CLAY AND SILT: < 0.063 MM (%)	SAND: 0.063 – 2 MM (%)	GRAVEL: 2 – 37.5 MM (%)
Godfrey's	356.0	1431.9	0.07	77	23
Neem trees	480.9	1943.2	n/a	n/a	n/a
Road Bridge	328.0	1262.0	0.17	36	64
Rocky View	318.6	796.1	n/a	n/a	n/a
Forest Home	377.5	1492.9	0	28	72
Blancourt	413.6	1791.3	0.01	24	76
River View	470.3	2832.6	0.02	60	40
Prestwood	465.3	1542.4	n/a	n/a	n/a
Average	401.3	1636.5	0.054	45	55

Table 1.10 Estimated bed load sediment mobilisation in the Gilbert River at Rockfields based on the drilling results in Table 1.9. If 1/16th of the sediment is assumed to be active, this equates to the upper 25 cm of the bed surface. If 1/8th is assumed active (upper ~50 cm), estimates of the volume and sediment yield should be doubled

PARAMETER	VALUE
Total volume of bed load sediment stored in 60 km reach	98,192,438 m^3
Assume 1/16th is mobile	6,137,027 m^3
Volume of mobile bed load sediment per km	102,284 m^3 km^{-1}
Bed load sediment yield, assuming bulk density of 2.65 t m^{-3} adjusted for a void ratio of 30% = 1.855 t m^{-3}	189,736 t km^{-1}

Table 1.11 Calculations of the estimated total load at Rockfields based on Table 1.9 and Table 1.10, assuming a 54:46 wash load to bed load ratio, similar to Table 1.6

PARAMETER	VALUE
Volume of mobile bed load sediment per km	102,284 m^3 km^{-1}
Bed load sediment yield, assuming bulk density of 2.65 t m^{-3} adjusted for a void ratio of 30% = 1.855 t m^{-3}	189,736 t km^{-1}
Volume of wash load per km	120,073 m^3 km^{-1}
Wash load sediment yield assuming bulk density of 1 t m^{-3}	120,073 t km^{-1}
Total sediment load	309,809 t km^{-1}

Table 1.12 Estimates of sediment yields from catchments in northern Australia

CATCHMENT	RIVER	CATCHMENT AREA (km^2)	SEDIMENT YIELD ($t\ yr^{-1}$)	SEDIMENT COMPOSITION	DOMINANT SEDIMENT SOURCE	METHOD USED TO DETERMINE YIELD	SOURCE
Burdekin	Weany Creek	13.5	4,205	19% is fine, 81% is coarse	Gully erosion and remobilisation of channel bed sediment	Field measurements using flumes, erosion pins, cross-sectional changes and gauging data	Bartley *et al*., 2007
Mitchell (Queensland)	Mitchell River	63,000	2,900,000	Fine suspended sediment (< 63 μm)	Alluvial gully erosion	SedNet modelling combined with geochemical tracers, field load estimates and ANNEX modelling	Rustomji et al., 2010
	Rifle Ck @ Fonthill	365	8,000[a] / 5,000[b]		Hillslope erosion	Total suspended sediment measurements / SedNet modelling	
	McLeod R @ Mulligan Hwy	530	28,000[a] / 14,000[b]				
	Palmer R @ Goldfields	530	5,000[a] / 17,000[b]				
	Walsh R @ Flatrock	2,770	8,000[a] / 61,000[b]				
	Walsh R @ Rookwood	5,025	40,000[a] / 109,000[b]				
	Palmer R @ Drumduff	7,750	289,000[a] / 387,000[b]		Alluvial gully erosion		
	Walsh R @ Trimbles Crossing	9,040	168,000[a] / 436,000[b]				
	Mitchell R @ Gamboola	20,460	527,000[a] / 1,692,000[b]				
	Mitchell R @ Koolatah	46,050	2,079,000[a] / 2,814,000[b]				
	Mitchell River	71,360	>10,073,294	Suspended sediment and bed load	Alluvial gullying and channel bed turnover	Remote sensing and mapping	Brooks et al., 2008
Fitzroy (Queensland)	Sandy Creek	409	10,000[c]	Suspended sediment	Channel erosion, particularly gullying	Suspended sediment data and sediment rating curves	Hughes and Croke, 2011
	Theresa Creek	4,421	107,000[d]				

Daly	Daly River	47,500	503,000	Suspended sediment	Bank erosion (57%), hillslope erosion (23%) and gully erosion (20%)	SedNet and ANNEX modelling	Rustomji and Caitcheon, 2010
	Hayes (Fenton) Crk	20	1,200	Suspended sediment	Not specified	Total suspended sediment measurements	Robson et al., 2010
	Douglas R	830	22,000				
	Katherine R	8640	84,000		River bank		
	Lower Daly R	47,000	420,000				
	Lower Daly R	47,000	5,000,000	Suspended sediment	Not specified	Back-calculated from the area of deposition on the estuarine plains	Rustomji and Caitcheon 2010 (based on data in Chappell 1985)
	Daly River	52,500	16,800,000[e]	Suspended sediment	Alluvial gullying and channel widening	Previous estimates	Wasson et al., 2010
Ord (Western Australia)	Ord River u/s Lake Argyle	46,000	24,000,000	~ 80% is silt and clay and up to 37% sand	80 to 90% gully erosion and channel erosion, 10% sheet erosion	Mineral magnetics, isotopic ratios and ^{137}Cs of field samples	Wasson et al., 2002
East Aligator	Georgetown Ck2	4.8	85[f]				
	Georgetown Ck1	7.8	310[f]	50 to 65% is suspended sediment, 10 to 25% is solutes and ~25% is bed load			
	7J Creek	53.5	1558[f]		Slope wash	Sediment load calculations based on field sampling	Duggan, 1994
	Gulungak Creek	61.9	814[f]				
Sth Aligator	Koongarra Creek	15.4	391[f]				
Flinders	Flinders R @ Glendower	1,958	177,214	83% is suspended sediment; 17% is bed load	Not specified	Sediment load calculations based on field sampling	Poplawski et al., 1989; Poplawski, 1985

[a]Observed data
[b]Modelled data
[c]Calculated as the average of 4,000 t yr^{-1} (derived from an average of the suspended sediment data) and 16,000 t yr^{-1} (derived from sediment rating curves).
[d]Calculated as the average of 63,000 t yr^{-1} (derived from an average of the suspended sediment data) and 151,000 t yr^{-1} (derived from sediment rating curves).
[e]Calculated as the average of 11.2 to 22.4 Mt yr^{-1} as reported in Wasson et al. (2010)
[f]Calculated as the average of the annual data presented in Duggan (1994) including an extra 25% by volume for bed load

2 Estimates of sediment yields and rates of infilling in potential dams

2.1 Methods

The options for estimating catchment sediment yields are outlined in Table 1.1. The limited data on sediments and hydrology for those streams in the Flinders and Gilbert catchments where potential dam sites are being examined ruled out options 1 and 2 (i.e. field and desktop assessment; use of erosion rate equations such as USLE). Limited data also ruled out options for estimating channel and reservoir sediment loads. The known issues and limitations of using an unconstrained SedNet model to simulate sediment yields in rivers in northern Australia meant that option 4 was not preferred. The best option was to derive an empirical relationship between sediment yield and catchment area or discharge. That is, to use catchment area or mean annual discharge as the predictive variable of sediment yield.

Previous studies of sediment erosion and transport in catchments have shown that sediment yields tend to increase non-linearly with catchment area. For example, Wasson (1994) showed empirical relationships between sediment yield and catchment area for 12 regions across Australia including the monsoonal Northern Territory undisturbed ($y = 55x^{0.86}$), monsoonal Northern Territory moderately undisturbed ($y = 17x^{0.9}$) and the Ord River ($y = 96x^{1.12}$). It is recognised that fitting an empirical relationship to catchment area can be unsuitable for large catchments with extensive lowland floodplains or alluvial fans, since sediment yields and discharge can reach a maximum at the apex of deposition and then decline with distance downstream. However, all water storage options investigated in the Flinders and Gilbert catchments are located in the mid to upper reaches where there is more favourable topography for constructing large water storages.

A non-linear (power) function was fit to the sediment yield and catchment area data shown in Table 1.12 (Figure 2.1 and Figure 2.2). Discharge was not considered as an additional explanatory variable since few of the previous studies provided details on mean annual discharge. The function was fit to the data ensuring that the line passed through the Flinders River at Glendower datum, since this was from the study catchment. This meant excluding the data from the South and East Alligator Rivers, and the data from the tributaries in the Mitchell and Daly River catchments where they formed a strong downward leverage on the function. It was decided that this was a reasonable approach since the Alligator Rivers have very rocky catchments (quite different to the Gilbert and Flinders) and the sediment data from the Mitchell and Daly Rivers is of fine suspended sediment only, so the data are a significant under-prediction of the total yields in these tributary catchments. However, all data were used to calculate the uncertainty bounds. Based on these reasons, it was decided that the predicted sediment yields for the 22 potential dams were likely to be within the ball-park of true yields derived from the existing data and estimates of uncertainty.

The predicted yields for the 22 dams were also cross-checked with the information on catchment sediment supply potential (Table 1.2 and Table 1.3) and other information on sediment characteristics and hydrology from northern Australia and the Flinders and Gilbert catchments as outlined in Section 1.3. This was because there would be some variability in sediment yields between the sites based on geology, landforms and discharge. The cross-checking involved an assessment of whether the yields were likely to be an under-estimate, over-estimate or a reasonable estimate. For example, 100% of the catchments of Chinamans Creek, Corella Dam, Corella River and Cameron River dam sites drain geology with a low sediment supply potential, so the predicted sediment yields are likely to be a considerable over-estimation. Whereas, the catchments of Mt Beckford and Richmond dams have < 3% their area draining geology with a low sediment supply potential, 45 to 60% draining moderate supply potential and 38 to 47% draining moderate-high and high supply potential, suggesting that the predicted yields are probably an under-estimation.

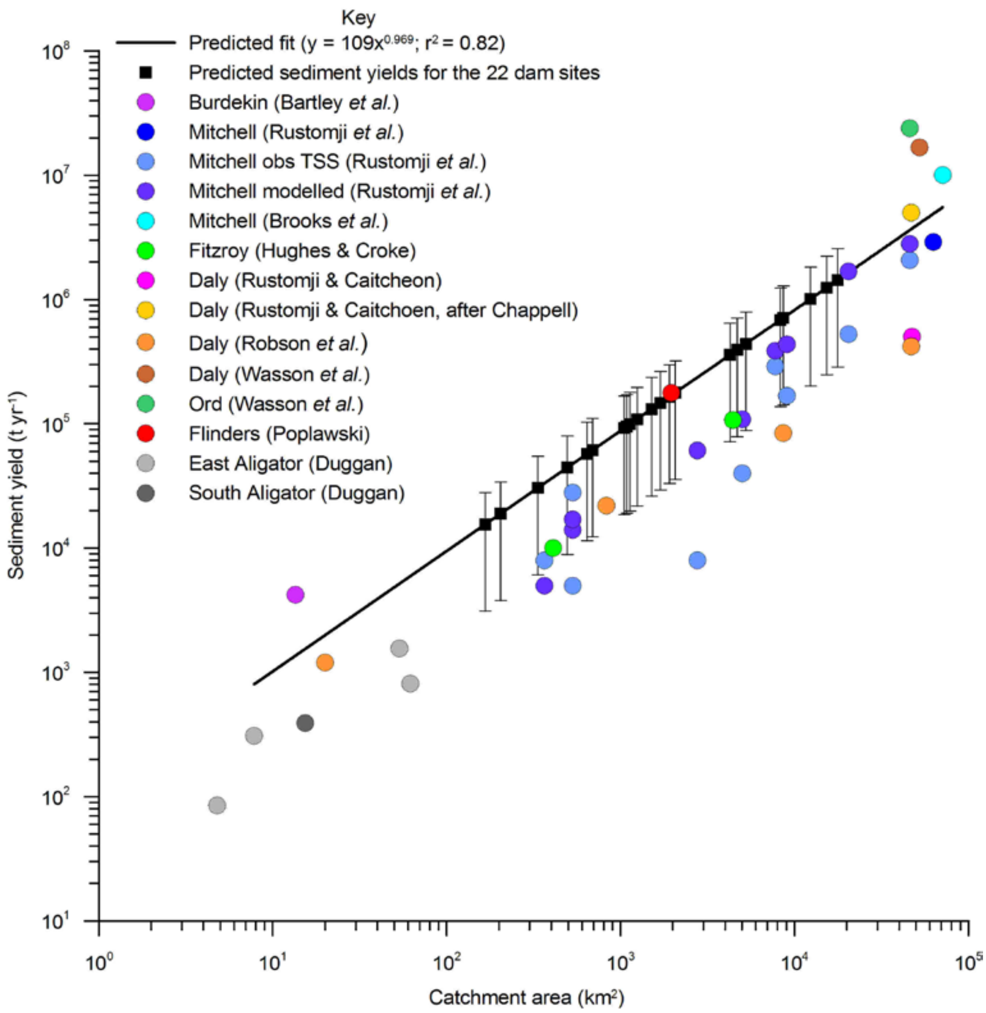

Figure 2.1 Sediment yield data from rivers in northern Australia and predicted sediment yields for the 22 potential dam sites. The average uncertainty of the predictions (± 79%) is shown by the error bars

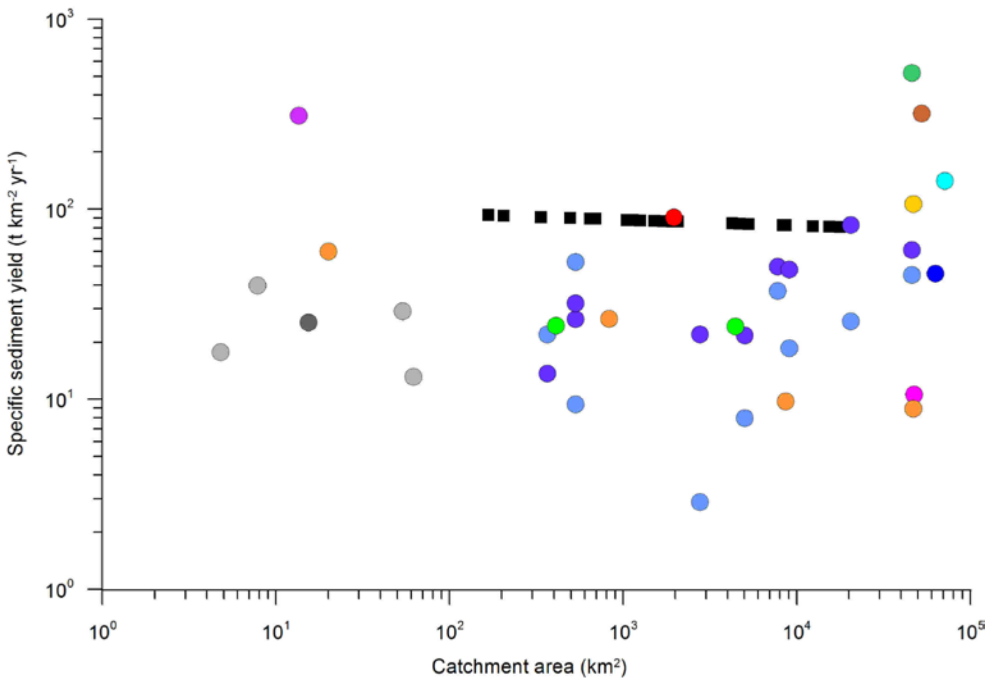

Figure 2.2 Data from Figure 2.1 expressed as specific sediment yields. The key is identical to Figure 2.1

To incorporate the effect of geology and sediment supply potential on sediment yields, the predicted yields were adjusted using the values indicated in Table 2.1. The uncertainty bounds (which were not adjusted) were used as a guide to indicate whether the adjustments were reasonable. The magnitude of the adjustments were determined using the existing sediment yield data and knowledge of the catchment sediment supply potential and other characteristics as the physical basis. However, as a precautionary principal it is thought that the adjusted sediment yields err on the side of being conservative.

The rates of sediment infilling for the potential dam sites were determined for 30, 100 and 1000 years using linear scaling. The number of years until 100% sedimentation were also determined to indicate the maximum life of each dam. Dam trapping efficiencies were based on the values given by Poplawski (1985) for Glendower Dam and Lewis et al. (2009; 2013) for the Burdekin Falls Dam. A 60% overall trap efficiency was considered the absolute minimum based on the Burdekin Falls Dam data, while a 100% overall trapping efficiency was considered the maximum based on the Glendower estimates. A trapping efficiency of 85 to 95% was considered most likely, allowing for variability between dams depending on the frequency of fill and spill. In the absence of exact estimates of sediment trapping for each dam, an average of 90% was adopted.

Calculations of the minimum (best case), maximum (worst case) and expected rates for the dams were made using the following:

- Expected - adjusted sediment yield with a 90% dam trapping efficiency.
- Best case - minimum predicted sediment yield with a 60% dam trapping efficiency.
- Worst case - maximum predicted sediment yield with a 100% dam trapping efficiency.

Some additional calculations were undertaken for the O'Connell Creek Dam, which is planned to operate as an off-stream storage for the Flinders River near Richmond. The proposal is to divert, on average, around 20% of flow per annum from the Flinders River into the dam. To account for the additional sediments that would also be diverted, 20% of the predicted and adjusted yields calculated for the Richmond Dam were added to the yields calculated for the O'Connell Creek Dam.

Table 2.1 Adjustments made to the predicted sediment yields on the basis of expert judgement

CATCHMENT SEDIMENT SUPPLY POTENTIAL	EXPERT JUDGEMENT (BASED ON GEOLOGY, SEDIMENT SUPPLY AND OTHER CATCHMENT CHARACTERISTICS)	ADJUSTMENTS APPLIED TO THE PREDICTED SEDIMENT YIELDS DERIVED FROM THE POWER FUNCTION
Low	Considerable over-estimate	-40%
Mostly low, with some% mod or high	Over-estimate	-25%
Mostly moderate, and/or small% of low	Slight-over estimate	-10%
Moderate, and/or small% of low and high	Reasonable	0
Mostly moderate, with small% of high	Slight under-estimate	+10%
Moderate to high	Under-estimate	+25%
High	Considerable under-estimate	+40%

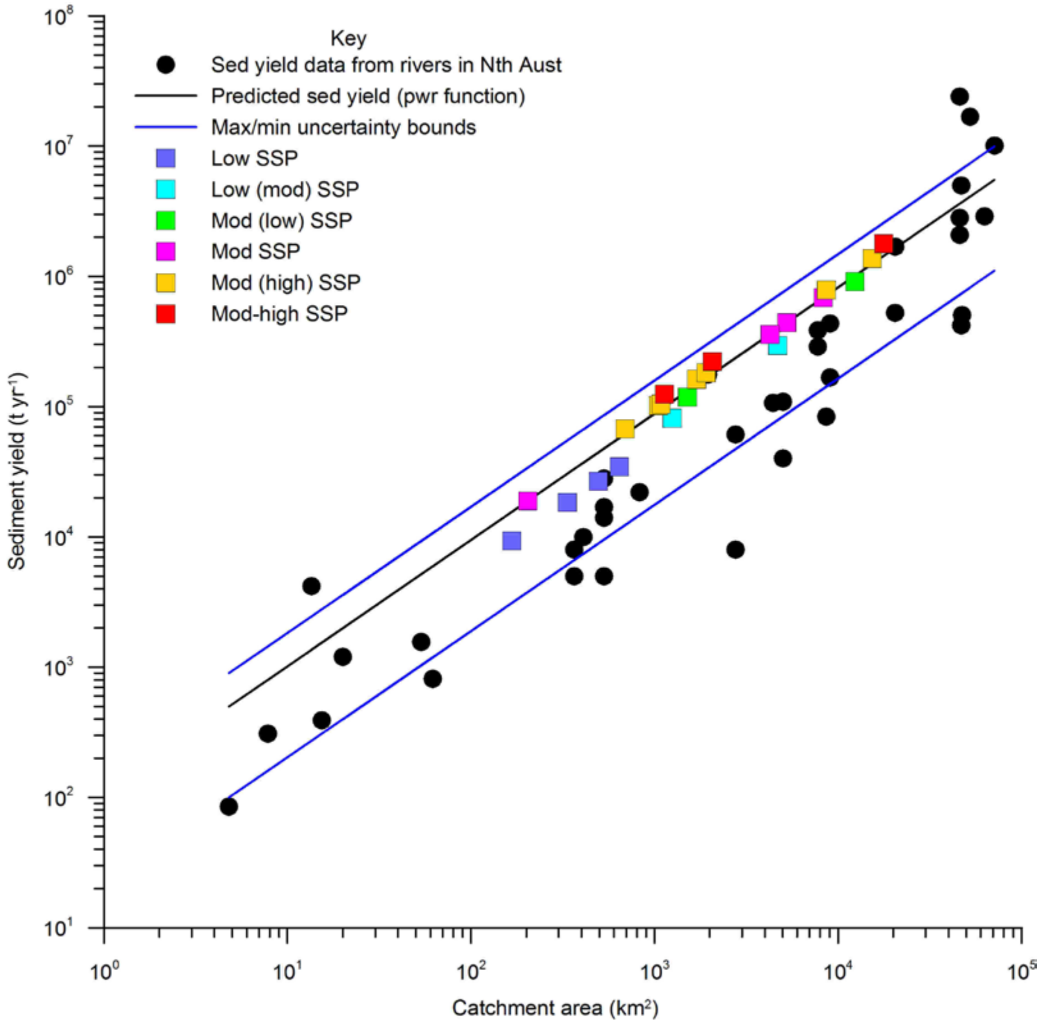

Figure 2.3 Adjusted sediment yields for the 22 potential dam sites, based on the assessment of sediment supply potential and whether predicted sediment yields were an over- or under-estimate (see Table 2.1) .

2.2 Results

The results for the 22 potential dam sites in the Flinders and Gilbert catchments are shown in Table 2.2 and Table 2.3, respectively, and Figure 2.4 to Figure 2.7. Using the infilling rates over 30 years as an example, the dams with the fastest rates of infilling based on the expected rates are Mt Adler (50%) and Mt Noble (17%) in the Gilbert catchment and, Richmond (17%) and Black Fort (16%) in the Flinders catchment. These are followed by O'Connell Creek (with diversion), Chinamans Creek, Porcupine Gorge, Copperfield River and Green Hills dams (~6% in 30 years), then Dagworth, North Head, Flinders 856, Cave Hill and Mt Oxley dams (2 to 5% in 30 years). The remaining 8 dams are predicted to infill < 2% in 30 years.

Under the worst case (maximum) yield scenario, Mt Alder dam could reach 90% sedimentation after 30 years, while Mt Noble, Black Fort and Richmond dams could have filled to around 38%, 32% and 28%, respectively. Chinamans Creek, Copperfield River, O'Connell Creek (with diversion), Green Hills, Porcupine Gorge and North Head dams are estimated to have 12 to 22% sedimentation, with the remainder of dams infilled < 10% after 30 years. On average, under the worst case scenario, infilling rates are calculated to be more than double the expected rates. There is variability between the dams, with Corella Dam potentially infilling at more than triple the expected rate under the worst case, whereas at the lower end of the scale, Mt Beckford is calculated to infill at just over 1.5 times the expected rate under worst case.

Under the best case (minimum) yield scenario, Mt Adler dam is predicted to infill 6.3% after 30 years, Mt Noble, Black Fort and Richmond dams are predicted to infill by 2 to 3%, while the majority of the remaining dams are predicted to infill < 1% after 30 years. On average, under the best case scenario, infilling rates are calculated to be around 1/5th or 19% of the expected rates, with similar variability between dams as described above for the worst case.

Similar trends apply to the infilling rates calculated over 100 and 1000 years. Eighty-two percent of the potential dams are expected to have between 1% and 24% sediment infilling after 100 years and between 9% and 100% sediment infilling after 1000 years. Mt Adler, Mt Noble, Black Fort and Richmond dams are expected to infill much more rapidly, with Mt Adler predicted to have completely filled within 100 years and the other three dams infilled > 50% over the same period. More than half of the dams are predicted to be at or close to 100% infilling after 1000 years and another 4 dams are predicted to have between 50% and 70% of their storage filled with sediment. The expected median time to complete infilling is estimated at around 780 years. Under the worst case, the median time is around 375 years and under the best case, the median time is around 5300 years.

The range between the best case (minimum) and worst case (maximum) values shown in Figure 2.4 to Figure 2.7 demonstrate that there is a large uncertainty in the infilling estimates and expected life of the dams, which extends over approximately an order of magnitude for all of the dam sites. However, the expected rates are considered to be reasonable estimates, set within the context of a large uncertainty. These uncertainties arise from assumptions in the method used to estimate sediment yields and the limited number of existing yield estimates available to derive the estimates. To better constrain the estimated values and uncertainty bounds, site specific studies of sediment yields would be required.

In addition to sediment yield, the rates of sediment infilling are very strongly linked to the potential dam capacity. For example, when analysed on the basis of the sediment yield per km^2 of catchment area, Mt Adler dam is mid-range at 90.8 t km^{-2} yr^{-1} but the potential dam capacity is very small relative to the size of the catchment, 3.5 ML km^{-2} (Table 2-3). A similar explanation applies to Chinamans Creek which has one of the lowest sediment yields at 55.9 t km^{-2} yr^{-1} but has the fifth smallest dam capacity relative to catchment size (Table 2-2). The opposite applies to the Cameron River dam which is predicted to have the lowest rate of infill due to a low sediment yield of 54.1 t km^{-2} yr^{-1} and a high capacity dam of 385.4 ML km^{-2}.

Clearly, there is strong relationship between the capacity of the dams and the infilling rates. Small dams with a large catchment area and large sediment yield will infill much more rapidly than large dams with a small catchment area and small sediment yield, because in the former the dam is under-fit relative to the size of the catchment and sediment yield. These trends are very evident from the results computed for the 22 potential dams. Dams that will rapidly infill have a small capacity relatively to catchment area-sediment yield. Whereas a dam site with a relatively high sediment yield will not infill quicker than others if the volume of the potential dam is also high.

Table 2.2 Predicted and adjusted sediment yields for potential dam sites in the Flinders catchment

DAM SITE	FSL DAM CAPACITY (ML)	CAPACITY TO CATCH. AREA (ML KM^{-2})	PREDICTED SEDIMENT YIELD (T YR^{-1})	PREDICTED SEDIMENT VOLUME (M^3)[A]	CATCHMENT SEDIMENT SUPPLY POTENTIAL BASED ON Table 1.2	ASSESSMENT OF UNDER- OR OVER-ESTIMATION BASED ON SEDIMENT SUPPLY POTENTIAL AND OTHER INFO	ADJUSTED SEDIMENT YIELD (T YR^{-1})	ADJUSTED SPECIFIC SEDIMENT YIELD (T KM^{-2} YR^{-1})	ADJUSTED SEDIMENT VOLUME (M^3)[A]
Alstonvale	240,770	212.7	99,476	71,396	100% mod-high	Under-est	124,345	109.8	89,245
Black Fort	42,901	10.1	358,529	257,323	45% low, 30% mod, 25% high	Reasonable	358,529	84.4	257,323
Cameron R	190,411	385.4	44,530	31,960	100% low	Consid over-est	26,718	54.1	19,176
Cave Hill	248,067	47.1	441,263	316,703	65% low, 20% mod, 15% high	Probably ok	441,263	83.8	316,703
Chinamans Ck	2,750	16.5	15,518	11,138	100% low	Consid over-est	9,311	55.9	6,683
Corella Dam	20,476	61.2	30,516	21,902	100% low	Consid over-est	18,309	54.7	13,141
Corella R	100,674	156.8	57,408	41,203	100% low	Consid over-est	34,445	53.7	24,722
Flinders 856	88,934	52.5	147,032	105,528	5% low, 60% mod, 15% mod-high 20% high	Slight under-est	161,735	95.5	116,081
Glendower Dam	308,713	161.5	165,338	118,666	5% low, 55% mod, 20% mod-high, 20% high	Slight under-est	181,871	95.1	130,533
Mt Beckford	245,237	118.8	178,147	127,860	3% low, 45% mod, 27% mod-high, 20% high	Under-est	222,683	107.8	159,824
Mt Oxley	62,268	90.2	61,563	44,185	10% low, 80% mod, 10% mod-high	Slight under-est	67,720	98.1	48,604
O'Connell Ck	127,499	84.5	131,356	94,277	100% mod	Slight over-est	118,220	78.4	84,849
O’Connell Ck (with Flinders R diversion)	127,499	-	417,633[b]	299,744[b]	-	-	476,067[b]	-	341,683[b]
Porcupine Gorge	30,691	29.2	92,569	66,439	15% low, 60% mod-high, 25% high	Slight under-est	101,826	96.9	73,082
Richmond	200,089	11.3	1,431,385	1,027,335	2% low, 60% mod, 30% mod-high, 8% high	Under-est	1,789,232	100.9	1,284,168
White Mtns	110,504	101.8	95,470	68,521	5% low, 85% mod, 10% mod-high	Slight under-est	105,017	96.8	75,373

[a]Using a weighted bulk density of 1.3933 t m^3, calculated based on the bulk densities shown in Table 1.11 and a wash load:bed load ratio of 54:46.
[b]Calculated using the predicted and adjusted yields for O’Connell Creek, plus 20% of the predicted and adjusted yields determined for Richmond dam.

Table 2.3 Predicted and adjusted sediment yields for potential dam sites in the Gilbert catchment

DAM SITE	FSL DAM CAPACITY (ML)	CAPACITY TO CATCH. AREA (ML KM^{-2})	PREDICTED SEDIMENT YIELD (T YR^{-1})	PREDICTED SEDIMENT VOLUME $(M^3)^A$	CATCHMENT SEDIMENT SUPPLY POTENTIAL BASED ON Table 1.3	ASSESSMENT OF UNDER- OR OVER-ESTIMATION BASED ON SEDIMENT SUPPLY POTENTIAL AND OTHER INFO	ADJUSTED SEDIMENT YIELD (T YR^{-1})	ADJUSTED SPECIFIC SEDIMENT YIELD (T KM^{-2} YR^{-1})	ADJUSTED SEDIMENT VOLUME $(M^3)^A$
Bundock Ck	29,961	146.5	18,940	13,594	60% low; 40% high	Reasonable	18,940	92.6	13,594
Copperfield R	25,000	20.1	109,002	78,233	50% low, 50% mod	Over-estimate	81,752	65.7	58,675
Dagworth	498,187	32.5	1,245,225	893,724	31.5% low, 52% mod, 16.5% high	Slight under-est	1,369,748	89.2	983,096
Green Hills	227,197	27.3	686,902	493,004	65% low, 10% mod, 25% high	Reasonable	686,902	82.7	493,004
Mt Adler	30,533	3.5	713,407	512,027	30% low; 50% mod, 20% high	Slight under-est	784,747	90.8	563,229
Mt Noble	103,326	8.3	1,011,118	725,700	30% low, 60% mod, 10% high	Slight over-est	910,006	73.5	653,130
North Head	136,252	29.1	393,727	282,586	80% low, 20% high	Over-estimate	295,295	63.1	211,939

[a]Using a weighted bulk density of 1.3933 t m3, calculated based on the bulk densities shown in Table 1.11 and a wash load:bed load ratio of 54:46.

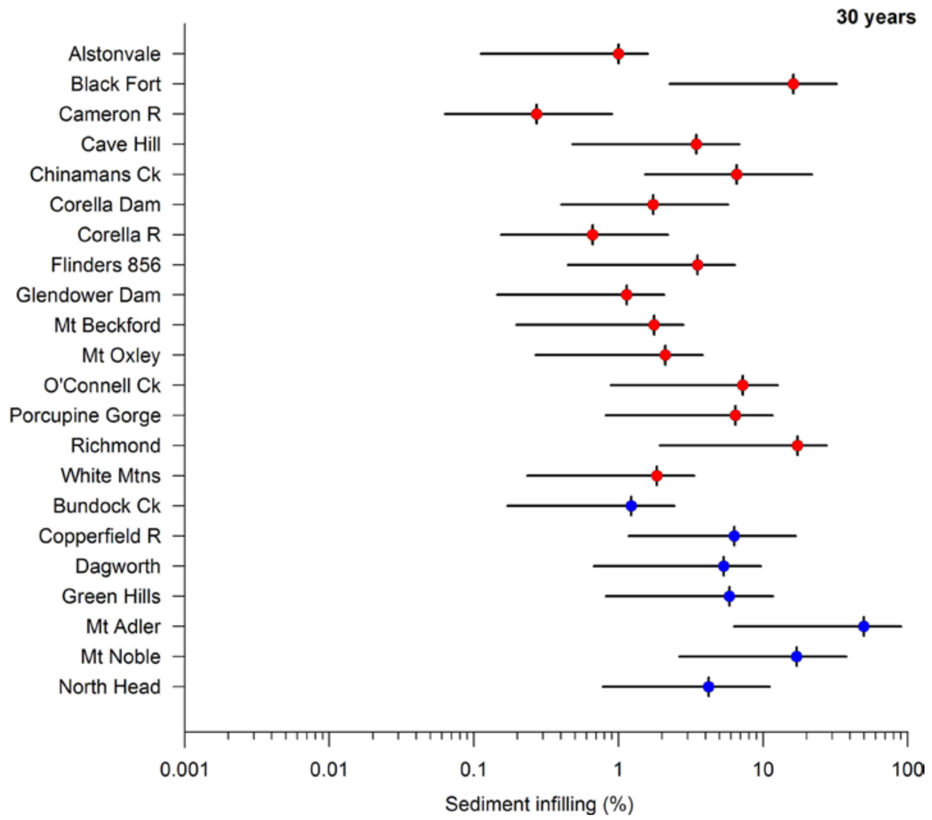

Figure 2.4 Rates of sediment filling after 30 years for each of the potential dams examined in the Flinders (red) and Gilbert (blue) catchments

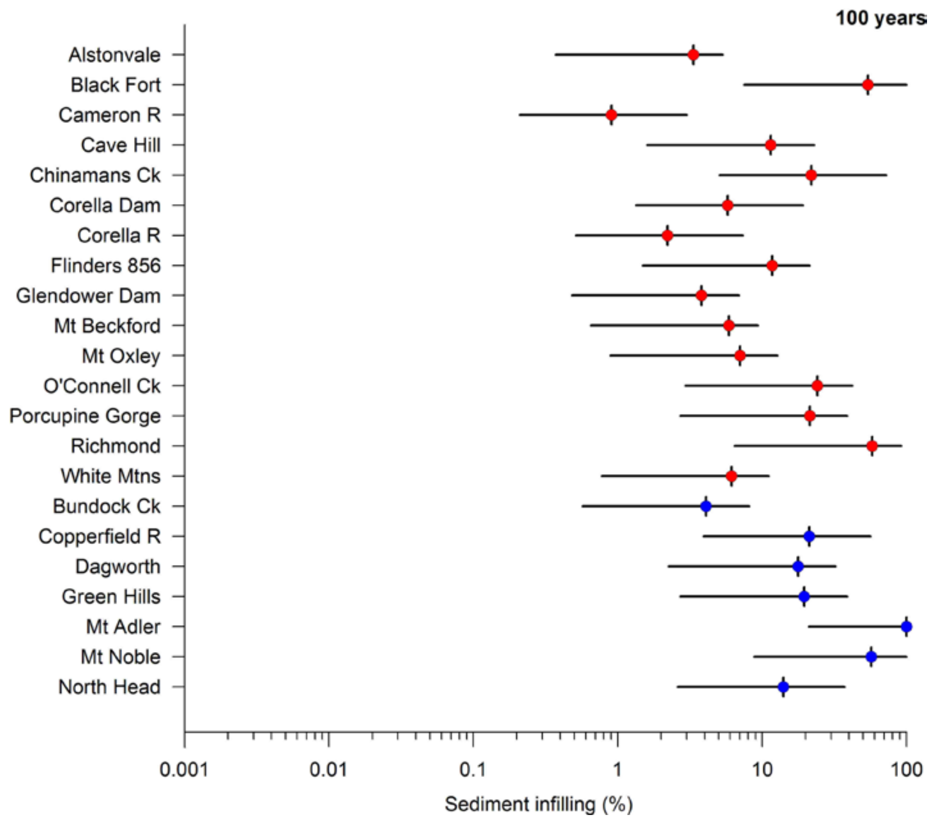

Figure 2.5 Rates of sediment filling after 100 years for each of the potential dams examined in the Flinders (red) and Gilbert (blue) catchments

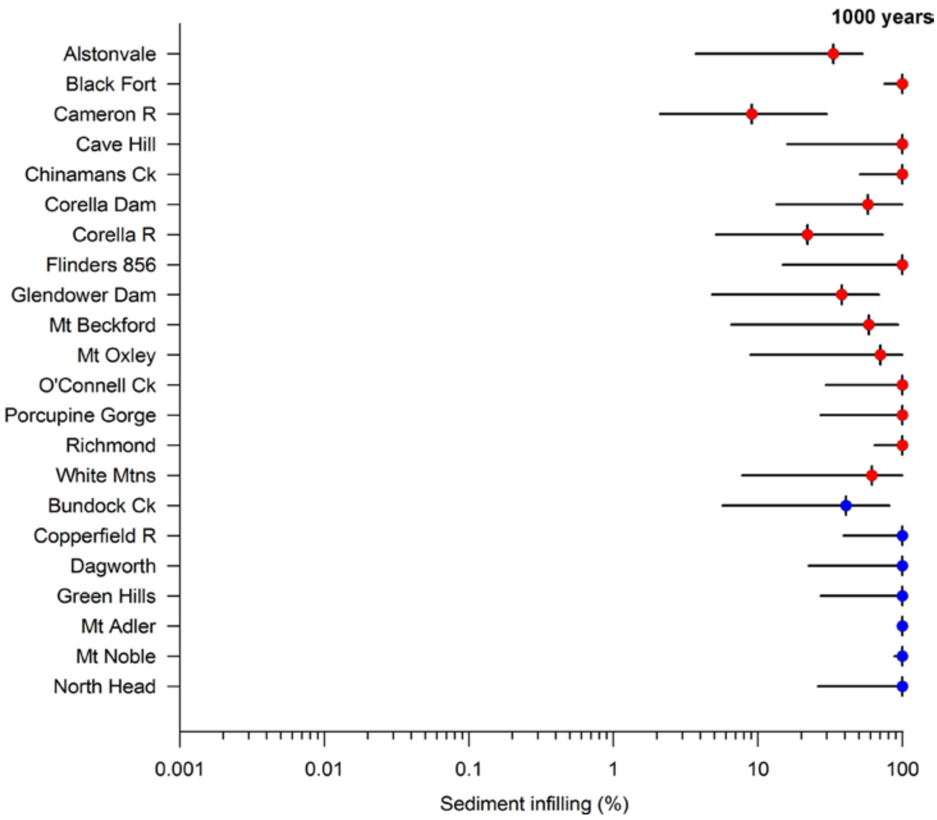

Figure 2.6 Rates of sediment filling after 1000 years for each of the potential dams examined in the Flinders (red) and Gilbert (blue) catchments

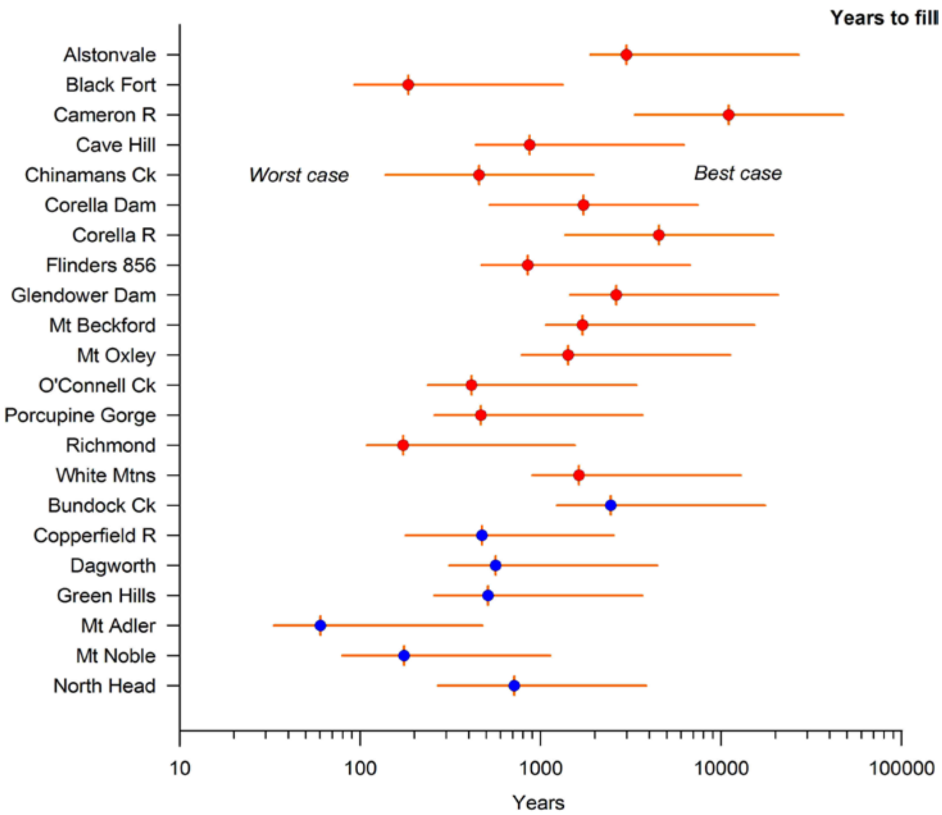

Figure 2.7 Number of years to fill each of the potential dams examined in the Flinders (red) and Gilbert (blue) catchments

3 Summary comments

The estimated sediment infilling rates for the dams in the Flinders and Gilbert catchments are considered to be reasonable estimates based on the limited existing data, previous literature, field observations and expert judgement. However, there are many assumptions in the analysis and a large uncertainty in the predicted sediment yields. Based on this, there is a good argument for the need to verify the predicted and adjusted sediment yields through field measurement studies at each site. Sediment modelling could also be used to provide a comparison of the results.

The sediment yield estimates presented here represent long-term average yields applicable on the order of decades. However, in any given year, the sediment yields could be substantially higher-than-average, or lower-than-average, due to annual variability in the broad scale climate drivers that govern rainfall and runoff, such as ENSO (El Niño-Southern Oscillation). For example, Poplawski (1985) showed that the sediment yield in the Flinders River in a dry year could be < 1% of the average, and up to 300% of the average yield in a wet year (Table 1.6). While Kuhnert et al. (2012) showed that the annual sediment yields in the Burdekin catchment can vary by four orders of magnitude and the 10-year average yields can vary by greater than a factor of two.

The frequency-magnitude of extreme events is also of major significance for the estimated sediment infilling rates. In this study a linear scaling approach was used to estimate the average infilling rates over these longer periods. Extreme events can have the capacity to transport considerable volumes of sediment, which could significantly impact on the storage capacity of a dam regardless of the time since construction. Any further investigations should consider the variability in sediment yields on annual and longer timescales by considering intra- or inter-decadal changes in sediment supply and hydrology driven by variability in climate and other land use factors.

The future impacts of global climate change on sediment generation and transport should also be considered in any further work. Climate change predictions and the impacts on hydrology are reasonably well modelled and understood, but what is not clear is whether sediment yields will change systematically with climate and hydrology due to other factors such as thresholds and feedbacks. It is likely that sediment yields will tend to increase with increasing rainfall erosivity (e.g. storminess) and increasing discharge (e.g. large-extreme floods). It is almost certain that the predicted climates will increase the variability of yields, and hence the uncertainty of the mean sediment yield estimation. The impacts of this increase should be factored into the longer-term predictions of sediment infilling in the potential dams. Sediment modelling could be a useful tool to achieve this.

This study has not considered a number of other impacts of sediments on dams, or impacts resulting from dams. These include the downstream impacts of sediment starvation in channels such as bed and bank erosion. This is likely to be extremely important in many of the rivers investigated here, especially those adjusted to relatively high sediment loads in the upper Flinders catchment and upper Gilbert catchment. It is also likely to be extremely important in dams that have a very high sediment trapping efficiency and a high frequency of spill and fill. In natural channels some of the flow energy is expended in transporting sediment. If those sediments are effectively removed from the system through trapping, downstream flows will have a much greater erosive force than pre-dam flows of a similar size. The severest impacts would occur during large floods when the dams are spilling.

The pattern of sedimentation in dams is also important in terms of how sediments impact on the active storage of each dam, as well as the likelihood of back flooding. In this study, the pattern of sedimentation was not factored into the infilling rates, but it may be very significant in some dams depending on the percentage of time a dam is maintained at full storage level, the number of tributaries and the shape of the reservoir. For example, the pattern of sedimentation is likely to be significant for the potential Richmond dam where the backwater limit is estimated to be close to the Richmond township. Further investigations should address sedimentation patterns in the potential dams.

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