Earth-Science Reviews 236 (2023) 104288

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

A chronological database assessing the late Quaternary palaeoenvironmental record from fluvial sediments in southwestern Africa

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ARTICLE INFO

Keywords:
Fluvial sediments
Dryland
Quaternary
Chronology
Palaeoenvironmental change
Database
Southern Africa

ABSTRACT

Fluvial sediments preserve evidence of past hydroclimatic regimes and are important but potentially under-utilised indicators of palaeoenvironmental change in drylands. This paper presents a new chronological database of 603 ages from late Quaternary fluvial sediments at 70 sites in southern Africa's western dryland regions. This synthesis assesses the spatial and temporal trends in both the palaeoenvironmental record and the supporting data that underpins these interpretations. We find that topographic and climatic characteristics of river catchments influence the nature of fluvial archive formation and preservation. Channel confinement, legacies of research, and sampling strategies in specific river basins are found to control the sedimentary context and length of documented record available for palaeoenvironmental reconstruction. The age of dated deposits and associated magnitude of chronological uncertainties influence the temporal range and resolution of climate and fluvial variability that can be discerned. Where calendar year uncertainties are small enough, predominantly dating to the last millennium, individual flood *events* and multi-year *episodes* within flash flood deposits can be linked to synoptic climate patterns, yet when uncertainties are larger, interpretations are restricted to understanding multidecadal to centennial-scale *phases* of flow regimes.

This paper collates a scattered literature to detail the current state of southwestern Africa's fluvial record and highlights opportunities for future research. We consider controls on fluvial archive interpretation that are pertinent to wider dryland contexts and argue that fluvial records provide useful information for inclusion in regional palaeoenvironmental syntheses. Following a filtering process, quality-assessed chronologies are compiled to establish the combined fluvial history of 22 rivers to consider the response of fluvial systems to hydroclimatic drivers. At the Last Glacial Maximum (LGM; 24–18 ka), records detail a regionally consistent signal of intermittent to perennial flow under relatively humid conditions in what are currently ephemeral systems. The mid Holocene (MH; 8-4 ka) is also characterised by the occurrence of sustained river flow and higher discharge events than present, but with greater spatial variability. Sedimentary archives display evidence of both intermittent flow and extreme flood events within ephemeral regimes, and two rivers, the Hoanib and Molopo, are characterised by reduced fluvial activity. Within the last millennium, flash flood regimes within an arid to hyper-arid climate were established with coherence in the timing of flood frequency variations recorded between catchments.

1. Introduction

Drylands can support extensive fluvial systems (Jacobson et al., 1995; Nanson et al., 2002; Tooth, 2000; Tooth and Nanson, 2011; Tooth, 2013). While some are perennial, such as the Orange River in South Africa, the flow of many dryland rivers today is intermittent or ephemeral (Messager et al., 2021). Fluvial sedimentary archives attest to the response of rivers to past hydroclimatic regimes (Bull, 1991; Reid, 1994): in drylands these may display evidence of greater fluvial activity or even perennial flow in rivers that are currently ephemeral. Water is a powerful erosive agent (Wainwright and Bracken, 2011) and plays a key role in shaping the geomorphological landscape (Grenfell and Grenfell, 2021; Reid and Frostick, 1997; Tooth and Nanson, 2011; Tooth, 2013). Processes of sediment transfer propagate signals of hydrological

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https://doi.org/10.1016/j.earscirev.2022.104288
Received 16 June 2022; Received in revised form 6 December 2022; Accepted 8 December 2022

response to climate conditions (Tofelde et al., 2021) and these signals are ultimately recorded in sediment stores (Allen, 2017; Caracciolo, 2020; Romans et al., 2016).

Geomorphological records are extensive across drylands and are important for understanding late Quaternary terrestrial environmental response to climate dynamics (Fitzsimmons et al., 2013; Nanson et al., 1995; Stone, 2021; Thomas, 2013; Thomas and Burrough, 2012; Woor et al., 2022). Sedimentary landform archives, or *geoproxies* (cf. Thomas, 2013), are relied on for assessing paleoenvironmental conditions in locations that have few alternative long-term palaeoproxy records. Low levels of precipitation and poor organic preservation have often limited the formation and preservation of high-resolution geochemical or botanical proxies (Chase and Meadows, 2007; Thomas, 2013). In the relatively dry western and central parts of southern Africa, lake and speleothem records are commonly discontinuous (e.g. Brook et al., 1999; Hipondoka et al., 2014) or located in regions fed by large catchments draining the tropics (e.g. palaeolake Makgadikgadi; Burrough et al., 2009), and elemental and dendrochronological records are scarce (Humphries, 2021). Evidence of terrestrial environmental response to palaeoclimate change is also preserved in marine (e.g. Farmer et al., 2005) and hyrax midden (Chase et al., 2012) archives, yet the potential to extrapolate findings to southern Africa is limited by respective challenges of correlating large, often unknown, areas of the terrestrial system to interpretations of marine sediments (Scott et al., 2012), or the restricted distribution of suitable midden sites (Humphries, 2021).

Spanning important latitudinal and longitudinal gradients, data generated from southern African fluvial deposits are now substantial (Dollar, 1998; Grenfell and Grenfell, 2021; Stone and Thomas, 2013; Tooth, 2016). The potential for these archives to address questions of past hydroclimates is particularly important for western and central southern Africa. The dryland centre and west of the subcontinent encompasses the desert areas of the Namib (Goudie and Viles, 2015) and Kalahari (Shaw and Goudie, 2002; Thomas and Shaw, 1991) and has a long-standing history of focus within palaeoclimate and palaeoenvironmental literature (e.g. Burrough and Thomas, 2013; Chase et al., 2019; Collins et al., 2014; Heine, 1982; Stone, 2021; Thomas and Shaw, 2002; van Zinderen Bakker, 1984). The palaeoclimate history, however, has been difficult to interpret and controversies exist regarding the relative importance of temperate and tropical climate systems on Quaternary timescales and the nature and magnitude of precipitation changes (Chase et al., 2019; Chase and Meadows, 2007; Gasse et al., 2008; Singarayer and Burrough, 2015). Fluvial systems commence within or flow through these desert regions and provide evidence for assessing temporal and spatial patterns of palaeoenvironmental change, such as changes in seasonality and demarcating past extents of summer and winter-dominated rainfall zones (e.g. Lyons et al., 2014).

Topographically, southern Africa's setting has generated a diversity of fluvial styles (Tooth, 2016), from high gradient rivers draining Namibia's coast-parallel Escarpment zone towards the sea (Jacobson et al., 1995), to internally draining endoreic rivers in the Kalahari basin (McCarthy and Ellery, 1998). To assess both the combined fluvial history available from research into these systems, and the controls on sedimentary archive formation and preservation in the region's range of fluvial contexts, a synthesis of records is required. Robust reconstruction of palaeoenvironmental change from sedimentary archives is dependent on both the accuracy and precision of chronology and the proxies used to reach palaeoenvironmental interpretations, but quality-assurance processes are rarely undertaken. With a large chronological dataset, data quality assessments can be performed to obtain a subset of the most robust ages (Small et al., 2017; Woor et al., 2022). A quality-assured chronology allows for an assessment of the 'real' timing and direction of geomorphological change, reducing potential heterogeneity introduced through chronological uncertainty, and enabling correlation with other proxy records. A regional analysis also enables an assessment of the spatial trends in the sources of evidence used and the impact this has on the type of information that can be retrieved from fluvial deposits. Convergence of datasets from different archives also allow for meaningful paleoenvironmental synthesis at the regional scale. Chronological databases now exist for other geomorphological features in southern Africa, including aeolian dunes (Lancaster et al., 2016; Thomas and Burrough, 2016) and lakes (De Cort et al., 2021), but not yet for fluvial archives.

The aim of this paper is first to create a new chronological database of late Quaternary fluvial records from the relatively dry western and central regions of southern Africa, hereafter referred to as southwestern Africa (south of 17°S and west of 26°E; Fig. 1). This compilation encompasses records from 22 rivers (70 sites, 603 ages) spanning from 132 ka to present. Following this, this paper then aims to: i) establish a river typology in terms of climatic setting and hydrological parameters; ii) assess the nature and controls on documented fluvial histories; iii) evaluate associated palaeoenvironmental evidence using an assessment of data quality; and iv) reconstruct the direction and amplitude of hydrological change during the late Quaternary.

1.1. *Dryland rivers and fluvial palaeoenvironmental archives*

Intermittent and ephemeral rivers comprise ~60% of global rivers by length (Messager et al., 2021). In drylands, rivers that periodically cease to flow are prevalent. In hot and dry to extremely hot and arid environments (following the bioclimate map of Metzger et al., 2013), 62 to 98% of river network lengths are prone to flow cessation (Messager et al., 2021). There is increasing recognition that river systems exist across a continuum of hydrological conditions (Knighton and Nanson, 1997; Tooth and Nanson, 2011) and a range of fluvial types occur as a response (Larkin et al., 2020), yet non-perennial rivers have commonly been overlooked (Acuña et al., 2014; Messager et al., 2021; Sullivan et al., 2020) and the dynamics of hydrological activity in dryland ephemeral rivers are poorly understood (Reid and Frostick, 2011).

Drylands host both exogenous perennial fluvial systems sourced in humid regions and non-perennial endogenous intermittent and ephemeral rivers fed by rainfall within the dryland itself and/or by variable groundwater contributions (Busch et al., 2020; Tooth and Nanson, 2011). Ephemeral hydrological activity in particular is characterised by flashy discharge with steep rising hydrographs (Busch et al., 2020; Reid and Frostick, 1987). Intense runoff events are short lived and interrupt extended periods of relative channel stability where river flow is limited (Tooth and Nanson, 2011). Rainfall in drylands is frequently associated with spatially discrete convective cells (Diskin and Lane, 1972; Sharon, 1974). Reaching high rainfall intensities, the infiltration and storage capacities of typically thin, poorly developed, or near-absent soils can rapidly be overwhelmed (Liu et al., 2004; Mavimbela and van Rensburg, 2017), and surface runoff occurs predominantly through Hortonian overland flow (Tooth, 2000). Overland flow is further amplified through the development of surface duricrusts and biological soil crusts (Belnap, 2006). Intermittent river flow typically occurs on timescales longer than individual rainfall events and flow can be sustained by connection to groundwater (Busch et al., 2020). Together with variable transmission losses (Lange, 2005) and variable surface vegetation cover (Reid and Frostick, 2011), dryland river flow has the potential to erode and mobilise substantial amounts of sediment as bedload (Alnedeij and Diplas, 2005; Rust and Nanson, 1989; Wainwright and Bracken, 2011) and as suspended load (Jacobson et al., 2000; Reid and Frostick, 1987).

In response to climate perturbations, fluvial systems experience geomorphological change and evidence of which is recorded in sedimentary archives (Macklin et al., 2012) on scales of individual *events* to multiyear *episodes* to multidecadal- to centennial-scale *phases* (Toonen et al., 2017). Across drylands globally, a range of fluvial sedimentary contexts have been studied as records of Quaternary palaeoenvironmental change. These include the formation of slackwater deposits (SWDs) from extreme floods (e.g. Greenbaum et al., 2000; Haberlah et al., 2010; Kale et al., 2000), overbank floodplain deposits (e.

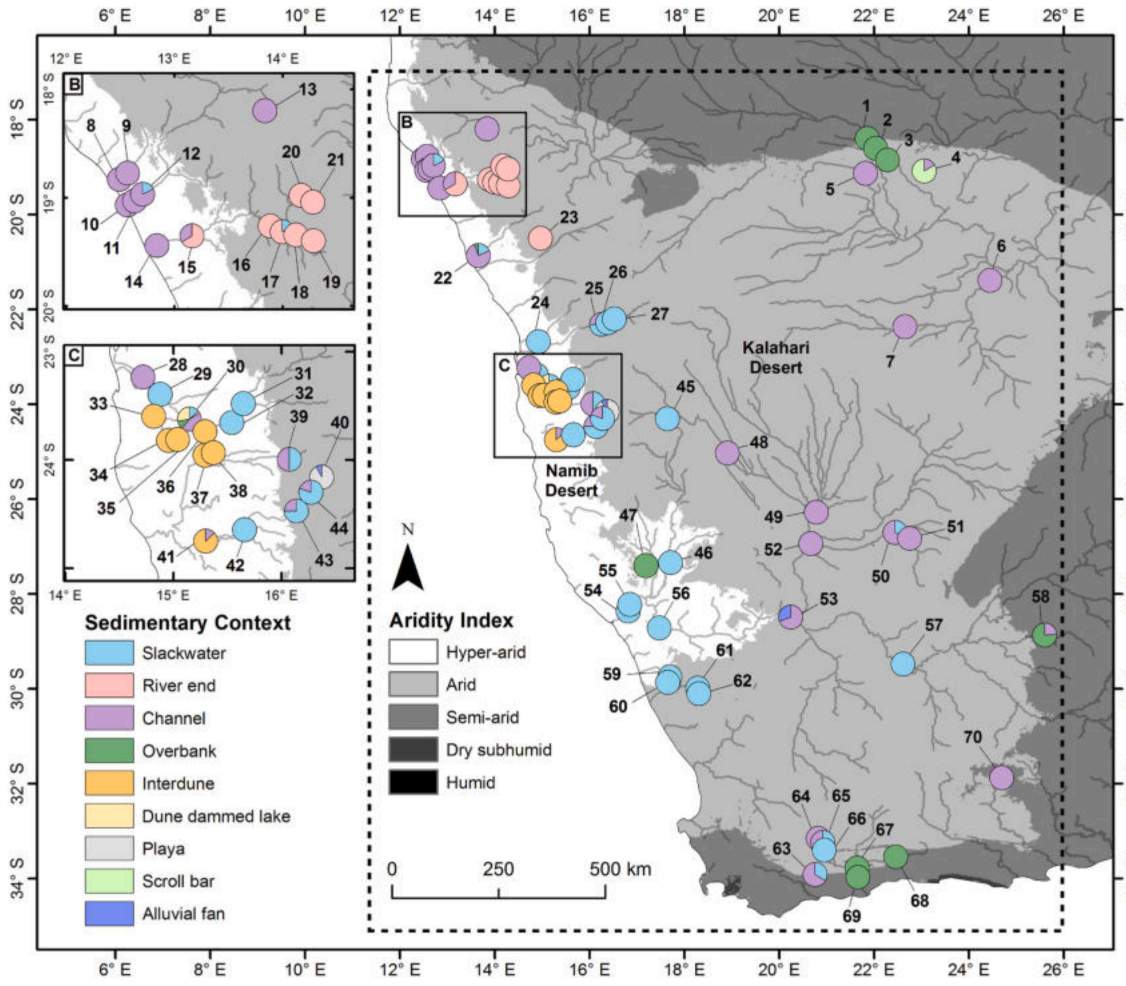

Fig. 1. All sites in the fluvial chronological database coloured by sedimentary context. Pie charts represent the proportion of ages in each site of each sedimentary context. Black dotted box demarcates the boundary used in this study to define southwestern Africa and to determine inclusion of records. Contemporary aridity index (AI; Trabucco and Zomer, 2022) is defined by mean annual precipitation over mean annual evapotranspiration (P/PET) (UNEP, 1992). Drylands are defined by an AI of <0.65. Site numbers refer to Table S1, Supplementary Material.

g. Damm and Hagedorn, 2010; Williams et al., 2006), and interdune playa environments formed by settling of fine sediment in still water settings (e.g. Brook et al., 2006; Kocurek et al., 2020; Stanistreet and Stollhofen, 2002). In fluvial deposits, environmental signals can be derived from changes in sediment volume, character, and composition (Tofelde et al., 2021). First, this can include analysis of terrace height and distribution (e.g. Stokes et al., 2017), flow frequency (Benito et al., 2020), and meander dimensions (e.g. Hesse et al., 2018; Tooth et al., 2022). Second, sediment character can include the analysis of textural (e.g. Stone et al., 2010) and architectural facies elements (e.g. Miall, 2006; Srivastava et al., 2006). Third, analysis of sediment composition can assess mineralogical changes, such as for provenance analysis (e.g. Ramisch et al., 2017; Walsh et al., 2022), or components reflective of environmental conditions (e.g. Faust et al., 2004; Nash et al., 2006). Reconstructing fluvial regimes and associated climatic change from sedimentology and geomorphology, however, can be challenging for several reasons. Information passes through a set of filtering processes from climatic signal to interpretation of geomorphological archives (see Bailey and Thomas, 2014). Partial preservation of fluvial records can occur where environmental signals are modified through processes of sediment transport (Jerolmack and Paola, 2010), yet Macklin et al. (2012; 2022) argue that important palaeoenvironmental information can still be retrieved from these records.

1.2. *Regional setting*

This research focuses on the driest regions of southern Africa, principally the landmass south of approximately 17°S (Humphries, 2021; Knight and Fitchett, 2021; Stone, 2021; Thomas, 2019) and to the west of 26°E (Fig. 1). Within this study area, the Namib Desert occupies the coastal plain of Namibia spanning to ~32°S at the Olifants River (Western Cape, South Africa) and the Kalahari encompasses the continental interior covered by Kalahari Group sediments spanning to ~29°S at the Orange River (Stone, 2021) (Fig. 1).

Southern Africa's climate is broadly characterised by a north-east to west rainfall gradient from humid to hyper-arid. The east coast receives precipitation from the warm Indian Ocean (Crétat et al., 2012; Wang and Ding, 2008), diminishing in influence with increasing distance westwards. Aridity in the west is further enhanced by the South Atlantic Anticyclone and stabilisation of airmasses above the cold surface waters associated with the Benguela current, which blocks incursions of moisture (Nicholson, 2000; Reason, 2017; Tyson and Preston-Whyte, 2000). Across the majority of southern Africa, the seasonal cycle of rainfall maxima mirrors the migration of low-level convergence of the tropical rainbelt (Nicholson, 2018). At the southern edge of the rainbelt, precipitation is governed by the Congo Air Boundary (CAB) (Howard and Washington, 2019; Taljaard, 1972; Torrance, 1979). During the austral summer, localised convective systems bring incursions of rainfall to the southwestern coast of southern Africa as a result of intensification of the

Angola Low (Hermes and Reason, 2009). When coupled with mid-latitude waves, tropical-temperate troughs bring additional seasonal rainfall (Hart et al., 2010; Macron et al., 2014). Mid-latitude circumpolar westerlies bring rainfall in the winter months to the southwestern Cape of South Africa (Reason et al., 2002) and contribute to year-round rainfall along the southern coast.

The geological setting of southern Africa primarily comprises the Congo, Kaapvaal, Zimbabwe Cratons, and the Damara Belt (Jacobs et al., 2008; Miller, 2008). Since the break-up of Gondwana, uplift and river incision has resulted in the delineation of bedrock confined river courses in southern Africa (Tooth and Nanson, 2011). Trending north-south throughout Namibia and the west coast in South Africa, the Great Escarpment demarcates the central elevated interior of the continent and the low relief regions at the coast (Fig. S1, Supplementary Material). These coast-parallel ranges host many fluvial systems draining upland areas (Jacobson et al., 1995). In the interior of southern Africa, the Kalahari Group sediments represent infilling of the central basin since the Cretaceous (Garzanti et al., 2022; Haddon and McCarthy, 2005; Schulter, 2008). The Okavango Delta drains into the interior depression associated with the East African Rift system (McCarthy and Ellery, 1998). Today, southern Africa hosts large scale perennial exogenous rivers, such as the Orange and Okavango, but is dominated by non-perennial intermittent rivers and ephemeral streams (de Wit and Stankiewicz, 2006; Messager et al., 2021).

2. The database

2.1. Data selection

To be included in the database, fluvial studies had to meet the following set of criteria: 1) the source publication is peer-reviewed; 2) chronological data are presented (radiocarbon or luminescence ages); 3) sites fall within southwestern Africa, as defined by Fig. 1 (longitude and latitude data available or estimated from published maps); and 4) dated material was deposited via fluvial processes. Palaeosols developed on fluvial deposits are included if dating provides an estimate of original sediment deposition of the host material, not the age of palaeosol development. For any site where ages are included in several papers (for example in a review following original publication), the original publication was treated as the reference point. This was considered appropriate in order to acknowledge the primary work and to follow the intention and interpretation of the research underpinning the source publications. The full database is available in the Supplementary Material.

2.2. Database structure and content

The database contains information on: 1) publication details; 2) site and river details (including location and sedimentary context); 3) sample details; 4) chronology (chronologies and meta-data); 5) interpretation (fluvial, climate, and independent proxies used); and 6) data quality assessments. Details of these categories are provided below (Fig. 2) and in the Supplementary Material.

2.2.1. Regions

The river systems of southwestern Africa were divided into four regions based on catchment characteristics and the classification of river types by Tooth and Nanson (2011) and Tooth (2016) (Fig. 3A): 1) Namib, the rivers flowing towards the Atlantic Ocean from the coast-parallel Great Escarpment in Namibia and north-western South Africa; 2) Northern Kalahari, the rivers within the Okavango Basin draining internally to the Kalahari; 3) Orange, the rivers associated with the Orange catchment; and 4) Eastern Cape, the rivers flowing from the Great Escarpment to the south coast of South Africa.

To analyse the fluvial and climatic setting of these regions, the database has been populated with information on the characteristics of sites and river catchments (see Supplementary Material for full description of the methods for calculating these data). This includes data on: i) elevation (ALOS Global Digital Surface Model AW3D30; JAXA); ii) rainfall (WorldClim 2.0; Fick and Hijmans, 2017); iii) aridity index (Trabucco and Zomer, 2022; aridity zones, described following the UNEP (1992) definition); iv) probability of contemporary flow intermittence (0: perennial, 1: non-perennial; Messager et al., 2021; see Supplementary Material for a note on data quality in this region); and v) underlying geology (Garzanti et al., 2022; Fig. S1, Supplementary Material). Through investigation of site context using Google Earth, rivers styles at sites were classified according to channel confinement (setting: confined, partly confined, unconfined) and river sinuosity (pattern:

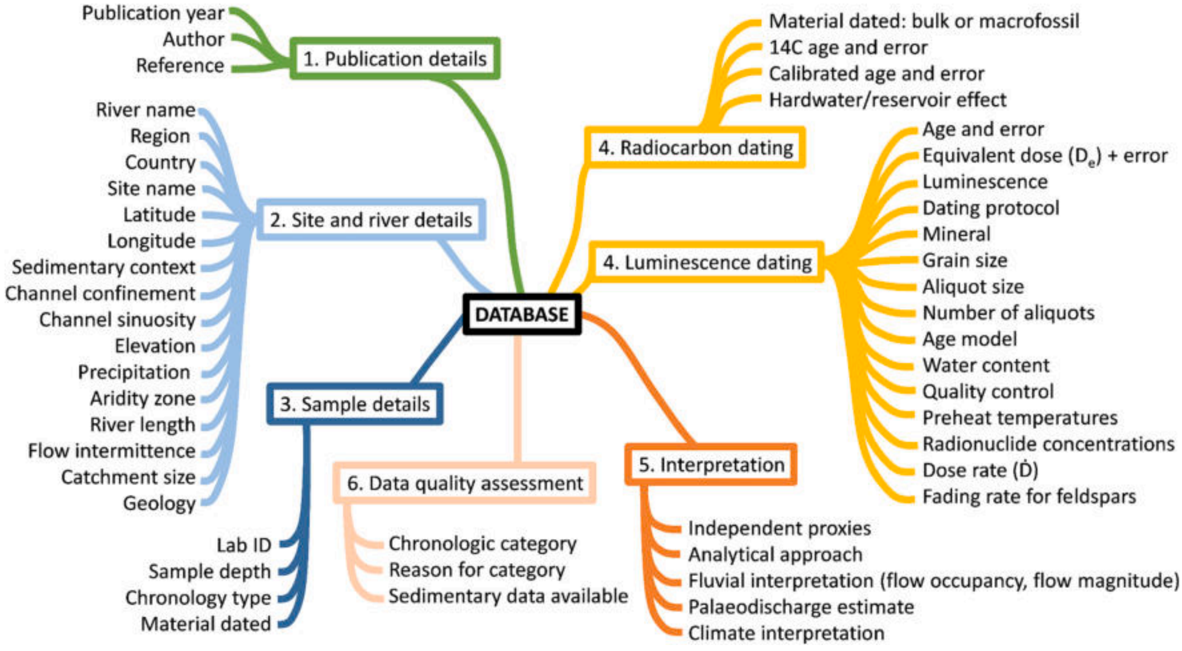

Fig. 2. Overview of the content of the Quaternary chronological fluvial database. See Supplementary Material for full detail on these categories.

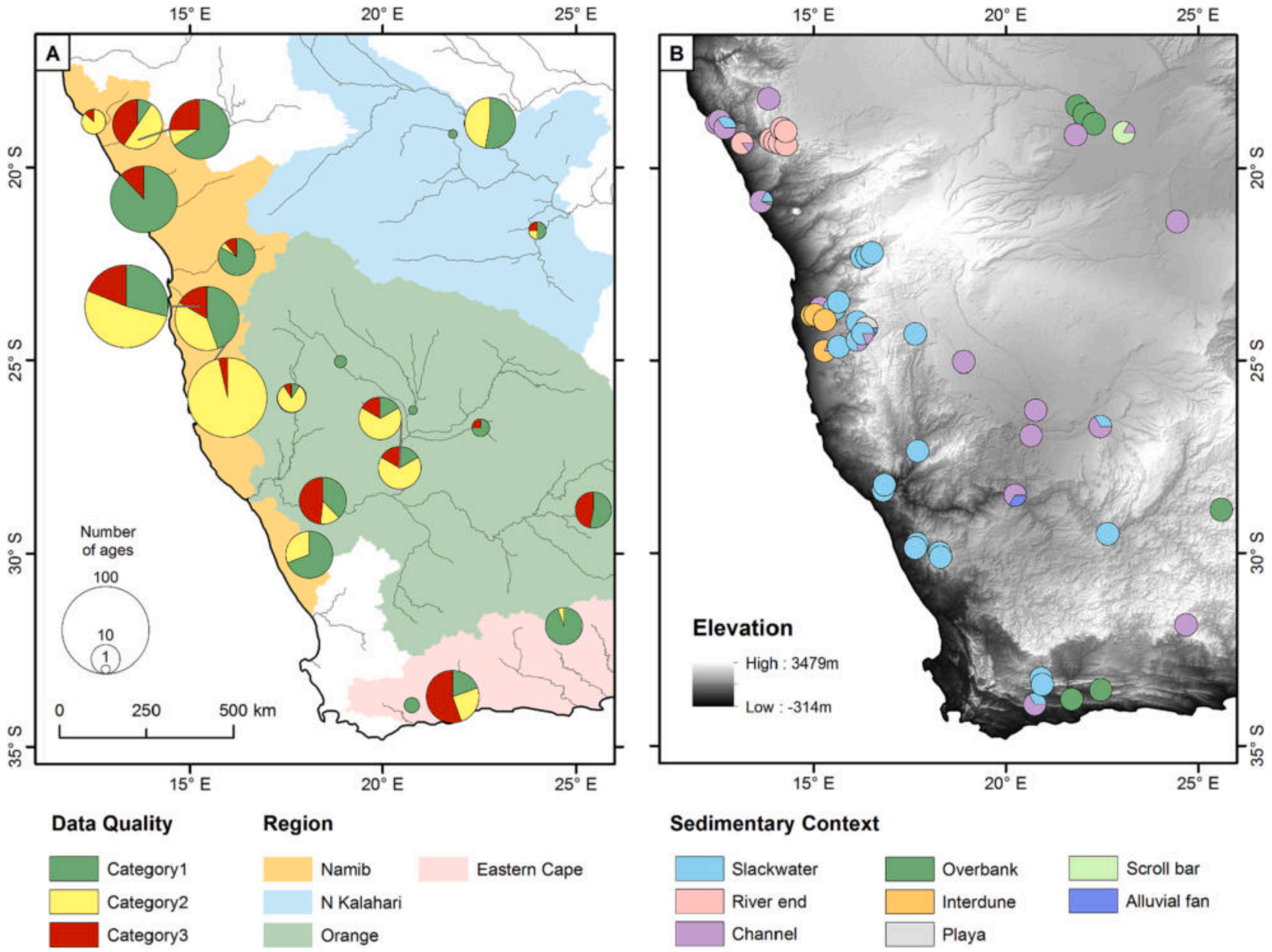

Fig. 3. Spatial distribution of fluvial sites in the database. A) Regions of interest and overview of data quality (see Section 2.3 for detailed description). Pie charts show percentage of ages grouped by river catchment in Category 1 (most robust), Category 2, Category 3 (least robust), with the size of each chart proportional to the number of ages from each catchment. B) Sedimentary context by individual site of all records that have passed the data quality filtering process (note that no ages from the sedimentary context 'dune dammed lake' passed these criteria). Pie charts represent the proportion of ages in each site of each sedimentary context.

straight (sinuosity index <1.05), sinuous (1.05–1.5), meandering (> 1.5) through calculation of reach scale channel sinuosity) following Fryirs et al. (2016), Grenfell et al. (2019), and Grenfell and Grenfell (2021). River catchments were mapped using the HydroSHEDS dataset (Lehner and Grill, 2013), and channel length, catchment size, relief (difference between highest and lowest point in the catchment), gradient (difference in elevation between the start and end of the main channel divided by the main channel length), average channel sinuosity (main channel length by the straight distance between start and end), and drainage density (total length of channels by catchment size) were calculated for each river catchment.

2.2.2. *Sedimentary context*

Interpretation of palaeoenvironmental change from fluvial geoproxies requires detailed description of the context under which sediments were deposited. Here, sedimentary contexts were differentiated into categories (Table 1).

2.2.3. *Fluvial interpretation*

To aid clarification and comparability between interpretations reached in each source publication, reporting of the nature of past river flow has been differentiated into detail on flow occupancy and on flow magnitude (Table 2). When describing flow occupancy, a wide range of terms have been used within the fluvial literature (e.g. epithets 'arid', 'discontinuous', 'episodic', and 'seasonal' are used for rivers that cease to flow for some period of time, Busch et al., 2020). To account for this, we follow Busch et al. (2020) in the use of terms 'intermittent' and 'ephemeral' for non-perennial rivers. This distinction maps onto the flow occupancy scale from Tooth and Nanson (2011) and is used by Messager et al. (2021) to define the prevalence of non-perennial river systems globally. Categories of flow magnitude were reached through assessment of the terminology used within southern African literature (Table 2).

2.2.4. *Chronologies*

Geochronological control of fluvial change in southern Africa has been established through luminescence (e.g. Srivastava et al., 2006; Tooth et al., 2022; Walsh et al., 2022), radiocarbon (e.g. Hurkamp et al., 2011; Nash et al., 2006; Vogel, 1989), uranium-thorium (e.g. Selby et al., 1979), palaeomagnetism (e.g. Brink et al., 2012), and cosmogenic nuclide burial dating (e.g. Erlanger et al., 2012; Matmon et al., 2015). The latter two have been used mainly to study fluvial processes predating the late Quaternary and have not been included in this database. Assessment of chronological data quality in this paper (Section 2.3) has focused on luminescence and radiocarbon chronologies, as these are the most widely used, and the scarcity of uranium-thorium ages make it difficult to make a holistic assessment.

A range of calibration curves have been used for radiocarbon

Table 1
Key characteristics of the sedimentary contexts recorded in the chronological database. Within a standardised framework, this classification aimed to follow the wording used in original source publications as closely as possible.

Sedimentary context	Description and key characteristics
Slackwater (SWD)	Unconsolidated sands and silts that accumulate rapidly from suspension during major palaeofloods (e.g. Cloete et al., 2018; Greenbaum et al., 2014). SWDs are commonly found in backflooded tributaries in confined bedrock reaches (Baker, 1987; Heine and Völkel, 2009; Kochel and Baker, 1982). The height of these deposits reflect the peak stage of a flood event and can be used to estimate palaeodischarge (Baker, 2008; Benito et al., 2020; Frances, 2004; Jarrett and England, 2002).
Channel	Within-channel sediment aggradation in valley fills can preserve evidence of confined channel infill facies and unconfined sheet flood deposits (e.g. Srivastava et al., 2004; Walsh et al., 2022). Incision can form fluvial terraces marking previous higher-elevation channel aggradation (e.g. Ramisch et al., 2017; Völkel et al., 2021). Channel networks that are currently inactive can preserve the location of past hydrological flow as palaeochannel infills (e.g. Tooth et al., 2022).
Scroll bar	Depositional point bar ridge features associated with channel margins. Scroll bars are indicative of lateral meander migration (e.g. Tooth et al., 2022).
Overbank	Deposition from suspension load in the overbank floodplain area (e.g. Damm and Hagedorn, 2010; Nash et al., 1997, 2006; Srivastava et al., 2006). Overbank deposits accrete vertically and can display laminated to massive clay silt facies (Grenfell and Grenfell, 2021). Floodplain deposits can be modified by processes of pedogenesis and bioturbation (Tooth et al., 2013) and can form stacked palaeosol sequences (e.g. Lyons et al., 2014).
Alluvial fan	Deposition when channel confinement and flow velocity is reduced (Blair and McPherson, 1994; Harvey, 2011). Fan deposits can be dissected by subsequent channel processes, forming relict fans (e.g. Ramisch et al., 2017).
River-end	Endoreic deposits in upland river reaches indicative of periods of flow incompetence and former termination of rivers upstream of contemporary end points (e.g. Eitel and Zoller, 1996; Eitel et al., 2005, Eitel et al., 2006; Rust, 1999). River-end deposits can be associated with short distance fluvial transport of fine-grained dust or loess (e.g. Brunotte et al., 2009; Eitel et al., 2001).
Interdune and playa	Endoreic water-lain sediments deposited within a sand sea at ancient terminal points of adjacent rivers (Feder et al., 2018; Krapf et al., 2003; Teller et al., 1990). Lacustrine mudstones form through deposition during low or still water phases of ponding and can contain diatoms and ostracods (Teller and Lancaster, 1986; Teller et al., 1990). Interdunes are a form of playa deposit, where playas can also be found upstream in water courses and are not restricted to the dune areas (e.g. Völkel et al., 2021).
Dune-dammed lake	Lacustrine-like sediments deposited when a river course is blocked by aeolian sand dunes (Goudie, 1972; Marker, 1977; Rust and Weinecke, 1974; Scholz, 1972; Vogel and Visser, 1981).

chronologies within the publications included in the database. Here, radiocarbon ages were individually recalibrated using standardised curves (SHCal20, Hogg et al., 2020; Bomb13SH12, Hua et al., 2013) in OxCal v 4.4.4. (Bronk Ramsey, 2021), to enable comparison between geochronologies (Bronk Ramsey et al., 2010). Details of ages as originally published are included in the database alongside the standardised chronological information (quoted to 2 sigma, 95.4%).

2.3. Data quality

Age-controlled fluvial archives from southwestern Africa have been obtained through publications spanning the last 40 years. Within this time, dating protocols and methodological approaches have been developed and adapted. Accurate reconstruction of palaeoenvironmental change from large datasets therefore requires an assessment of data quality to obtain a robust record of regional change. First, there are several established sources of uncertainty in geochronological methodologies (see Small et al., 2017). Through assessment of these uncertainties, it is possible to make judgments on whether anomalies and data conflicts are a relic of dating error, or if they detail palaeoenvironmental and geomorphological heterogeneity. Second, it is then critical to assess whether there is sufficient supporting information for palaeoenvironmental interpretation. Here, entries in the database were considered in terms of the lines of evidence used in association with dating to interrogate environmental response of rivers to past climates. Independent proxies were reported (see Supplementary Material for details) and proxies were grouped into sedimentary approaches following the framework discussed by Tofelde et al. (2021). Only records that constituted robust chronologies and palaeoenvironmental information generated through independent proxies passed this data quality filtering process and were considered for analysis of the Late Quaternary fluvial record (Section 4).

Table 2
Description of categories used to classify fluvial interpretation. Data are reported on flow occupancy and flow magnitude.

Fluvial interpretation		Description
Flow occupancy	Perennial	Year-round river flow. Precipitation regime sufficient to sustain continuous flow and connectivity within the drainage basin (Tooth and Nanson, 2011)
	Intermittent	Seasonal river flow with variable cycles of cessation. Persistent flow occurs through multi-peak floods (e.g. Bordy et al., 2018; Srivastava et al., 2004), commonly lasting longer than an individual storm event (Busch et al., 2020; Messager et al., 2021). Drainage networks are better connected than ephemeral systems (Tooth and Nanson, 2011), commonly with links to groundwater (Busch et al., 2020)
	Ephemeral	Sub-seasonal duration river flow. Floods commonly occur in response to spatially variable convective rainfall (Busch et al., 2020; Messager et al., 2021; Tooth and Nanson, 2011) and have lower predictability than intermittent rivers (Datry et al., 2017). Drainage networks are poorly connected (Tooth and Nanson, 2011), commonly without links to groundwater (Busch et al., 2020)
Flow magnitude	Extreme flood	Extraordinary high magnitude floods (Baker, 1987; e.g. Greenbaum et al., 2014; Zawada et al., 2000)
	High energy flow	Enhanced river flow, where the stream has a high competence (e.g. Brook et al., 2006) and has the capacity to carry a high sediment load (e.g. Srivastava et al., 2006; Walsh et al., 2022)
	Low energy flow	Periods of steady or declining river energy with smooth rising hydrographs (e.g. Srivastava et al., 2004), ponding through still water phases (e.g. Teller et al., 1990), or low capacity of a flow to transport sediment (e.g. Walsh et al., 2022)

A systematic classification approach for assessment of chronological data quality requires technique-specific standards in order to assess both luminescence and radiocarbon dating methodologies. To do this, a set of criteria were adapted from the schemes of Lancaster et al. (2016) (INQUA Dunes Atlas chronologic database) and Small et al. (2017) (BRITICE-CHRONO). Following Khider et al. (2019)'s crowdsourced standards on metadata reporting, we recognise that caution needs to be taken when applying contemporary data reporting standards to previous research that was not subject to the same exacting standards as present, so we differentiate between criteria that are essential and those that are *recommended*. Table 3 details the information used to classify ages from Category 1 (meeting all essential and *recommended* criteria), Category 2 (meeting all essential criteria), and Category 3 (not meeting the essential criteria), where Category 1 and 2 represent ages that passed the chronological filtering. For all luminescence and radiocarbon ages, the first set of criteria distinguishes between samples that are supported by other

Table 3

Chronological data quality criteria. Each age is classified from Category 1 (most robust) to Category 3 (least robust) based on their stratigraphic context and technique specific criteria. An age needs to have met all ticked requirements in a category to be classified as such. If any aspects are not met, it is placed in the category below.

	Criteria	Category 3	Category 2	Category 1
All ages	Stratigraphic context is well documented. Data on sample depth are available or stratigraphic relationships between ages can be inferred.	x	✓	✓
	Other geochronology is available from the site. This can be in the form of multiple dating methods (e.g. radiocarbon and luminescence) at the same depth, multiple luminescence dosimeters applied to the same sample, or multiple ages available from the site.	x	✓	✓
	Ages are stratigraphically-consistent (within 2σ) with other available geochronological evidence.	x	x	✓
Luminescence	Laboratory/sample number, luminescence age and error, and mineral dated are reported.	x	✓	✓
	Equivalent dose (D_e) and dose rate ($\dot{D}$) are reported.	x	✓	✓
	Dating protocol and corrections* applied are reported.	x	✓	✓
	Age obtained through the sensitivity normalised single-aliquot regenerative dose protocol (SAR).	x	✓	✓
	Potential for partial bleaching is interrogated. Small aliquots or single grain measurements undertaken for Category 1.	x	✓	✓
	Feldspar ages are accompanied by assessment of anomalous fading.	x	✓	✓
	Quality control** has been performed (e.g. dose recovery).	x	x	✓
	Age model and grain size dated are reported.	x	x	✓
Radiocarbon	Laboratory/sample number, conventional ^{14}C age and error, and material dated are reported.	x	✓	✓
	Potential for reservoir or hard water effects have been addressed.	x	✓	✓
	Age is obtained from a macrofossil or microfossil samples.	x	x	✓
	Age is obtained from a bulk sample.	✓	✓	x

* Corrections in luminescence dating include the reporting of water content, aliquot size, grain size, mineral dated, depth for calculation of cosmic dose rates, and rates of anomalous fading in feldspars.

** An assessment of the extent to which the SAR cycle can recover a known dose.

geochronology, and those that are not (Table 3). The presence of other geochronological data at a site enables a consideration of stratigraphic consistency. Multiple corroborating geochronological methods (including different luminescence dosimeters applied to the same sample) at a site increases the likelihood of a robust chronology of deposition. Reporting of sample depth is important here, as stratigraphic relationships between samples cannot be assessed without it.

Category 1 represents the most reliable ages with the highest levels of data reporting. These ages are produced through robust methods and are supported by other stratigraphically-consistent geochronology. Category 2 represents ages that are produced through robust methods and have stratigraphic context, but where the level of data reporting is not high enough to fully assess the quality of the age. Other geochronological data are available from the site, but ages are not stratigraphically consistent. In some cases, these ages can have less certain accuracy, such as where luminescence dose recoveries have not been reported, or bulk samples rather than macrofossils have been used for radiocarbon dating. Category 3 represents ages with the lowest data quality and the lowest level of data reporting. These ages commonly lack stratigraphic context or supporting ages from a site, are produced through methods that are not state of the art for dating fluvial sediments, or the author has stated concern about the age. If multiple ages are presented for a single sample (e.g. HS-1; Srivastava et al., 2006; which is dated through multiple aliquot sizes and age models), the age used for further interpretation in the paper is included in the database.

For luminescence dating, the key differentiating factors include the use of a sensitivity-normalised dating protocol, the reporting of key dating parameters, and the use of quality control such as dose recovery experiments. The SAR protocol (Murray and Wintle, 2000) includes an assessment of sensitivity change that was not incorporated in previous protocols such as the multiple aliquot additive dose (MAAD) approach (Jain et al., 2003; Wintle and Murray, 2006). The SAR protocol produces ages that are more precise (Duller, 2004; Hilgers et al., 2001; Wintle and Murray, 2006), makes it possible to measure a larger number of D_es per sample (improving the accuracy of ages) and is more suitable for dating sediments affected by partial bleaching expected for fluvial sediments. The luminescence signals in feldspars can fade anomalously (Lamothe and Auclair, 1999; Wintle, 1973). The post-IR IRSL (Infrared Stimulated Luminescence) protocol helps to minimise this fading (Thomsen et al., 2008), but assessments of the fading rate are required (Roberts, 2012) for feldspar ages to be Category 2 or above. Age model and grain size can influence the age obtained (Arnold et al., 2009; Timar-Gabor et al., 2017), yet these parameters are not used as a filtering criteria as the choice is often site and context specific. Partial bleaching is common in dating fluvial deposits, particularly in dryland regions where suspended load can be high (Ditlefsen, 1992; Olley et al., 2004). If partial bleaching is identified, small aliquots or single grain measurements are required for an age to be Category 1. These adjustments enable the bleached component of the signal to be isolated (Colarossi et al., 2020; Duller, 2008). Additionally, if the integrity of an age is questioned by the author, for example if radioactive disequilibrium is expected, the age is classified as Category 3.

For radiocarbon dating, the distinction between Category 1 and 2 ages is defined by the use of macrofossil rather than bulk samples. Bulk samples, such as organic or calcareous sediment, can combine multiple organisms, can date the formation of a unit over a period of time, and can incorporate dissolved land-derived ‘old carbon’ (Strunk et al., 2020). This has the potential to present the mean of several depositional events or yield ages exceeding the timing of deposition of interest. Assuming there is no fluvial reworking and material is in situ, age estimates from macrofossils, such as shells or wood, on the other hand are more precise as they are obtained from individual organisms with discrete timings of death (Rey et al., 2019; Strunk et al., 2020). To be Category 2 or above, the ^{14}C date and error must be reported, as this information is required for recalibration. ^{13}C values are variably reported across publications and are not used as a criterion in this data quality assessment. Finally, if the potential for hard water effects is identified but not accounted for, or authors suspect contamination by modern carbon or re-deposition of fossil wood, ages were classified as Category 3, as these effects can result in the production of anomalously young or old ages (Deevey et al., 1954; Wright, 2017).

3. Current status of the database

Quaternary fluvial data from southwestern Africa are derived from 44 sources (as at 1/4/2022). Chronologies have been established for 70 sites across 22 rivers (Fig. 1, Table S1, Supplementary Material). These rivers are located across four regions (Fig. 3) that span a range of hydrological, topographic, and climatic contexts (Table 4). The Namib region is the most intensely studied (41 sites), followed by Orange (14 sites), Eastern Cape (8 sites), and Northern Kalahari (7 sites). Contemporary mean annual precipitation in these fluvial catchments range from 10 mm yr^{-1} (Kuiseb River at the coast) to 1426 mm yr^{-1} (headwaters of the Okavango River). Along the main channels of these rivers, two of the studied rivers have a probability of intermittence of <0.5 (Orange, Okavango; where 0 is perennial and 1 is non-perennial; Messager et al., 2021), and all other studied rivers of >0.7. Average channel gradients range from 0.0003 (Okavango) to 0.0078 (Khumib) and the river styles are predominantly sinuous to meandering, with average sinuosity of the main channels ranging from 1.22 (Huab) to 1.91 (Orange).

Chronology from 603 ages within 44 publications met the initial data selection criteria to be included in this database (Section 2.1). These

Table 4

Characteristics of southwestern Africa's rivers that have been studied for records of palaeoenvironmental change. See Supplementary Material for detail on data collection methods.

River catchment	Region	Catchment size (km^2)[a]	Probability of intermittence[b]	Mean catchment relief (m)[c]	Length of main channel (km)[a]	Mean channel gradient[a,c]	Drainage density[a]	Average channel sinuosity[d]	Mean precipitation (mm yr^{-1})[e]	Mean catchment aridity index and range of aridity zones encompassed[f]
Okavango	N Kalahari	280,157	0.44	1406	1275	0.0003	0.081	1.32	351–1426	0.32 (humid to arid)
Okwa	N Kalahari	136,357	0.96	719	612	0.0004	0.087	1.83	295–441	0.13 (Arid)
Xaudum	N Kalahari	130,516	0.91	849	763	0.0005	0.103	1.37	317–553	0.16 (Arid)
Khumib	Namib	2315	0.90	1444	124	0.0078	0.074	1.26	29–216	0.05 (arid to hyper-arid)
Hoarusib	Namib	15,314	0.88	1966	254	0.0045	0.072	1.29	25–409	0.10 (arid to hyper-arid)
Hoanib	Namib	16,072	0.91	1869	263	0.0047	0.076	1.38	22–393	0.09 (arid to hyper-arid)
Huab	Namib	16,853	0.93	1648	289	0.0041	0.074	1.22	21–336	0.08 (arid to hyper-arid)
Swakop	Namib	29,535	0.95	2462	416	0.0039	0.073	1.28	13–453	0.10 (arid to hyper-arid)
Kuiseb	Namib	16,879	0.95	2351	387	0.0045	0.083	1.59	10–384	0.06 (arid to hyper-arid)
Tsondab	Namib	6680	0.94	1737	148	0.0052	0.088	1.25	13–240	0.05 (arid to hyper-arid)
Tsauchab	Namib	6343	0.94	1546	144	0.0051	0.082	1.27	28–232	0.04 (arid to hyper-arid)
Buffels	Namib	10,171	0.89	1576	234	0.0043	0.068	1.58	69–259	0.09 (arid to hyper-arid)
Fish	Orange	87,006	0.94	2153	869	0.0018	0.081	1.68	34–299	0.06 (arid to hyper-arid)
Auob	Orange	58,781	0.94	1609	707	0.0014	0.132	1.27	180–453	0.10 (arid)
Nossob	Orange	159,793	0.97	1641	924	0.0010	0.119	1.46	180–453	0.11 (arid)
Molopo	Orange	360,759	0.84	2039	1185	0.0009	0.101	1.76	123–630	0.12 (semi-arid to arid)
Kuruman	Orange	40,007	0.94	1009	414	0.0014	0.080	1.31	205–479	0.14 (semi-arid to arid)
Orange	Orange	978,189	0.41	3479	2288	0.0012	0.084	1.91	31–1061	0.16 (humid to hyper-arid)
Modder	Orange	35,784	0.98	1260	412	0.0011	0.405	1.47	354–714	0.22 (semi-arid to arid)
Huis	Eastern Cape	15,651	0.72	2243	310	0.0019	0.067	1.76	282–875	0.27 (arid to semi-arid)
Gourits	Eastern Cape	45,037	0.86	2315	373	0.0036	0.074	1.48	150–554	0.15 (arid to semi-arid)
Wilgerbosch	Eastern Cape	21,362	0.93	2493	423	0.0034	0.079	1.74	277–591	0.19 (arid to semi-arid)

[a] HydroSHEDS dataset (Lehner and Grill, 2013).

[b] 0: perennial, 1: non-perennial (Messager et al., 2021). See Supplementary Material for note on data quality in this region.

[c] Elevation data from ALOS Global Digital Surface Model AW3D30 (JAXA).

[d] Straight: <1.05, sinuous: 1.05–1.5, and meandering: >1.5 (Google Earth).

[e] WorldClim 2.0 dataset (Fick and Hijmans, 2017).

[f] Mean catchment aridity index calculated from the Trabucco and Zomer (2022) dataset. Aridity zones described following the UNEP (1992) definition.

ages comprise 55% optically stimulated luminescence, 43% radiocarbon, and 1% thermoluminescence ages. The single-aliquot regenerative dose protocol (SAR; Murray and Wintle, 2000; Wintle and Murray, 2006) was used for 92% of luminescence ages. Of the full dataset, 490 ages met the criteria for chronological data quality (Section 2.3) and of these, 424 ages (70.3% of total ages) were accompanied by independent proxies for palaeoenvironmental interpretation and were considered for further analysis. In the chronological data quality filtering, 249 ages (41%) were classified as Category 1, 241 ages (40%) as Category 2, and 113 ages (19%) as Category 3. The percentage of filtered ages varies by region (Table 5, Fig. 3A), with the highest acceptance rate recorded in the Northern Kalahari and lowest in the Eastern Cape. Ages were placed within Category 3 most commonly due to a lack of stratigraphic context or supporting geochronology from the site (75 ages), because the integrity of the age was questioned within the original publication (24 ages), or because the luminescence dating method was not state of the art for fluvial sediments (e.g. MAAD) (20 ages). The proportion of high quality, Category 1, ages increases with publication year (from 13% between 1980 and 1990, to 54% between 2010 and 2022; Fig. 4).

The dataset spans the last 132 ka, but around 45% of the ages in the filtered dataset fall within the last 1 ka (Fig. 5). There is a steady decay in the number of ages in older millennia, but the majority of ages (97%) date to within the last 50 ka and the majority of sites (except some on the Namib) have maximum ages of 25 ka. As is typical of most chronological data, precision generally decreases with increasing age. Within the filtered dataset, 139 ages have a 2-sigma error of less than ±100 years, 196 ages between ±100 and ± 1000 years, and 77 ages greater than ±1000 years. Site 43 in the Tsauchab River valley (24.47°S, 16.14°E) has the largest number of ages, with 39 luminescence and 21 radiocarbon ages (from Völkel et al., 2021). Site 22, the Skeleton Coast valley fill Huab River (20.87°S, 13.65°E) has 50 luminescence ages (Thomas et al., 2017; Walsh et al., 2022). Four sites have >15 ages: site 4 (Okavango), site 30 (Kuiseb), site 43 (Tsauchab), and site 31 (Kuiseb). All other sites have fewer than 15 ages, where 22 sites have three or fewer ages.

Records from SWDs and channel deposits (Table 1) make up the majority of this dataset, comprising 34% and 32% of sites respectively (Table 6). Overbank (12%), river end (10%) and interdune deposits (7%) are also common. The investigation of different sedimentary contexts varies by region (Figs. 1 and 3B, Table 6). Over half of the sites are from unconfined river settings (57%), with confined and partly confined settings comprising 25% and 18% respectively. To interpret changes in sediment deposition and infer the fluvial response to past hydroclimates, the most commonly used data are: stratigraphy, grain size, and sediment colour, closely followed by hydraulic discharge estimates, instrumental data, topography, mineral composition, and carbonate content (Table 7). These proxies have been used to reconstruct palaeoenvironmental change through five key approaches: analysis of sediment architecture (main approach used alongside 78 ages), texture (128 ages), discharge (131 ages), sediment composition to infer prevailing environmental conditions (129 ages), and provenance (32 ages), yet 105 ages are not accompanied by independent proxies (considering the full suite of unfiltered ages). Despite this, 66 of the ages with no accompanying proxies still reach interpretations about climate. These ages were removed through the filtering process and were not used in further analysis. The dominance of each approach used varies by publication year (Fig. 4C) and age of deposit (Fig. 5D).

A range of fluvial dynamics have been recorded in evidence dating to the late Quaternary. In terms of flow magnitude, these range from low energy flow representing steady or declining river energy (e.g. Hoanib River, Eitel et al., 2005), to extreme floods of flashy discharge (e.g. Swakop, Greenbaum et al., 2014). In terms of flow occupancy, studies have interpreted the occurrence of ephemeral (220 ages), intermittent (123 ages) and perennial (21 ages) river flow. Deposition of fluvial sediments are interpreted to record evidence of wet climates (221 ages), and evidence of drier climates than present (81 ages).

Table 5
Results of data quality assessment by region. Number of ages in Category 3 (lowest data quality) to Category 1 (highest data quality), and number of ages that passed the chronology filtering (Category 1 or Category 2) but were not accompanied by independent proxies to inform palaeoenvironmental interpretation. Filtered ages are those that passed both methodological and chronological filtering, and are the ages used in further analysis. Regions are defined by major basin, ordered in the table by total number of ages available by basin: Namib (26 papers), Orange (11 papers), Eastern Cape (5 papers), Northern Kalahari (4 papers).

Region	Chronology			Independent proxies		Total ages	% Passed filtering process	Max. age of filtered (ka)
	Category 1 ages	Category 2 ages	Category 3 ages	Category 1 + 2 ages without independent proxies	Category 3 ages without independent proxies			
Namib	170	185	64	51	36	419	72.6	132.3 ± 15.0
Orange	31	29	28	0	3	88	68.2	43.5 ± 3.2
E Cape	27	10	20	15	0	57	38.6	17.0 ± 2.5
N Kalahari	21	17	1	0	0	39	97.4	17.8 ± 0.4
Total	249	241	113	66	39	603	70.3%	–

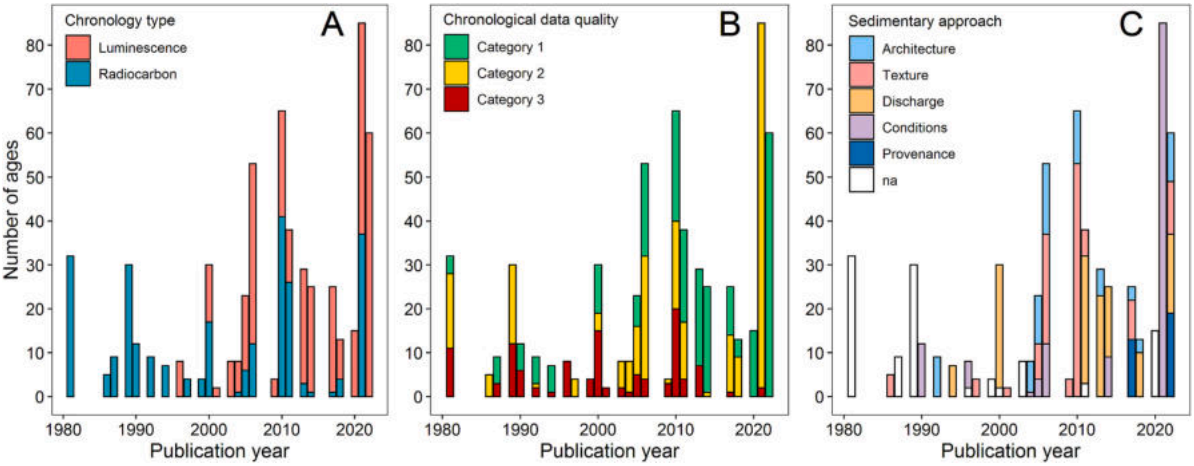

Fig. 4. Histograms of the number of ages by publication year for all data within the database. Ages classified as Category 1 and Category 2 with supporting independent proxies passed the data quality assurance process and were included in further analysis. A) Chronology type: luminescence and radiocarbon. B) Results of data quality assessment coloured by category of age: Category 1 to Category 3. C) Assessment of approaches used alongside chronology to interpret palaeoenvironmental change, where 'na' means that no independent proxies were used. The distribution of the number of ages by publication year can be influenced by several factors, such as intensity of sampling at a site yielding numerous ages in a single publication, and gaps between research and publication timings, but this visualisation is useful for assessing the status of research and providing an overview of the progression of data quality and approaches used.

4. Discussion

Analyses of the database will be discussed here in terms of: 1) the typology of rivers studied; 2) the nature and controls on the preserved fluvial record; 3) the sources of evidence and approaches used for palaeoenvironmental interpretation; and 4) the spatial and temporal trends in the regional quality-assessed Quaternary fluvial record.

4.1. River typology

Data on the topographical, hydrological, and climatological setting of river catchments (Table 4) detail a suite of river typologies that have been studied for evidence of palaeoenvironmental change across southwestern Africa. Ocean-draining moderate gradient rivers from coast-parallel high elevation ranges are located in coastal Namibia, the westward draining rivers in the South African portion of the Namib, and the southward draining rivers of the Eastern Cape, South Africa (Fig. 3). The Namib rivers have the highest average channel gradients (>0.0036), the smallest catchments (<30,000 km^2), are currently ephemeral (flow intermittence 0.88–0.95, Messager et al., 2021), and all drain from arid to hyper-arid climate zones. The Eastern Cape rivers of the Huis, Gourits and Wilgerbosch have lower gradients (0.0019 to 0.0036), encompass larger catchment sizes (e.g. Gourits River: 45,000 km^2), have lower probabilities of intermittence (e.g. Huis River: 0.7), and all drain from arid to semi-arid zones.

In the northern Kalahari, the Okavango, Okwa, and Xaudum drain internally towards the interior of southern Africa. These rivers all terminate at an elevation of ~850 m a.s.l. and are characterised by low average channel gradients of <0.0005. The Okwa and Xaudum are located within the arid climate zone (Fig. 1), have calculated probabilities of flow intermittence of >0.9 (Messager et al., 2021), and have not flowed historically (Shaw et al., 1992; Nash, 2022). The Okavango has its headwaters in the humid tropics and the main channel possesses perennial river flow with probability of flow intermittence of 0.44. The Orange catchment encompasses a range of climatic contexts spanning from humid to hyper-arid regimes, and a suite of river types are recorded. In the Namibian and southern Kalahari portions of the Orange basin, the Fish and Molopo Rivers flow predominantly through arid climate zones towards the Orange River and have probabilities of intermittence of >0.84 and gradients of >0.008. Parts of these rivers are deeply incised into bedrock, with a dominant meandering river style (Table 4). The main channel of the Orange has a moderate gradient (0.0011) and is perennial (probability of flow intermittence: 0.41), but the catchment encompasses a range of intermittence with an average probability of flow intermittence of 0.89.

4.2. Controls on the preserved fluvial record

4.2.1. Controls on the type of sedimentary contexts

Regional variability in the diversity of documented sedimentary contexts (Fig. 1, Table 6) can in part be explained by the characteristics of the river typologies. Interdune deposits have only been studied in the Namib region (Table 6) under the hyper-arid zone (Fig. 1; Table 4). In coastal Namibia, dunefields dominate the landscape in the Namib Desert and Skeleton Coast and can restrict adjacent rivers from terminating at the sea (Stanistreet and Stollhofen, 2002). At the eastern edge of the Namib Desert, channel facies are preserved (Brook et al., 2006), yet further into the dunefield, interdune facies dominate (Stone et al., 2010). Within the dunefield, evidence is preserved of times where rivers were able to pass through interdunal depressions and deposition occurred under still water ponding (Stanistreet and Stollhofen, 2002; Teller and Lancaster, 1986).

Scroll bars have been studied in the Northern Kalahari (Tooth et al., 2022), where relict fluvial features in the Okavango Delta are preserved through peat organic overburden after channel abandonment. Exhumation through peat fires (Ellery et al., 1989) has unveiled scroll bars that are evidence of lateral meander migration (Tooth et al., 2022). Slackwater deposits (SWD) have been studied extensively in the Orange, Eastern Cape, Namib, and yet have not been studied in the Northern Kalahari, where records are available instead from channel, overbank, and scroll bar sequences (Table 6). The low gradient endoreic nature and lack of bedrock gorges of the rivers of the Northern Kalahari makes these systems distinct from the fluvial systems of the Fish and Molopo within the Orange region that do contain SWDs (Table 5; Shaw et al., 1992). Whilst sporadic flooding occurs in Namibia and the southern Kalahari (e.g. Kuruman River) in response to high precipitation events, surface flow in dry mekgacha of the Northern Kalahari, (e.g. Okwa and Xaudum) is rare and short lived in response to high-intensity events (Mazor et al., 1977; Shaw et al., 1992). The chaotic nature of channel switching in the Northern Kalahari means that, whilst slackwater conditions occur, the palaeoenvironmental information preserved is more limited than other settings and SWDs have not been studied.

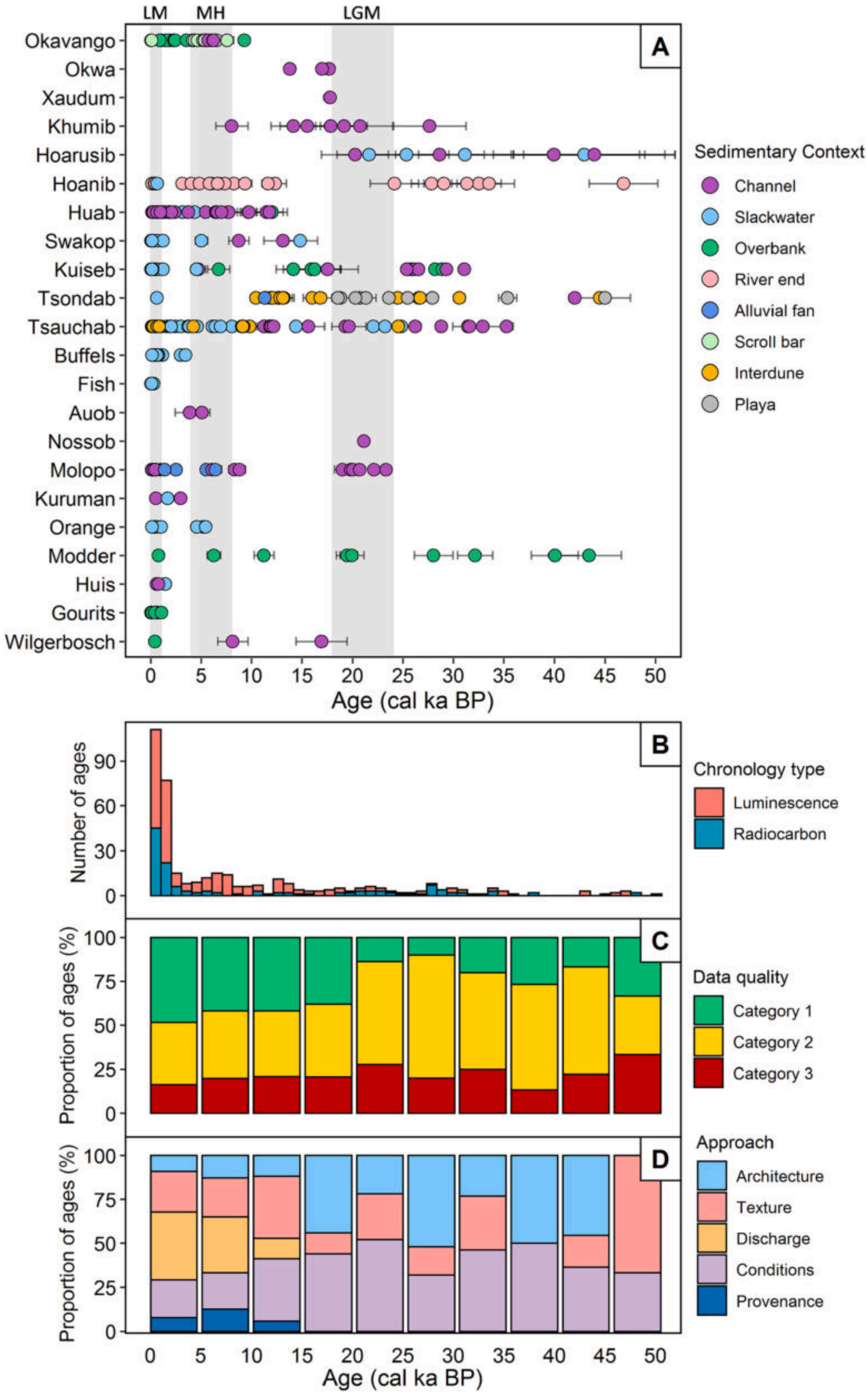

Fig. 5. Temporal distribution of ages, sedimentary contexts, chronology types, data quality, and analytical approaches applied to southwestern Africa's fluvial deposits. These plots show the results for the last 50 ka that have passed the quality assurance criteria. The full dataset extends to 132 ka, but only 20 ages from 5 sites cover the period 50 ka–132 ka, limiting the potential for comparison of results. A) Ages by river, colours represent sedimentary context. Grey boxes represent time periods discussed in the text: last millennium (LM; 1 ka-present), Last Glacial Maximum (LGM; 24–18 ka BP), mid Holocene (MH; 8–4 ka BP). B) Distribution of ages binned in 1 ka intervals and coloured by chronology type: luminescence and radiocarbon. C) Relationship between chronological data quality category and the age of deposit. D) Relationship between sedimentary analytical approach and age of deposit. 5 ka intervals have been used for plots C) and D) to reduce the bias of certain time steps with limited ages.

Table 6
Summary of the number of sites in the full database by sedimentary context and river setting. Data are grouped by region and the river settings that these sites are found in. Some sites contain multiple sedimentary contexts.

		Sedimentary Context									River Setting		
		Alluvial fan	Channel	Dune-dammed lake	Interdune	Overbank	Playa	River end	Scroll bar	SWD	Confined	Partially confined	Unconfined
Region	N Kalahari	0	4	0	0	3	0	0	1	0	0	0	7
	Namib	1	16	1	7	2	1	9	0	19	5	11	25
	Orange	1	7	0	0	2	0	0	0	7	7	1	8
	E Cape	0	4	0	0	4	0	0	0	3	6	1	1
Setting	Confined	0	3	0	0	4	0	0	0	13	–	–	–
	Partly confined	1	7	1	0	1	0	3	0	10	–	–	–
	Unconfined	1	21	0	7	6	1	6	1	6	–	–	–

Channel confinement has a strong control on reach-scale river character and behaviour in fluvial systems and is important for explaining the distribution of documented sedimentary contexts in southwestern Africa (following findings by Fryirs et al., 2016; Keen-Zebert et al., 2013). The number of sites from confined, partly confined, or unconfined settings differs between regions, and corresponding differences are recorded in the suite of sedimentary contexts studied (Table 6). All confinement settings have been studied in the Namib, yet in the Northern Kalahari all studied sites are unconfined. SWDs are predominantly found along confined reaches in rivers of both large and small catchment sizes (e.g. Kuiseb, Grodek et al., 2013; Orange, Zawada et al., 2000). Confined bedrock reaches favour the accumulation of suspended silt and sand from exceptional floods (Baker, 1987; Cloete et al., 2018). In these settings, preservation of sediment deposition from sub-bankfull channel aggradation is limited (Toonen et al., 2017) and channel migration is restricted where laterally confined channels lack a substantial alluvial bed (Fryirs et al., 2016; Tooth and Nanson, 2000). In contrast, channel, overbank, and scroll bar sedimentary contexts are more predominantly located in partly confined or unconfined reaches (Table 6). Unconfined alluvial rivers possess erodible banks and rivers have a wider range of lateral variability (Fryirs et al., 2016; Grenfell and Grenfell, 2021), so can host aggradational sites, and preserve abandoned channels where non-equilibrium conditions prevail (Tooth and Nanson, 2000). All interdune and playa deposits are found in unconfined settings where ponding of sediment and drainage in lacustrine settings is possible (e.g. Völkel et al., 2021).

The tendency towards formation of specific deposit types is also dependent on palaeohydrological conditions at deposition and the river's sedimentary response to climatic drivers (Fig. 6). SWDs have predominantly been interpreted as records of extreme floods or high energy flow as a response to high precipitation events within ephemeral flow regimes (e.g. Cloete et al., 2018; Greenbaum et al., 2014). River end deposits are consistently interpreted in southern African literature as representing low energy flow during periods of low precipitation, resulting in termination of the river further upstream within a dry or semi-arid climate of an ephemeral flow regime (Eitel et al., 2005; Eitel et al., 2006). When located beyond the contemporary end point of rivers, interdune deposits are indicative of increased rainfall and increased competence of a river to overcome transmission losses and penetrate into the dunefield (Brook et al., 2006; Stone et al., 2010). These deposits then attest to low energy flow and settling of water, and the presence of diatoms and ostracods indicate calm, ponded environments (Teller et al., 1990). Channel and overbank deposits have a broader range of characteristics and therefore encompass a range of fluvial processes: from different flow occupancy under ephemeral to perennial regimes and flow magnitudes of extreme floods to low energy flow (e.g. Eitel et al., 2005; Hurkamp et al., 2011; Ramisch et al., 2017; Srivastava et al., 2005; Tooth et al., 2022; Walsh et al., 2022).

4.2.2. *Controls on length of fluvial record*

By region, the longest fluvial histories are preserved at sites in the Namib (Table 5; Fig. 7). Here, the record from Narabeb, Tsondab River (site 34; Stone et al., 2010), extends to 132 ka, yet the majority of sites from all other regions have maximum ages of <25 ka. The geomorphological setting plays a role in controlling sediment production and preservation, and channel confinement in particular is found to be a control on the length of the fluvial history preserved (Fig. 7; following findings by Harden et al., 2010). Across the regions studied, the longest chronologies are established from unconfined river settings. This contrasts to confined settings where 85% of filtered ages (Category 1 or 2 ages with independent proxies available) date to the last millennium. Sedimentary archives along bedrock controlled reaches have a lower preservation potential as sediment is removed by subsequent floods (Fryirs and Brierley, 2012; Lewin and Macklin, 2003) and tend to only be preserved in sheltered backflooded tributaries (Grodek et al., 2013). As a result, long-term sediment preservation in sedimentary contexts such as in SWDs is limited (Figs. 5A and 7). In unconfined settings, the ability of rivers to adjust their width and meander position in response to hydroclimatic changes (Grenfell and Grenfell, 2021) results in a combination of aggradation and incision rather than removal of sediment. Whilst incision within this process can result in sediment recycling (Grenfell and Grenfell, 2021), and overbank sedimentation can be self-limiting (Lewin and Macklin, 2003), wide valleys have the potential to possess long sedimentary records particularly in abandoned channels and elevated alluvial terraces (Lewin and Macklin, 2003; Tooth et al., 2013). In the case of interdune deposits at the distal end of the Tsondab and Tsauchab Rivers in Namibia (sites 33 to 38, and 41), aggradational environments exist where deposition occurred in still water conditions. Subsequent floods accumulate rather than erode and remobilise sediment downstream, therefore enabling the potential to preserve a long history of fluvial sedimentation.

River sinuosity and resulting pattern (e.g. straight, meandering) can influence the characteristics of sedimentary deposits (Tooth et al., 2013). Analysis of sinuosity at the reach scale, however, indicates that for the southwestern African Quaternary fluvial dataset there is no relationship between channel sinuosity and length of documented chronology ($r^2 = 0$, $p = 0.94$).

The temporal extent of documented fluvial histories within this database also reflects the choice of units sampled and the aims of scientific studies. Within the filtered dataset, ~45% of ages fall within the last millennium (Fig. 5B) and whilst the length of the chronologies established shows a relationship with confinement of the channel (Fig. 7), there is variability in the distribution of chronology lengths between confinement categories and between regions. First, the majority of ages (86%) within this database were obtained from samples collected from natural exposures. Whilst this section type has numerous advantages (e.g. enabling the identification of clear stratigraphic boundaries), exposures often do not uncover the full extent of fluvial deposition and where exposures do not exist, major periods of

Table 7
Summary of the sources of evidence used to reconstruct palaeoenvironmental change. This summary groups the use of methods by river to detail the full suite of approaches across a range of papers and sites for each river. Site numbers refer to Fig. 1 and Table S1, Supplementary Material.

River	Method												Sites
	Stratigraphy	Sedimentary facies	Grain size	Carbonate/ organic content	Soil characteristics	XRD, XRF, mineralogy, heavy minerals	DRS, mineral magnetism	Stable isotopes	Palaeontology Palynology	Hydraulic palaeodischarge estimates	Topography	Instrumental/ Documentary	
Okavango	x		x	x				x	x	x			1–4
Xaudum	x		x						x				5
Okwa	x		x						x				6–7
Khumib	x	x	x										8–9
Hoarusib	x	x	x	x	x	x							10–13
Hoanib	x		x	x		x							14–21
Huab	x	x	x	x	x	x							22–23
Swakop	x									x	x	x	24–27
Kuiseb	x	x	x		x	x				x	x	x	28–32
Tsondab	x		x	x	x	x		x	x				33–40
Tsauchab		x	x	x	x								41–44
Fish	x	x		x	x				x	x	x	x	45–47
Auob			x		x	x			x				48
Nossob			x		x	x			x				49
Kuruman	x		x						x				50–51
Molopo	x		x	x	x	x			x				52–53
Orange	x					x				x	x	x	54–57
Modder	x		x		x		x		x				58
Buffels	x									x		x	59–62
Huis		x				x					x		63
Gourits	x		x	x						x		x	64–69
Wilgerbosch	x	x	x				x				x		70

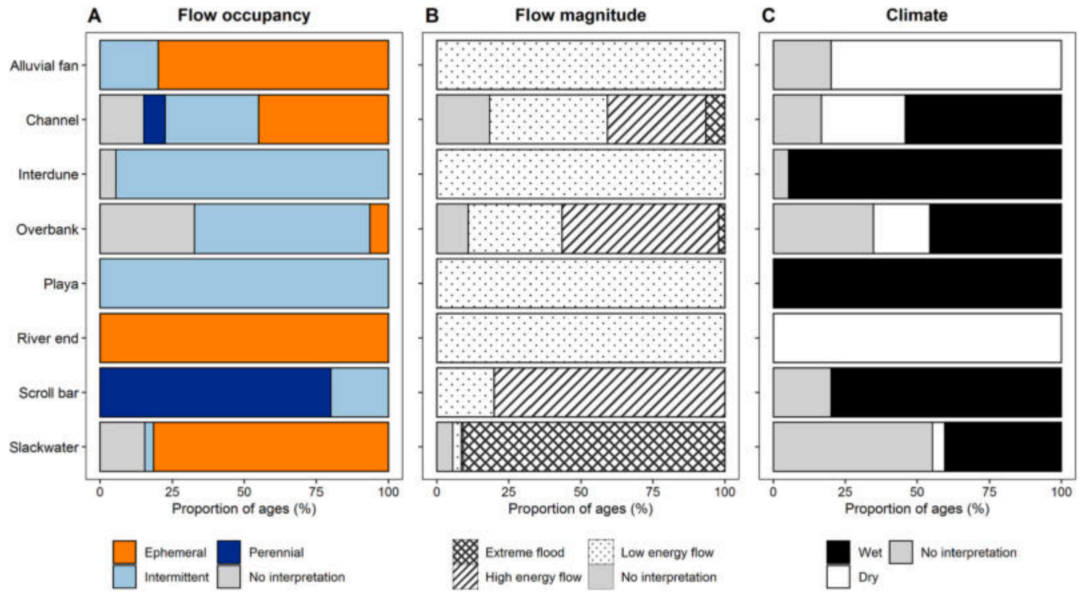

Fig. 6. Association between sedimentary context and fluvial interpretation (flow occupancy, A, and magnitude, B) and climate interpretations, C. Data includes records that have passed the data quality assessment. Bars are coloured by percentage of ages relating to each interpretation.

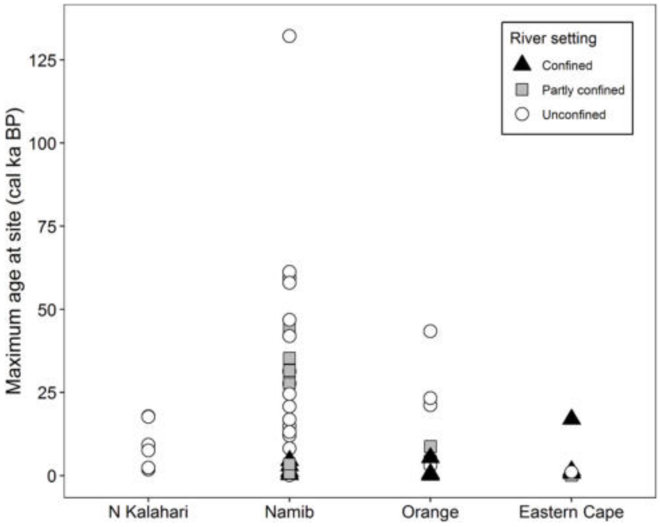

Fig. 7. Maximum age at each site by region and by river setting. River setting is defined on a scale from confined to unconfined following Fryirs et al. (2016).

deposition are not studied (Eitel et al., 2006). Second, the Namib has the longest established history of late Quaternary fluvial sedimentation and is the region that has received the largest research focus in terms of the number of sites, distribution of sedimentary contexts (Table 6), and number of ages used to establish chronologies (Table 5). A greater number of dated units is likely to pick up a more complete suite of depositional periods. And third, the skew in the distribution of ages could also be driven by the aims of studies to reconstruct specific aspects of late Quaternary change. Several papers (e.g. Zawada et al., 2000; Cloete et al., 2018) produce chronologies from SWDs of recent floods that map on to the documented timing of historical events.

4.2.3. *Drivers of geomorphic change*

Whilst deposition of fluvial sediment has commonly been linked to changes in hydroclimate, geomorphic change can also occur as a response to a suite of allogenic and autogenic processes (Fryirs and Brierley, 2012; Grenfell and Grenfell, 2021; Tooth et al., 2004, 2013). In the case of the fluvial records within this database, 132 filtered ages (31% of the full dataset) are reported without interpretation of the palaeoclimate context under which sediments were deposited (Fig. 6C). Non-climatic drivers have been drawn on to explain fluvial sedimentation in three rivers in the Eastern Cape region in particular. These include the role of wildfires on extreme floods in the Huis River (Bordy et al., 2018, site 63, Fig. 1), fluvial channel connectivity in the Wilgerbosch River (Oldknow and Hooke, 2017, site 70), and anthropogenic land use in the Gourits River (Damm and Hagedorn, 2010, sites 67 to 69). At Erfkroon on the Modder River, Orange catchment (Lyons et al., 2014; site 58) a luminescence chronology details almost continuous sedimentation throughout the last 44 ka regardless of changes in prevailing climate. Here, it is the magnetic parameters of palaeosols developed contemporaneously that reflect changes in climate, rather than the rate of fluvial sedimentation. Of the filtered ages without climate interpretation, 110 ages are accompanied by interpretations of flow dynamics, where studies focus on investigation of the timing of fluvial sedimentation rather than the nature of drivers of this change (e.g. Thomas et al., 2017).

4.3. *Sources of evidence*

The ability to reconstruct palaeoenvironmental change requires both a robust chronology and a suite of independent proxies for interpretation of depositional contexts. Here, we look at the spatial (Fig. 3, Table 5) and temporal (Figs. 4 and 5) distribution of the quality of chronological data and use of sedimentary approaches. From this, we create a framework that considers both the data required to reach specific interpretations and the spatial and temporal scales that these interpretations can be applied.

4.3.1. *Chronological data quality*

De Cort et al. (2021) note that the collation of palaeoenvironmental data is susceptible to the “synthesis dilemma”, where a trade-off exists between: i) selecting a small number of high-quality records at the expense of reducing the temporal and spatial coverage of the synthesis; and ii) including as much data as possible whilst accepting that the dataset may include more ‘noise’ in the form of lower quality data. Following the chronological data quality assessment (Table 3), the number of filtered ages by chronology in this database remains substantial (490 ages, 81% of all ages). The proportion of filtered ages has increased with publication year (Fig. 4B), which is indicative of advances in dating methods and data reporting over time. Older publications (e.g. published between 1980 and 1990) had: i) a higher use of luminescence dating protocols that are less precise (e.g. use of MAAD and SAAD in Eitel and Zoller, 1996; Zawada et al., 2000); ii) more limited data reporting (e.g. limited description of stratigraphic context in Vogel and Visser, 1981); and iii) incorporate a larger number of sites that have few ages reported. Approximately 45% of sites studied between 1980 and 1990 have three or less ages, compared to only 26% of sites studied since 2010. The former derives from a period of infancy in radiocarbon applications when a focus was placed on capturing a dataset that was spatially broad, rather than targeting specific palaeoenvironmental questions through detailed assessments of individual sites. The age of the deposit is not a determinant of data quality (Fig. 5C), meaning that older deposits have as equal a chance of having high quality chronological control as younger deposits.

4.3.2. *Sedimentary approaches*

Different sources of evidence have the ability to inform us about different aspects of an environmental response to climate perturbations (Tofelde et al., 2021). A suite of sedimentary approaches have been used within the southern African dryland fluvial literature (Table 6), including analysis of: i) textural (e.g. grain size; Thomas et al., 2017) and architectural elements (e.g. stratigraphic and lithofacies analysis; Srivastava et al., 2006; Walsh et al., 2022) to indicate of the nature of river flow; ii) the topographic setting of deposits and meander dimensions to reconstruct palaeodischarge (e.g. Benito et al., 2011; Greenbaum et al., 2014; Tooth et al., 2022); iii) sediment composition to consider provenance (e.g. petrographic datasets to infer source regions; Ramisch et al., 2017; Walsh et al., 2022); and iv) analysis of sediment content such as characteristics of soil formation, palaeoecology, and palaeontology (e.g. Lyons et al., 2014; Nash et al., 2006) to assess environmental conditions. The majority of publications without any sedimentary detail are those published in the 1980s, where research was more exploratory with a focus on generating radiocarbon chronologies. Over the last four decades, there has been an increase in the assessment of sediment composition, particularly through the analysis of pedogenic characteristics (e.g. Völkel et al., 2021). Analysis of sediment provenance, however, remains a particular research gap in this literature, where it has only formed the main approach of two studies here to date (Ramisch et al., 2017; Walsh et al., 2022). Provenance analyses in Namibia and across the wider Kalahari (Garzanti et al., 2012, 2014, 2022) provide extensive datasets on the mineralogical signatures of many of the rivers considered in the database and could be used to provide insights on source-terrane weathering on Late Quaternary timescales.

Regional differences emerge in the use of specific proxies (Table 7). Analyses of palaeodischarge have been performed at sites along seven rivers within the database (Table 7). This work shows that palaeodischarge data can be obtained from different types of rivers in different settings, e.g. the confined reaches of rivers in the Orange, Namib, and Eastern Cape regions and the low gradient alluvial rivers and palaeochannels in the Okavango in Northern Kalahari (Table 4). For each of these types, a set of conditions need to be met. Estimates from SWDs assume that the topography of bedrock channels has remained stable over time (Benito et al., 2020, e.g. Cloete et al., 2018), and estimates from meander dimensions of palaeochannels assume that channel width increases with discharge (based on hydraulic geometry relationships; Tooth et al., 2022). Palaeontology and palynology proxies have also only been used in specific environments, such as Okavango Delta (Nash et al., 2006; Shaw et al., 1992), the interdune region at the distal end of the Tsondab (Teller and Lancaster, 1986), and in the Huns (Stengel and Leser, 2004), Molopo (Heine, 1990), and Modder rivers (Churchill et al., 2000). The majority of these settings include ponding and still water deposition, enabling the preservation of organisms within the fluvial sediments.

4.3.3. *Establishing interpretations of palaeoenvironmental change*

Fig. 8 links the methodological approaches within this dataset to the type of information gained and considers interpretations in the context of the scale of chronological uncertainties and availability of corroborating records. These factors have an influence on the choice of appropriate proxy analyses to answer specific questions about fluvial change (Fig. 8A), the temporal resolution of climate variability that can be discerned (Fig. 8B), and the implications for reconstructing local or regional scale change (Fig. 8C). Fluvial systems in southwestern Africa are being studied in increasing detail (e.g. 144 ages published in 2021–2022, Völkel et al., 2021; Tooth et al., 2022; Walsh et al., 2022), and this framework highlights the need for consideration of the data required to reach robust and justifiable conclusions on defined spatial and temporal scales.

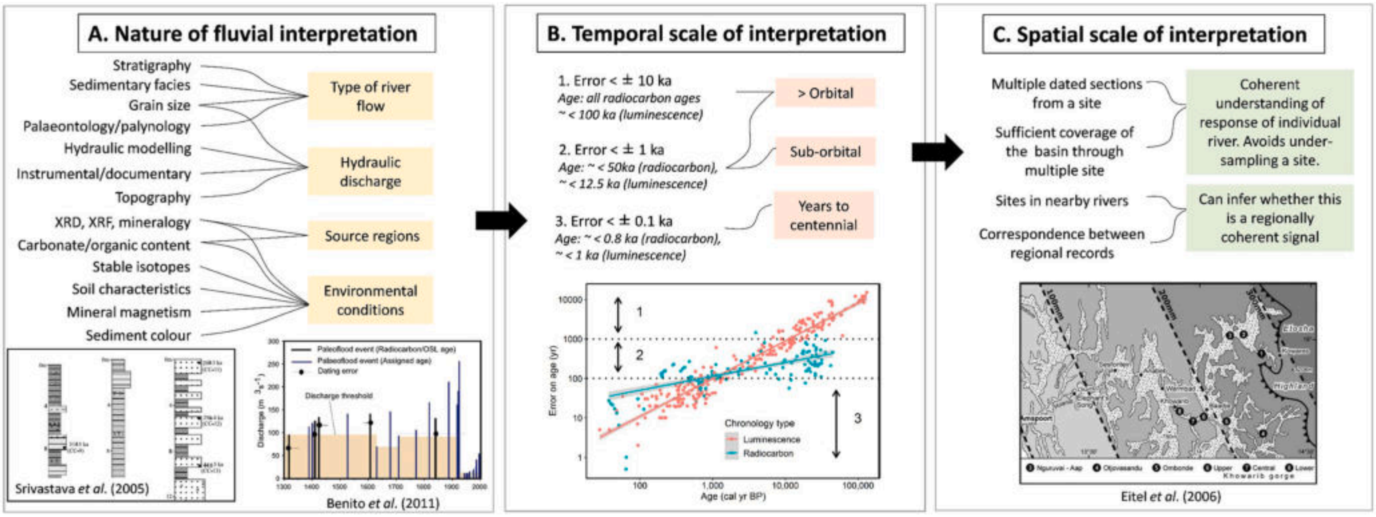

Fig. 8. Framework for considering the data required for interpretation of dryland fluvial sedimentary records. A) Link between independent proxies and the nature of fluvial interpretation that can be reached. Examples: Lithofacies analysis of Hoarusib River sediments (Srivastava et al., 2005), palaeoflood discharge estimates, Buffels River (Benito et al., 2011). B) Link between the scale of chronological uncertainties and the resolution of climate variability that can be discerned. Scales of uncertainty are highlighted on this plot as numbers 1 to 3 (reflecting errors < ±10 ka to < ±1 ka). C) Spatial scale of interpretation: linking the number of sites in both a river basin and across nearby catchments with the ability to interpret regional palaeoenvironmental change. Example: high coverage of sites across the Hoanib River catchment (Eitel et al., 2006).

Chronologies with the smallest absolute uncertainties (<100 years: 33% of the filtered dataset) can be used to establish the timing of river flow on the scale of individual *events* to multi-year *episodes* (cf. Toonen et al., 2017). Where there is overlap with instrumental or historical data (e.g. Cloete et al., 2018), this temporal resolution enables links to be made between magnitudes of documented floods and climate events (cf. Baker, 2008; Woodward and Tooth, 2010). In the southwestern African dataset, these ages predominantly date to the last 1000 years (Fig. 8B). When the scale of uncertainty increases (e.g. in the range of ±100 to ±1000 years; 46% of ages), the ability to distinguish individual flood events decreases, and the sedimentary record can be more appropriately interpreted in terms of *phases* of river flow (Toonen et al., 2017) as a record of millennial scale climate change (Macklin et al., 2012). Due to the largest number of ages falling in the Holocene (Fig. 8B; where the majority of radiocarbon ages have uncertainties of <1000 years), and where there are cases of overlapping chronologies (e.g. in the headwaters of the Hoanib, Eitel et al., 2006; and BüllsPort playa, Völkel et al., 2021), investigations at this temporal scale are able to identify periods of distinct fluvial regimes.

The oldest portion of this fluvial dataset (particularly luminescence ages >12.5 ka) have absolute uncertainties of > ±1000 years (18% of ages). Here, statistical errors impact the ability to distinguish between distinct geomorphological events and have the effect of conflating events into averaged packets of features (Bailey and Thomas, 2014). At this scale, it is possible to link fluvial interpretations to marine isotope stages and sub-stages (Macklin et al., 2012), but when errors are larger (> ±10,000 years; 1% of the filtered dataset), the timing of fluvial change are increasingly difficult to pinpoint. The absolute increase in errors associated with older ages is a universally recognised problem for dated sediments (e.g. Burrough et al., 2007; Fitzsimmons et al., 2013; Macklin et al., 2012) and is important to recognise when considering the temporal scales of change possible to resolve with the achievable temporal resolution offered by dating precision. Where uncertainties are small enough, individual flood *events* within flash flood deposits have been linked to high precipitation climate events (e.g. Greenbaum et al., 2014; Grodek et al., 2013), yet when errors are larger, multidecadal- to

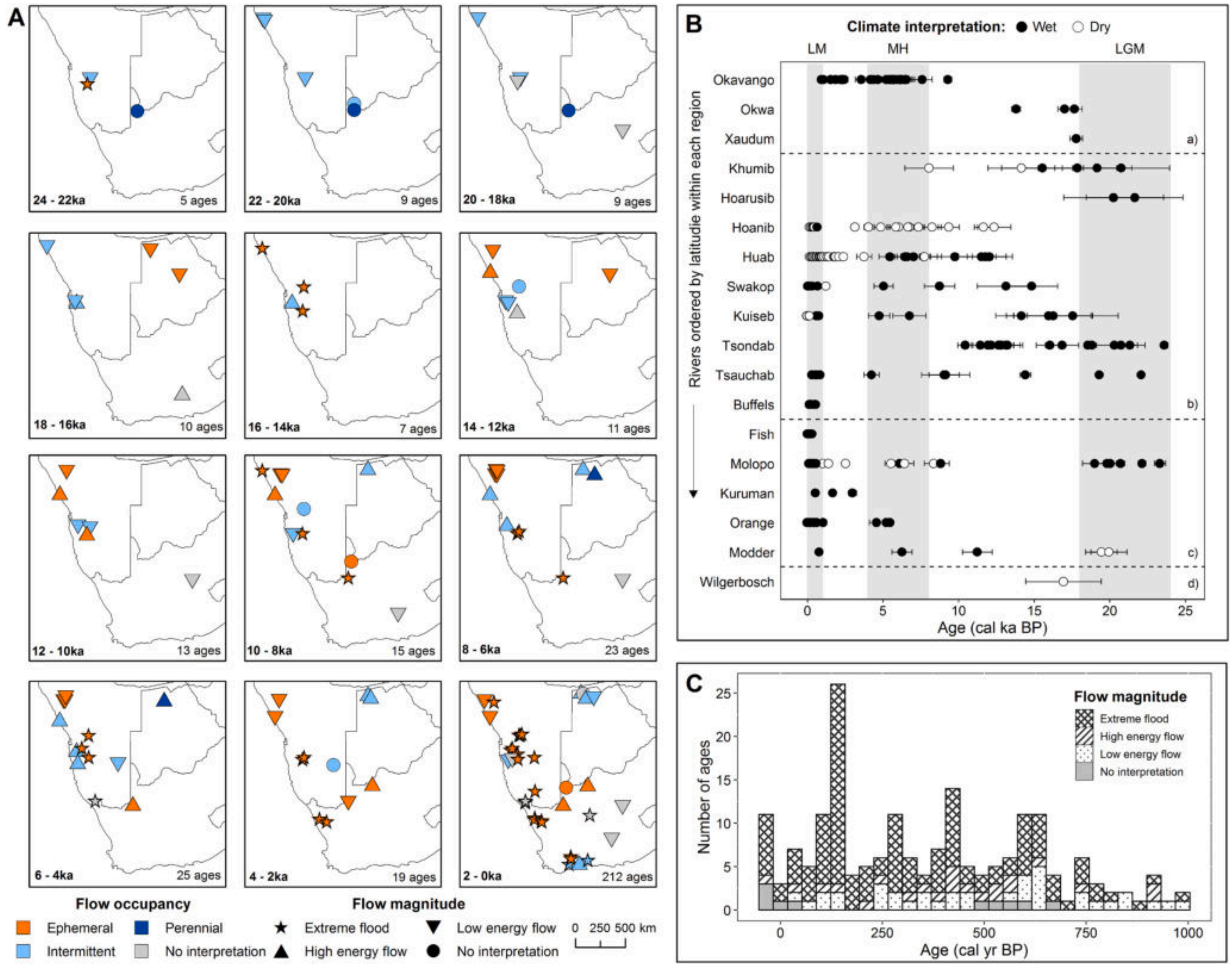

Fig. 9. Southwestern Africa's late Quaternary fluvial and climate conditions inferred from the fluvial records with chronologies (n.b. changes without chronology have not been possible to include). A) Fluvial interpretation from quality assessed records for the last 24 ka at 2 ka timeslices. The data presented here (<24 ka) make up 82% of the filtered dataset. The number of ages dating to each timeslice are recorded in the corner of each map. B) Climate interpretations of fluvial deposits (quoted as wetter or drier relative to contemporary conditions). Only records that reach climate interpretations are included. Rivers ordered in the y axis by latitude and region (a: Northern Kalahari, b: Namib, c: Orange, d: Eastern Cape). Grey boxes represent time periods discussed in the text: last millennium (LM; 1 ka-present), Last Glacial Maximum (LGM; 24–18 ka BP), mid Holocene (MH; 8–4 ka BP). C) Frequency distribution of ages within the last millennium, coloured by fluvial interpretation (na = no interpretation).

centennial-scale *phases* of flash floods can be identified and these conditions are commonly interpreted as episodes of high ephemeral discharge within the context of an otherwise arid climate (e.g. Srivastava et al., 2004). The scale of analysis therefore has an influence on the palaeoenvironmental interpretation as wet or dry (e.g. the difference between identification of a wet event or a dry period) and needs to be taken into account when interpreting the combined regional Quaternary record.

Given the limited sampling of river deposits in southwestern Africa to date, Fig. 8 also details considerations for reaching conclusions about local versus regional scales of change. Dryland geomorphological archives are commonly discontinuous with variable preservation of depositional events. Amongst a number of modification processes from the climate signal to interpretation (see Allen, 2017; Bailey and Thomas, 2014; Jerolmack and Paola, 2010; Kemp, 2012; Macklin et al., 2012), processes of cut and fill and bioturbation can result in sediment recycling and removal of sedimentary units (Grenfell and Grenfell, 2021; Lewin and Macklin, 2003) and have significant implications for luminescence and radiocarbon sample integrity. Investigation of a sufficient number of sections and sites within a fluvial basin is therefore important to increase the stratigraphic completeness and avoid aliasing the record through under-sampling (Toonen et al., 2017). If correlations and trends emerge between records across a region, it is possible to start interpreting regional controls on fluvial change. This requirement for nearby sites helps avoid over-interpreting regional change from site specific records, and acknowledges potential limitations of using findings based on spatially and temporally limited ranges of dates.

Following this regional compilation of fluvial records, we suggest that there are important sites within southwestern Africa that could benefit from being revisited and investigated more intensively than to date. First, this could include a focus on establishing additional chronologies from a larger suite of sections at studied sites. The number of ages used to establish chronologies across southern Africa's fluvial systems is highly variable (Fig. 3A), and whilst several sites have been studied intensively (e.g. the Homeb Silts, Kuiseb River), around 38% of the sites in the full dataset have three or fewer ages (Table S1, Supplementary Material). Second, early thermoluminescence work, such as in the Namib region on alluvially-reworked loess in the headwaters of the Hoanib and Huab Rivers (Eitel and Zoller, 1996; Eitel et al., 2001) and the Orange on SWDs (Zawada et al., 2000), highlights potentially important sites that could benefit from being revisited with the application of newer luminescence protocols. Third, 20% of the ages within the database were not included in further analysis because they were not accompanied by independent proxies for palaeoenvironmental interpretation. The use of robust analytical methods has increased in recent decades, and approaches such as analysis of sediment provenance and architectural elements (e.g. following standardised methodological frameworks such as Miall, 2006) could be used to revisit these sites.

4.4. The late Quaternary fluvial record

With appropriate dating control and acknowledgement of the complexities associated with the analyses of proxies and scale of chronological uncertainties, the Quaternary history of southwestern Africa's rivers is now interrogated (Fig. 9). We discuss the fluvial history preserved in quality-assessed record (Fig. 9A and C) at three key timesteps: the Last Glacial Maximum (LGM, 24–18 ka BP; following the conservative EPILOG definition; Chase and Meadows, 2007; Clark and Mix, 2002; Mix et al., 2001), the mid Holocene (MH, 8–4 ka BP), and the last millennium (1 ka-present). These timesteps were chosen based on the availability of fluvial data and for the relevance to existing regional syntheses of palaeodata (e.g. Burrough and Thomas, 2013; Chase and Meadows, 2007; Gasse et al., 2008) and palaeoclimate modelling simulations (Engelbrecht et al., 2019; Kageyama et al., 2021; Taylor et al., 2012). Interpretation of the nature of palaeoclimate change from the fluvial archives are discussed here (Fig. 9B) and the drivers of this change are assessed in further detail in the context of palaeoclimate model outputs in Walsh et al. (in review).

4.4.1. The last Glacial Maximum (LGM; 24–18 ka BP)

The timing of river flow within the LGM is established through 23 ages from seven sites along seven rivers. Sedimentary deposits along currently ephemeral Namibian rivers detail evidence of regionally wetter climatic conditions at the LGM in the Khumib, Hoarusib, Tsondab and Tsauchab catchments (Fig. 9B). Higher rainfall levels increased the flow occupancy in the Hoarusib River, with deposits providing evidence for intermittent low energy flow (Fig. 9A; at 21.7 ± 3.2 ka to 20.3 ± 3.3 ka; Srivastava et al., 2005; site 12, Fig. 1). Lithofacies analysis indicates a river system characterised by more continuous flow than today with cohesive river banks (Srivastava et al., 2005). A climate with long periods of rainfall during this period is also inferred from evidence of persistent, low energy, slowly charging floods along the Khumib River (20.8 ± 3.2 ka to 19.2 ± 2.3 ka; Srivastava et al., 2004; site 9). Playa sediments within the Tsondab catchment also provide a record of fluvial response to wetter conditions than present at the LGM (Völkel et al., 2021; site 40). Geochemical analysis of soil characteristics of radiocarbon dated sediment from the BüllsPort Playa (23.6 ± 0.2 cal ka BP to 18.5 ± 0.2 cal ka BP) indicate continuous deposition and sustained water availability in the system (Völkel et al., 2021). Sedimentary sequences along the Tsauchab River also attest to a wet LGM (Völkel et al., 2021; site 43), in the form of channel aggradation under low energy flow (19.7 ± 1.7 ka) and SWDs from extreme floods (22.1 ± 0.1 cal ka BP).

Records from channel deposits along the Molopo and Nossob Rivers detail evidence of perennial and intermittent flow respectively under wet conditions (Fig. 9A, B; Heine, 1990; Hurkamp et al., 2011; sites 49 and 52). Macrofossil freshwater mollusc and ostrich egg shell radiocarbon ages place fluvial deposition in the Molopo from 23.3 ± 0.7 cal ka BP to 18.9 ± 0.8 cal ka BP (Heine, 1990; Hurkamp et al., 2011). Analysis of sediment texture indicates persistent flow of the Molopo alongside evidence of lunette dune cessation. However, across the wider Orange River basin, in the contemporary semi-arid region (Fig. 1), a mineral magnetism record from an alluvial-palaeosol sequence in the Modder River shows evidence of cold and dry conditions at the LGM (Lyons et al., 2014; site 58). The magnetism parameters of sedimentary units within vertically aggrading overbank sedimentary deposits date to 20.0 ± 1.2 ka and 19.5 ± 1.0 ka and reflect prevailing rainfall levels of around 100–200 mm yr^{-1} (much lower than contemporary levels of 400–500 mm yr^{-1}) (Lyons et al., 2014).

4.4.2. The mid-Holocene (MH; 8–4 ka BP)

At 18 sites along ten rivers, evidence of fluvial deposition at the MH is established through 48 ages. Records from eight rivers within the Namib, Northern Kalahari, and Orange regions (Fig. 3) indicate conditions of enhanced river flow under a climate wetter than present at the MH (Fig. 9A and B). Reduced river flow under dry climate conditions is recorded in the northern Namib throughout the MH and a transition from wet to dry conditions occurred within this period in the southern Kalahari portion of the Orange region.

Stratigraphic, textural, and compositional analysis of channel and overbank sedimentary contexts within the Huab River Skeleton Coast valley fill provide evidence of more humid conditions than present at the MH, where Huab River flow occurred as a more channelised and confined fluvial system from 7.1 ± 1.1 ka to 5.5 ± 0.7 ka (Walsh et al., 2022; site 22). The climate setting was conducive to more sustained intermittent, compared to contemporary ephemeral, river flow that enabled transport of coarse sediment fractions throughout the fluvial system. This record corroborates findings from the Homeb Silts in the Kuiseb River (site 30), reflecting a period of sediment mobilisation under a wet climate at the MH (6.8 ± 1.1 ka; Srivastava et al., 2006). Along the Swakop and Kuiseb in Namibia's present-day hyper-arid to arid zone (Fig. 1), sedimentary deposits further this interpretation of seasonal rains coincident with high energy flow (Greenbaum et al., 2014; Grodek et al., 2013; sites 25 and 32). From 9 to 7 ka, deposition of interdune sediments indicates an extension of the Tsauchab River beyond its current end point during wetter climate conditions (Brook et al., 2006). Evidence is preserved as both channel deposits from river flow beyond the Tsauchab vlei and interdune deposition as ponding and low energy flow enable settling of sediment.

Wet conditions during the MH are recorded in sedimentary deposits in the Okavango Delta, Northern Kalahari (Fig. 3). In the Xugana region, evidence of enhanced fluvial activity is preserved in scroll bars of abandoned channel meanders and a sinuous palaeochannel from 7.7 ± 0.6 ka to 4.2 ± 0.2 ka (Tooth et al., 2022; site 4). Palaeodischarge estimates of 350–450 $m^3 s^{-1}$ are up to nine times greater than contemporary discharge (at the equivalent point in the delta) and suggest a fluvial response to a period of higher rainfall than present (Tooth et al., 2022). Enhanced Okavango channel flow under wetter conditions is also dated to 6.1 ± 0.2 cal ka BP in a record of sedimentology and palynology from the panhandle region (Nash et al., 2006; site 2). Within the Orange River system, SWDs from high discharge floods (12930–14,660 $m^3 s^{-1}$; site 55) indicate a period of hydroclimatic stability with increased rainfall and warmer temperatures (Zawada et al., 2000). Along the Modder River (site 58), an increase in hematite content within palaeosols developed in an overbank sedimentary unit indicates a rise in temperature at the site and a period of seasonally and annually higher rainfall (Lyons et al., 2014).

In the north of the Namib region and in the southern Kalahari part of the Orange region (Fig. 3), evidence of reduced fluvial activity in response to conditions drier than present is preserved (Fig. 9A). River-end deposits within the Hoanib catchment (7.4 ± 0.4 ka to 4.1 ± 0.3 ka; Eitel et al., 2006; sites 17–21) are interpreted as records of low energy flow where the river terminated further upstream than its contemporary end point. These deposits reflect a period of sporadic rainfall and ephemeral river flow within a climate more arid than today. Along the Molopo River, southern Kalahari, a transition from flash flood archives within channel deposits to low energy aggradation of fan deposits is recorded (Ramisch et al., 2017; site 53). These fan units were deposited due to decreasing flood intensity at 6.5 ± 0.6 ka and 5.6 ± 0.4 ka as a response to a more arid climate. Provenance analysis of these sediments indicate that the Molopo River was endoreic and connection between the Kalahari drainage and Orange River was limited during the Holocene.

4.4.3. *The last millennium (1 ka BP to present)*

Records from the last millennium, with smaller absolute uncertainties on ages and records overlapping with historical and instrumental datasets, have enabled a consideration of changes in flood frequency, in some cases at an annual resolution (e.g. Zawada et al., 2000). Here ages are quoted with the units 'yr' rather than 'ka' used above. From 33 sites along 16 rivers, 188 ages date to the last millennium. The frequency distribution of ages within this period highlights the dominance of records of extreme floods and high energy flow (75% of filtered ages dating to the last millennium; Fig. 9C), predominantly reconstructed from SWDs.

Quantitative discharge estimates from flash flood sequences have been calculated for 61 palaeoflood events within this period. In the Swakop River, three intervals of differing flood frequencies are recorded (Greenbaum et al., 2014; sites 25–27). These show an increase from i) one extraordinary flood every 180 years between 1280 and 740 yr BP, ii) one large flood every 80 years from 740 to 200 yr BP, to iii) one large flood every 7 years in the last 200 years. These intervals of changing flood frequencies are also preserved in the Kuiseb SWD record (Grodek et al., 2013; sites 31 and 32), but here with evidence of a large flood every 30–40 years, and periodic increases to flood frequencies of up to 7 floods in 20 years. In the Buffels River, warmer climate conditions resulted in a decreased flood frequency from 525 to 350 yr BP, and a colder wetter period resulted in higher flood occurrence from 350 to 150 yr BP (Benito et al., 2011; sites 59–62). SWDs along the Tsauchab (Völkel et al., 2021; site 43) and Tsondab (Völkel et al., 2021; site 39) correspond in timing to interdune deposits at Sossus Vlei, Tsauchab (Brook et al., 2006, site 41). From 0.9 to 0.3 ka, interdune and channel deposits within the Namib Desert indicate increased capacity of the Tsauchab River as a result of higher water availability in the system (Brook et al., 2006).

Flash flood records within SWDs have also been dated at sites within the Orange and Eastern Cape regions (Fig. 3), attesting to occurrence of high discharge events. In the Fish River, palaeodischarge estimates exceed historical records and indicate the occurrence of at least 12 large floods in the last 350 years (Cloete et al., 2018; sites 45–46). A regime of high energy ephemeral flow is also recorded in the Molopo River from 600 to 100 yr (Ramisch et al., 2017; site 53), and as extreme floods with high discharge in the Bloeddrift and Xobies regions of the Orange River (Zawada et al., 2000; sites 54, 55, 57), and Huis River (Bordy et al., 2018, site 63). Together, these records indicate evidence of ephemeral systems with extreme discharges within the last 1 ka, where decadal scale flood frequencies have been linked to synoptic climate patterns.

Chronologies have also been established from deposits of lower energy flow within the last millennium, indicative of arid conditions in the Namib and Northern Kalahari, and wetter conditions in the headwaters of the Orange. In the Namib, sedimentology of the Amspoort Silts in the Hoanib River indicates that their formation since 550 yr BP occurred as a result of decreasing runoff and aridification (Eitel et al., 2005; site 15). Analysis of Huab River sediments indicates an ephemeral flow regime with a lower capacity to transport sediment under lower precipitation than the MH (Walsh et al., 2022; site 22). This diminished fluvial activity is also recorded in the Xugana region of the Okavango at 180 to 200 yr (Tooth et al., 2022; site 4), with evidence of smaller channels with lower discharges. This is corroborated by the sedimentological and palynological record indicating a transition at 1 ka towards arid conditions similar to the present in the Okavango (Nash et al., 2006).

5. Conclusion

This paper presents an integrated assessment of late Quaternary palaeoenvironmental data from fluvial sedimentary archives in the relatively dry western and central regions of southern Africa. We present a new chronological database of ages, approaches, and interpretations of fluvial and climate conditions from 20 rivers. Analysis of associated river catchment data highlights the range of river types that have been studied: from moderate gradient ephemeral systems draining from the Great Escarpment in the Namib region, to low gradient endoreic rivers of the Northern Kalahari, and perennial river flow within the Orange River catchment. These systems are differentiated by catchment characteristics such as channel gradient, flow intermittence, and the precipitation regimes encompassed. Interrogation of the sedimentary contexts studied in these regions enables insight into the controls on sediment production and preservation. In particular, this analysis finds that reach-scale channel confinement has a strong control on both the type and length of fluvial histories preserved, supporting earlier investigations on channel confinement in other regions.

Whilst the number of studied fluvial archives is now substantial, the palaeoenvironmental histories they preserve are often complex. By filtering published research to ensure the integrity of their chronological underpinning, we are better able to distinguish between real heterogeneity in the environmental signal and that introduced through chronological uncertainty. We further argue that, as sedimentary archives in rivers can preserve a range of fluvial conditions, independent proxies such as information on the sedimentary context is required to confidently interpret late Quaternary environmental conditions. Here, we present a framework that identifies the types of data needed to reach interpretations of the nature of fluvial change and the spatial and temporal scales that these interpretations can be applied to. We find that a particular focus has been placed on assessments on the textural and architectural elements of sedimentary units and palaeodischarge estimates, yet analysis of sediment composition in terms of provenance is limited to date.

From this framework, we identify the importance of considering the magnitude of chronological uncertainties in determining the temporal resolution of climate variability that can be discerned, particularly in terms of distinguishing between *events*, *episodes*, and *phases*. The Quaternary fluvial record has therefore been interrogated at three timesteps with increasing resolution as absolute uncertainties decrease in younger deposits. At the LGM, sedimentary deposits preserve evidence of a fluvial response to predominantly wetter climate conditions, where currently ephemeral systems show evidence of intermittent and perennial flow in channelised systems, sustained water availability across the catchments, and ponding in playa environments. This signal is consistent across all studied rivers except the Modder River, located to the east of the study area, in which conditions drier than present prevailed. During the mid Holocene, evidence of seasonally intermittent flow is detailed in the Namibian ephemeral systems, enhanced palaeodischarge in the Northern Kalahari, extreme flood events in the Orange River, and a wetter climate than present at the Modder River site. Whilst these wet conditions represent a spatially extensive signal, records from the northern Namib and southern Kalahari indicate reduced fluvial capacity and aggradation of fan deposits under an arid climate. In the last millennium, an ephemeral flow regime is established in the majority of studied systems. Higher resolution chronologies have enabled detailed assessments of flood frequency changes and identification of intervals of increased occurrence of rainfall events with consistent timing, particularly amongst rivers in the Namib region.

This research highlights both the complexity and utility of southwestern Africa's fluvial archives and encourages the inclusion of quality-assessed fluvial records in palaeoenvironmental syntheses. At the regional scale, it would be useful to assess convergence between fluvial records and those from other hydrological proxies, such as datasets on calcrete formation, evidence of subsurface water movement from boreholes, and chronologies from lacustrine and aeolian settings. Mapping of the coverage of sites across the study area highlights priorities for future study. This could include a focus on sites where few ages have so far been used to establish chronologies and sites that would benefit from being revisited in the light of updated chronological protocols and robust independent approaches for palaeoenvironmental interpretation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data is available in the Supplementary Material

Acknowledgements

This research was funded by the UK Natural Environment Research Council (NERC, Grant No. NE/L002612/1).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.earscirev.2022.104288.

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