Australia's National Science Agency

River model calibration for the Southern Gulf catchments

A technical report from the CSIRO Southern Gulf Water Resource Assessment for the National Water Grid

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Aspects of the Assessment have been undertaken in conjunction with the Northern Territory and Queensland governments.

The Assessment was guided by two committees:

i. The Governance Committee: CRC for Northern Australia/James Cook University; CSIRO; National Water Grid (Department of Climate Change, Energy, the Environment and Water); Northern Land Council; NT Department of Environment, Parks and Water Security; NT Department of Industry, Tourism and Trade; Office of Northern Australia; Queensland Department of Agriculture and Fisheries; Queensland Department of Regional Development, Manufacturing and Water

ii. The Southern Gulf catchments Steering Committee: Amateur Fishermen's Association of the NT; Austral Fisheries; Burketown Shire; Carpentaria Land Council Aboriginal Corporation; Health and Wellbeing Queensland; National Water Grid (Department of Climate Change, Energy, the Environment and Water); Northern Prawn Fisheries; Queensland Department of Agriculture and Fisheries; NT Department of Environment, Parks and Water Security; NT Department of Industry, Tourism and Trade; Office of Northern Australia; Queensland Department of Regional Development, Manufacturing and Water; Southern Gulf NRM

Responsibility for the Assessment's content lies with CSIRO. The Assessment's committees did not have an opportunity to review the Assessment results or outputs prior to their release.

This report was reviewed by Assoc. Professor Mark Thyer, Systems Cooperative and School of Architecture and Civil Engineering, Faculty of Sciences, Engineering and Technology, the University of Adelaide.

The authors acknowledge useful conversations and data provided by Department of Regional Development, Manufacturing and Water hydrographers, Neal Searle and Mark Randall, to understand streamflow gauging station history and data quality.

Acknowledgement of Country

CSIRO acknowledges the Traditional Owners of the lands, seas and waters, of the area that we live and work on across Australia. We acknowledge their continuing connection to their culture and pay our respects to their elders past and present.

Photo

Leichhardt Falls on the Leichhardt River. Source: CSIRO

Director’s foreword

Sustainable development and regional economic prosperity are priorities for the Australian, Queensland and Northern Territory (NT) governments. However, more comprehensive information on land and water resources across northern Australia is required to complement local information held by Indigenous Peoples and other landholders.

Knowledge of the scale, nature, location and distribution of likely environmental, social, cultural and economic opportunities and the risks of any proposed developments is critical to sustainable development. Especially where resource use is contested, this knowledge informs the consultation and planning that underpin the resource security required to unlock investment, while at the same time protecting the environment and cultural values.

In 2021, the Australian Government commissioned CSIRO to complete the Southern Gulf Water Resource Assessment. In response, CSIRO accessed expertise and collaborations from across Australia to generate data and provide insight to support consideration of the use of land and water resources in the Southern Gulf catchments. The Assessment focuses mainly on the potential for agricultural development, and the opportunities and constraints that development could experience. It also considers climate change impacts and a range of future development pathways without being prescriptive of what they might be. The detailed information provided on land and water resources, their potential uses and the consequences of those uses are carefully designed to be relevant to a wide range of regional-scale planning considerations by Indigenous Peoples, landholders, citizens, investors, local government, and the Australian, Queensland and NT governments. By fostering shared understanding of the opportunities and the risks among this wide array of stakeholders and decision makers, better informed conversations about future options will be possible.

Importantly, the Assessment does not recommend one development over another, nor assume any particular development pathway, nor even assume that water resource development will occur. It provides a range of possibilities and the information required to interpret them (including risks that may attend any opportunities), consistent with regional values and aspirations.

All data and reports produced by the Assessment will be publicly available.

Chris Chilcott

Project Director

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Shortened forms

SHORT FORM	FULL FORM
ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
AET	actual evapotranspiration
API	application programming interface
AWAP	Australian Water Availability Project
AWRA-R	Australian Water Resources Assessment – River (a river model)
AWRC	Australian Water Resources Council
CITEC	Queensland Government Data Centre Services
CMRSET	CSIRO MODIS Reflectance-based Scaling evapotranspiration (a remotely sensed AET data product)
DE	differential evolution
DRDMW	Department of Regional Development, Manufacturing and Water, Queensland
DNRME	Department of Natural Resources, Mines and Energy, Queensland
EPD	error probability distance
ET	evapotranspiration
FAO56	Food and Agriculture Organization – Irrigation paper 56
FDC	flow duration curve
FSL	full supply level
GLUE	Generalized Likelihood Uncertainty Estimation (methodology)
GR4J	modèle du Génie Rural à 4 paramètres Journalier (rainfall-runoff model)
HRU	hydrological response unit
IQQM	Integrated Quantity and Quality model
KGE	Kling–Gupta efficiency
MIWB	Mount Isa Water Board
Mwet	Morton's wet area potential evapotranspiration
NASY	Northern Australia Sustainable Yields
netCDF	Network Common Data Form (a file format for storing multidimensional data)
NLWRA	National Land and Water Resources Audit
NSE	Nash–Sutcliff efficiency
OF	objective function
PU	physiographic unit
RR	rainfall-runoff
SILO	Scientific Information for Land Owners (climate data product)
Source	eWater Source (hydrological modelling software)

Units

Unit	Description
DOI	Digital Object Identifier
GL	gigalitre
ha	hectare
km	kilometre
L	litre
m	metre
mAHD	metres above Australian Height Datum
ML	megalitre
mm	millimetre
s	second
y	year

Preface

Sustainable development and regional economic prosperity are priorities for the Australian, NT and Queensland governments. In the Queensland Water Strategy, for example, the Queensland Government (2023) looks to enable regional economic prosperity through a vision that states 'Sustainable and secure water resources are central to Queensland's economic transformation and the legacy we pass on to future generations.' Acknowledging the need for continued research, the NT Government (2023) announced a Territory Water Plan priority action to accelerate the existing water science program 'to support best practice water resource management and sustainable development.'

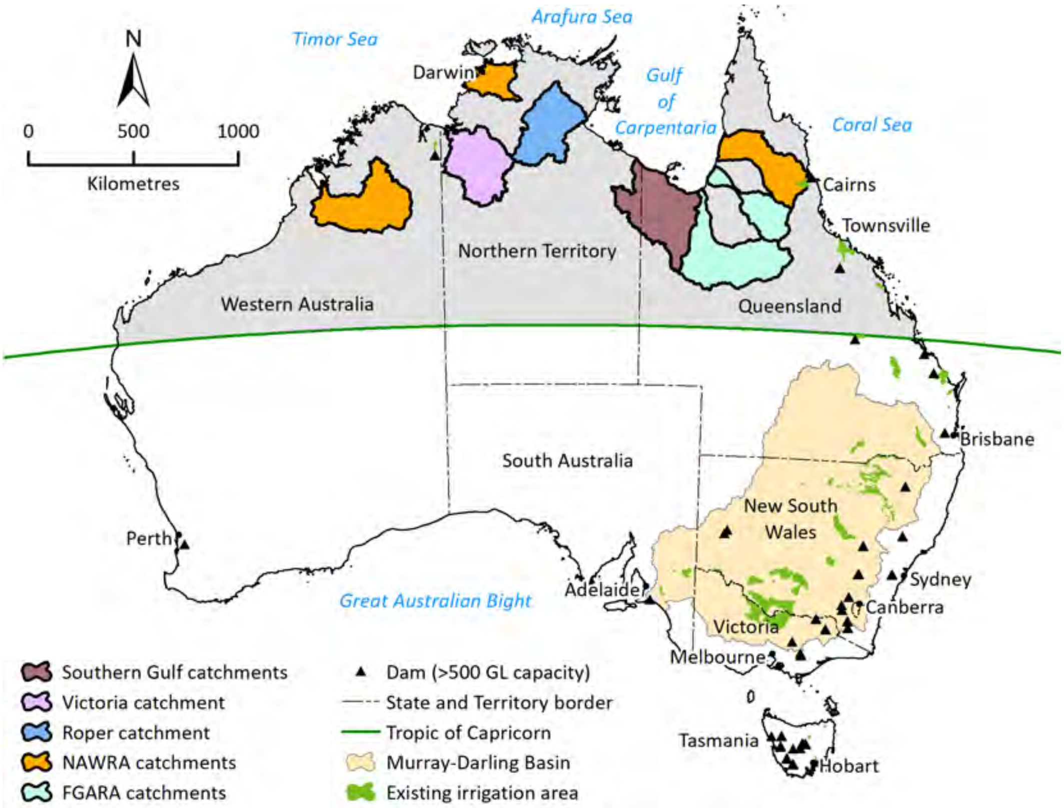
Governments are actively seeking to diversify regional economies, considering a range of factors, including Australia's energy transformation. The Queensland Government's economic diversification strategy for North West Queensland (Department of State Development, Manufacturing, Infrastructure and Planning, 2019) includes mining and mineral processing; beef cattle production, cropping and commercial fishing; tourism with an outback focus; and small business, supply chains and emerging industry sectors. In its 2024–25 Budget, the Australian Government announced large investment in renewable hydrogen, low-carbon liquid fuels, critical minerals processing and clean energy processing (Budget Strategy and Outlook, 2024). This includes investing in regions that have 'traditionally powered Australia' – as the North West Minerals Province, situated mostly within the Southern Gulf catchments, has done.

For very remote areas like the Southern Gulf catchments (Preface Figure 1-1), the land, water and other environmental resources or assets will be key in determining how sustainable regional development might occur. Primary questions in any consideration of sustainable regional development relate to the nature and the scale of opportunities, and their risks.

How people perceive those risks is critical, especially in the context of areas such as the Southern Gulf catchments, where approximately 27% of the population is Indigenous (compared to 3.2% for Australia as a whole) and where many Indigenous Peoples still live on the same lands they have inhabited for tens of thousands of years. About 12% of the Southern Gulf catchments are owned by Indigenous Peoples as inalienable freehold.

Access to reliable information about resources enables informed discussion and good decision making. Such information includes the amount and type of a resource or asset, where it is found (including in relation to complementary resources), what commercial uses it might have, how the resource changes within a year and across years, the underlying socio-economic context and the possible impacts of development.

Most of northern Australia's land and water resources have not been mapped in sufficient detail to provide the level of information required for reliable resource allocation, to mitigate investment or environmental risks, or to build policy settings that can support good judgments. The Southern Gulf Water Resource Assessment aims to partly address this gap by providing data to better inform decisions on private investment and government expenditure, to account for intersections between existing and potential resource users, and to ensure that net development benefits are maximised.



Preface Figure 1-1 Map of Australia showing Assessment area (Southern Gulf catchments) and other recent CSIRO Assessments

FGARA = Flinders and Gilbert Agricultural Resource Assessment; NAWRA = Northern Australia Water Resource Assessment.

The Assessment differs somewhat from many resource assessments in that it considers a wide range of resources or assets, rather than being a single mapping exercises of, say, soils. It provides a lot of contextual information about the socio-economic profile of the catchments, and the economic possibilities and environmental impacts of development. Further, it considers many of the different resource and asset types in an integrated way, rather than separately.

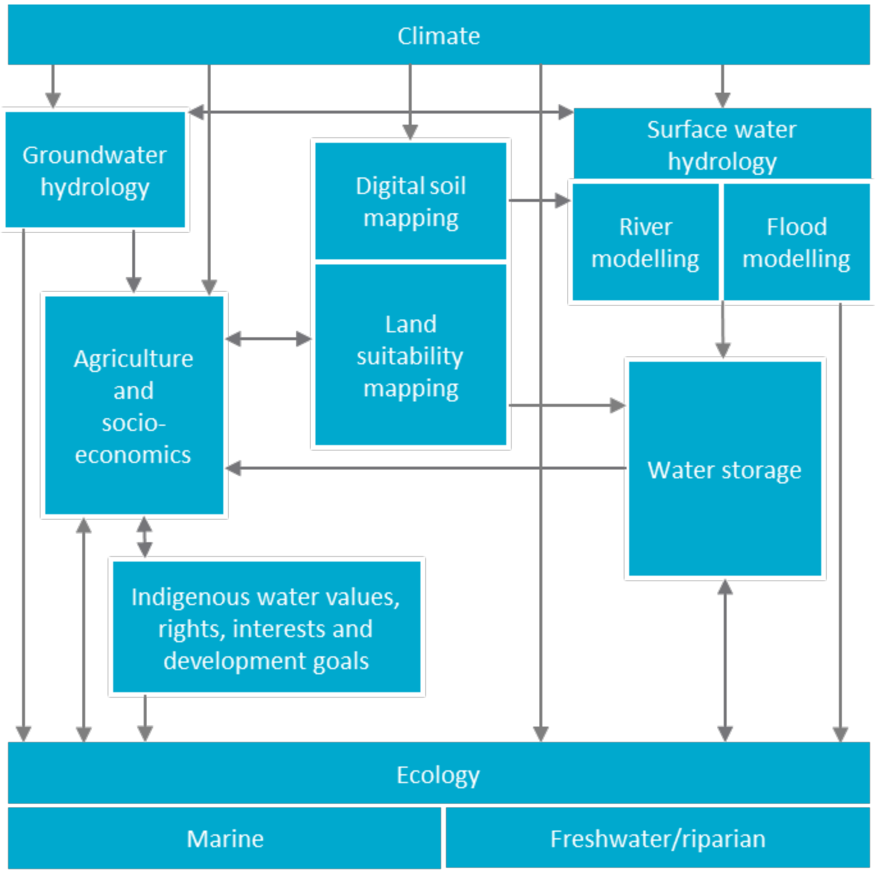
The Assessment has agricultural developments as its primary focus, but it also considers opportunities for and intersections between other types of water-dependent development. For example, the Assessment explores the nature, scale, location and impacts of developments relating to industrial, urban and aquaculture development, in relevant locations. The outcome of no change in land use or water resource development is also valid.

The Assessment was designed to inform consideration of development, not to enable any particular development to occur. As such, the Assessment informs – but does not seek to replace – existing planning, regulatory or approval processes. Importantly, the Assessment does not assume a given policy or regulatory environment. Policy and regulations can change, so this flexibility enables the results to be applied to the widest range of uses for the longest possible time frame.

It was not the intention of – and nor was it possible for – the Assessment to generate new information on all topics related to water and irrigation development in northern Australia. Topics not directly examined in the Assessment are discussed with reference to and in the context of the existing literature.

CSIRO has strong organisational commitments to Indigenous reconciliation and to conducting ethical research with the free, prior and informed consent of human participants. The Assessment allocated significant time to consulting with Indigenous representative organisations and Traditional Owner groups from the catchments to aid their understanding and potential engagement with its requirements. The Assessment did not conduct significant fieldwork without the consent of Traditional Owners. CSIRO met the requirement to create new scientific knowledge about the catchments (e.g. on land suitability) by synthesising new material from existing information, complemented by remotely sensed data and numerical modelling.

Functionally, the Assessment adopted an activities-based approach (reflected in the content and structure of the outputs and products), comprising activity groups, each contributing its part to create a cohesive picture of regional development opportunities, costs and benefits, but also risks. Preface Figure 1-2 illustrates the high-level links between the activities and the general flow of information in the Assessment.



Preface Figure 1-2 Schematic of the high-level linkages between the eight activity groups and the general flow of information in the Assessment

Assessment reporting structure

Development opportunities and their impacts are frequently highly interdependent and, consequently, so is the research undertaken through this Assessment. While each report may be read as a stand-alone document, the suite of reports for each Assessment most reliably informs discussion and decisions concerning regional development when read as a whole.

Executive summary

There are substantial opportunities for targeted development in northern Australia, and access to the water resources of the region is integral to their success. However, the extraction of water from rivers, particularly for water-intensive industries such as irrigated agriculture, can result in large perturbations to streamflow, which can affect existing users and result in ecological change. Hydrological river modelling is commonly used to quantify the water resources of a catchment and examine the trade-offs associated with water regulation and extraction.

This report outlines the development of the river model for the Southern Gulf catchments in northwest Queensland. In a subsequent scenario analysis report the model will be used to quantify past and future water availability in the region and to what degree of reliability can increasing volumes of water be extracted and how will streamflow be perturbed downstream.

The Southern Gulf catchments comprise four northerly draining catchments defined by the Australian Water Resources Council (AWRC) river basin boundaries of Settlement Creek (17,600 km^2), Nicholson River (52,200 km^2), Leichhardt River (33,400 km^2), Morning Inlet (3700 km^2), and the islands within the AWRC Mornington Island Basin (total 1240 km^2). The rivers and creeks in the area are seasonal (January to March) due to the vast majority of rainfall occurring during the wet season, with cease-to-flow periods for 30 to 60% of the time. The watercourses in the Gregory River catchment are a notable exception, with perennial flow associated with limestone and dolostone aquifers.

The Australian Water Resources Assessment – River (AWRA-R) model has been selected as a modelling platform for the Southern Gulf Water Resource Assessment. The AWRA-R model is based upon a series of connected subcatchments that can receive streamflow from upstream nodes, simulate various processes within each subcatchment, and, using a water balance approach, calculate various fluxes including subcatchment outflow, which may be used as an input to a downstream subcatchment. Existing town, mining and irrigation demands were estimated and included in the model, along with existing water storages such as Lake Moondarra and Lake Julius. The resulting model structure has a total of 77 flow simulation locations, based on existing streamflow gauging stations, the confluence of large catchment areas resulting in reasonably evenly distributed subcatchments, existing storages such as Lake Julius and Lake Moondarra, existing irrigation and mining demands, and other locations of interest.

Rainfall data are the key input to hydrological models. The rain gauge density in the catchments with streamflow data was one gauge every 2572 km^2, on average, for the Leichhardt River catchment, and every 3731 km^2 for the Gregory-Nicholson catchment. Rainfall data are sparse for the Settlement Creek and Morning Inlet catchments. Despite a low rainfall gauge density compared to parts of southern Australia, the rainfall data quality is considered acceptable for rainfall-runoff modelling, particularly compared to other regions in northern Australia.

Streamflow level and discharge data have been recorded at 23 streamflow gauging stations in the Leichhardt and Gregory–Nicholson River catchments, with no stations outside of these basins.

Only seven of these stations are currently operating. Due to the remoteness of the region and difficulty accessing streamflow gauging stations during the wet season, many stations only have dry-season low-flow streamflow discharge measurements, resulting in high uncertainty in mid-to-high flow estimates of streamflow at these sites. Also, at stations without a bedrock or constructed control structure, low-flow estimates of streamflow can also have a high uncertainty as river bed form can vary considerably from one season to the next or even within seasons. Given the variable runoff response relationship across the Southern Gulf catchments and limited coverage in suitable streamflow gauging station discharge data for model calibration, a hydrological response unit approach based on physiographic units was used to calibrate model parameters and provide a mechanism to regionalise parameters across the Assessment area.

The model was calibrated between September 1967 (when streamflow data became available in the region) to August 2022. Model calibration metrics include daily Nash–Sutcliffe efficiency values between 0.5 and 0.8, and bias typically within 20% of the observed volume at each location with observed data. An independent validation period over 2000 to 2010 was withheld from the calibration process and similar performance was obtained on this period compared to the calibration period, suggesting the model can generalise to simulate the catchment response outside data used to configure the model. As well as identifying one best set of model parameters, a 'behavioural parameter set' approach was adopted to represent the parametric uncertainty in the model results, with all 427 similarly performing model configurations stored to represent the plausible range in outputs.

The calibrated model was used to derive end-of-system volumes for each of the AWRC basins, as well as at selected locations across the Assessment area over the period from 1890 to 2022. Mean (median) annual end-of-system volume for the Leichhardt River catchment was 1,733 GL (1,112 GL), with the mean 3% lower than the previous estimate by CSIRO (2009a). For the Gregory-Nicholson catchment the mean (median) annual end-of-system volume was 2,476 GL (1,873 GL), 11% higher than the previous National Land and Water Resources Audit estimate, but 18% lower than the Northern Australia Sustainable Yields study. Across all catchments in the Assessment area the mean (median) end of system volume was estimated to be 6,823 GL (5,035 GL).

It is highlighted that the river models developed as part of this Assessment differ from the one developed by the Queensland Government for the Leichhardt River. The river models developed by Queensland Government in 2004 aimed to support the establishment of statutory water plans with the primary user being state government water policy officers. The river models developed as part of this Assessment are designed to compare hypothetical development scenarios using historical and future climate inputs. As a result, the models (created with a modelling framework that supports different functionalities and levels of accessibility) have different spatial resolutions and were calibrated using different input data and different modelling approaches.

This report outlines the development of river system models for the Southern Gulf Water Resource Assessment area. The models will be used in subsequent work to assess the reliability of water extraction, diversion and storage and perturbations to streamflow under hypothetical development and potential future climate scenarios.

Contents

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Part I Main report

1 Introduction

The regulation of surface water resources in southern Australia meets about 70% of Australia's 25,000 GL mean annual water use (CSIRO, 2011). With the overallocation of water in southern states, the recent millennium drought and projections of a drier future climate in southern Australia, there is interest in developing the water resources of northern Australia. However, the extraction of water from rivers, particularly for water-intensive industries such as irrigated agriculture can result in large perturbations to streamflow, which can affect existing industries and users and result in ecological change.

This report outlines the development of the river model for the Southern Gulf catchments in northwest Queensland and northeast NT. The Southern Gulf catchments comprise four northerly draining catchments defined by the Australian Water Resources Council (AWRC) river basin boundaries of Settlement Creek (17,600 km^2), Nicholson River (52,200 km^2), Leichhardt River (33,400 km^2), Morning Inlet (3700 km^2), and the islands within the AWRC Mornington Island Basin (total 1240 km^2). Figure 1-1 shows how median annual streamflow increases towards the coast in the Southern Gulf catchments. The rivers and creeks in the area are seasonal (January to March) due to the vast majority of rainfall occurring during the wet season, with cease-to-flow periods for 30 to 60% of the time. The watercourses in the Gregory River catchment are a notable exception, with perennial flow associated with limestone and dolostone aquifers.

To quantify the water resources of a catchment and examine the trade-offs associated with water regulation and extraction, a variety of hydrological modelling frameworks exist. At their simplest, hydrological models can be simple statistical relationships, typically with few input data requirements, but can also have a low predictive capacity. At the more complex end are fully distributed physically based models, for which every parameter has physical meaning and can be assigned by measurement. However, a key challenge in using physically based models is their large data requirements, without which many parameters potentially need to be calibrated, which makes them difficult to apply with confidence, particularly across large areas. In between these two extremes are a wide variety of models of intermediate complexity, including those described in this report:

- lumped conceptual rainfall-runoff (RR) models (e.g. Sacramento, GR4J), which are used to model runoff based on climate (rainfall and potential evapotranspiration) inputs, and

- river system models (e.g. Source, IQQM, AWRA-R), which used runoff from lumped RR models as inputs to model regulated systems and explore trade-offs in water use, operation and management rules.

In selecting an appropriate model or suite of models, it is important to understand the modelling objectives and select a model that is commensurate with the level of data available and then to be cognisant of its predictive capacity and model limitations.

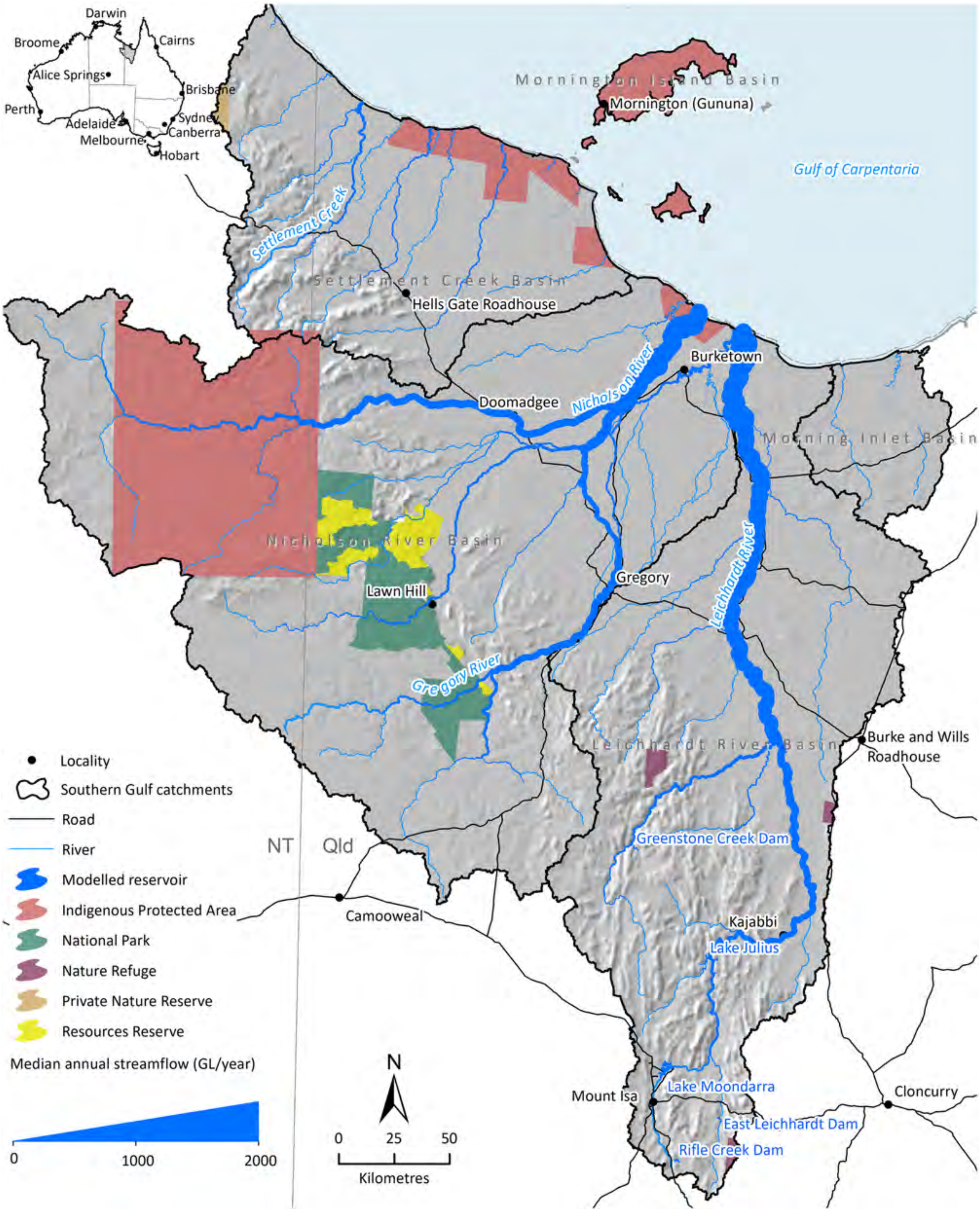

Figure 1-1 Southern Gulf Water Resource Assessment area showing the Leichhardt and Gregory–Nicholson rivers, Settlement Creek, Morning Inlet, Mornington Island and tributaries

River width represents the median annual streamflow, estimated using accumulated AWRA-L runoff

1.1 Surface water activity objectives

As outlined in CSIRO (2021), the surface water hydrology activity uses a modelling framework to obtain water storage and flux estimates over various spatial and temporal scales across the Southern Gulf catchments. This report outlines the development of the river model of the Southern Gulf catchments that will be used to answer the questions relevant to the surface water activity, detailed in a subsequent scenario analysis report.

The key questions that this activity seeks to address in the Southern Gulf catchments include:

- How much water has discharged from the catchment over different time frames since 1890?
- What are the opportunities to use surface water for multiple uses?
- Where is most runoff generated?
- With what degree of reliability can increasing volumes of water be extracted in different parts of the Southern Gulf catchments, and how will streamflow be perturbed downstream?
- How would changes in future climate potentially affect streamflow and water resource development in the Southern Gulf catchments?

1.2 Previous surface water modelling studies in the Southern Gulf catchments

The Department of Regional Development, Manufacturing and Water, Queensland (DNRME, 2004a) developed an Integrated Quantity and Quality Model (IQQM) river system model for the Leichhardt River basin, primarily to support the development of the Water Plan (Gulf) (Queensland Government, 2007). CSIRO (2009a) extended the climate inputs and used this IQQM model to report on water available in the Leichhardt River, where an annual end-of-system mean flow of 1785 GL was reported between 1890 and 2008. CSIRO (2009a) considered wet, mid and dry climate change scenarios resulting in changes in end-of-system flow of 29, 21 and –25% respectively.

No other river system modelling studies have been undertaken in the remainder of the Assessment area. The Northern Australia Sustainable Yields project (NASY) undertook rainfall-runoff (RR) modelling across northern Australia, including all of the Southern Gulf catchments (CSIRO, 2009a,b). Estimates of annual end-of-system mean flow volumes for the Australian Water Resources Council (AWRC) river basins were reported by Petheram et al. (2009). Petheram et al. (2009) also included other previous water balance estimates, from the National Land and Water Resources Audit in 2000 (ABARES, 2013) and from the Australian Water Availability Project (Raupach et al., 2007), with the volumes from all three studies reproduced in Table 1-1. The results are relatively consistent given the limited rainfall and streamflow data available in the region to calibrate RR models.

This surface water modelling activity builds on work previously undertaken in the Southern Gulf catchments, namely the NASY project (CSIRO, 2009b). As part of the NASY project, runoff was generated using an ensemble of conceptual RR models (Petheram et al., 2009). A more complex suite of hydrological models has been used in this work, most notably the node-link river model to represent travel times and losses and to also enable storages and diversion to be represented. Furthermore, a greater length of streamflow data is now available since the NASY project was completed in 2008.

Table 1-1 Comparison of modelled mean annual streamflow (GL) estimates for AWRC river basins in study area (reported by Petheram et al., 2009).

NLWRA volumes are as reported by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES, 2013)

AWRC RIVER BASIN	NASY	NLWRA	AWAP
Nicholson River	3,032	2,237	3,615
Settlement Creek	2,469	2,421	2,378
Mornington Island	364	393	243
Leichhardt River	1,932	2,158	1,979
Morning Inlet	298	422	409

Notes: AWRC = Australian Water Resources Council; NASY = Northern Australia Sustainable Yields; NLWRA = National Land and Water Resources Audit; AWAP = Australian Water Availability Project

2 Site characteristics

The physical characteristics of the Southern Gulf catchments are given in detail in companion technical reports on digital soil mapping and land suitability (Thomas et al., 2024) and climate (McJannet et al., 2023). To assist the reader, excerpts from these reports are reproduced here to provide an overview of the site characteristics.

2.1 Regional context

Mount Isa (population 17,936) is the region’s commercial, administrative and industrial centre. Elsewhere across the catchments, the population is generally sparse, with Doomadgee (1387 people), Gununa (on Mornington Island, 1136 people) and Burketown (167 people) being the largest towns. A substantial proportion of the population of the study area is Indigenous (27%), particularly in Doomadgee (more than 90%) and throughout Mornington Island and Wellesley Islands (80%). The main commercial land use is extensive grazing of beef cattle (84%) including on productive black soil plains, with nature conservation through national parks including Boodjamulla (formerly Lawn Hill) National Park, and Indigenous Protected Areas comprising 13% of the catchments’ area (Figure 1-1). Century Zinc Mine – formerly one of the world’s largest zinc mines – is located near Lawn Hill and there are large mining operations in and near Mount Isa.

2.2 Physiographic units

The mainland Assessment areas can be split into the uplands and the Carpentaria Plains. The upland area in the south and west reaches 620 m above sea level and is the headwaters for the Assessment area catchments. The uplands can be divided into four physiographic units (PUs), shown in Figure 2-1. The oldest, most elevated and rugged unit is the Isa Highlands. It consists of Precambrian (>545 years BP) volcanic and sedimentary rocks that have been metamorphosed, weathered and eroded. Soil parent materials within the Isa Highlands from west to east include rhyolite, basalt, dolomitic sediments, siltstone, meta basalt, granite, quartzite and metasediments. Land surface relief is moderate (200–230 m) and generally has a south to north alignment.

The next most elevated upland PU is a small part of Barkly Tableland to the west of the Isa Highland. The tableland started out as a sedimentary basin in Precambrian times, which was uplifted, folded and eroded. During the Cambrian period, seas transgressed the area and deposited carbonate sediments in the depressions. Later the Cambrian period sediments were exposed and eroded. During the Mesozoic era, isolated lakes and swamps developed, and during the Tertiary period the upland areas experienced deep weathering and laterisation. However, areas covered by lakes and swamps did not undergo strong leaching and subsequently, as the landscape dried, the current cracking clay soils formed on relatively fresh sediments. The clay soils overlie dolomitic rocks. Relief is very low (9–30 m) and Mitchell grasslands dominate. Since the Cambrian period the drainage network that flows toward the Gulf of Carpentaria has dissected the tableland leaving remnant land features defined by deep narrow gorges. This area is mapped as the Dissected Barkly Tablelands PU in Figure 2-1. Dissection has been amplified because the underlying rocks formed from dolomitic sediments are relatively soluble compared to surrounding rocks. These gorges have intersected the groundwater systems of the tableland resulting in spring-fed permanent creeks and rivers such as the O'Shannassy and Gregory rivers and Lawn Hill Creek.

The remaining parts of the Uplands, comprising mainly of Mesozoic era sedimentary formations (sandstones), have been eroded into a complex pattern of easterly flowing streams and valleys separated by ranges and outcrops of sedimentary formations. The PU is known as the Gulf Fall, and the Nicholson and South Nicholson rivers are the primary systems draining this area. Musselbrook, Lagoon, Settlement, Gold and Running creeks also drain this area.

To the east of the Uplands are the Carpentaria Plains comprising a series of plains, pediments and remanent plateaux that can be divided into six PUs. The most elevated sedimentary plain (30–150 mAHD) immediately east of the Uplands is the Cloncurry Plain PU in Figure 2-1. It consists of gently sloping colluvial and fluvial sedimentary plains and pediments with isolated low hills of Precambrian period rock. Streams are few and incised into the pediments with narrow alluvial plains. The Cloncurry Plain PU extends from the middle reach of the Leichhardt River to Lawn Hill Creek.

In the northern Assessment area, the Doomadgee Plain PU lies below and adjacent to the Cloncurry Plain PU and is predominantly a sandy, gently undulating plain overlying a deeply weathered Cenozoic era land surface. Low eucalypt and paperbark scrub cover the lands. Widely spaced creeks drain the plains currently in a radial north-westerly direction toward the coast. This suggests that the underlying old land surface could have been a large sedimentary fan.

In the southern half of the Assessment area, the Armraynald Plain PU (Figure 2-1) lies below and adjacent to the Cloncurry Plain PU and consists of argillaceous Cenozoic era (Quaternary period) sediments (Armraynald Beds) forming black soils covered in grasslands. Stream channels are few and widely spaced and deeply incised due to sea-level changes. The plains extend up the Lawn Hill Creek, Gregory and Leichhardt valleys. Lawn Hill Creek and Gregory River are spring-fed permanent running streams. The Gregory River splits into a giant braid (20 km at its widest) of permanent streams consisting of the Gregory River, Beames Brook, Barkly River and Running Creek downstream of the Gregory Crossing. Monsoonal rainforest grows immediately adjacent to these permanent streams that cross the otherwise grassland plains.

Down slope of both the Doomadgee Plain and Armraynald Plain lies the coastal Karumba Plain PU (Figure 2-1). This coastal unit extends 10 to 35 km inland from the Gulf of Carpentaria coast, and the plain is most extensive near the Albert River mouth. Some of the inland plains only flood when the rivers are in spate or when the north-westerly winds cause exceptionally high tides during the monsoon. Because the plain is wide and tidal range is moderate (about 3.5 m), and because the plain is generally flat, tidal waters can rapidly inundate the land. Mangroves and tidal flats dominate the coastline, and beaches are few and consist of white shelly sand. Small crescent dunes have formed in places from wind action. Strong north-easternly winds across the bare plains – especially in November – may cause a fog-like effect in Burketown from suspended particles. Due to the flatness of the plain. Streams meander in complex patterns.

To the east of the Armraynald Plains lies Donors Plateau PU. This slightly elevated unit (10–80 mAHD) forms the Morning Inlet AWRC basin on the eastern boundary of the Assessment area. The plateau consists of siliceous sediments laid down during the Albian (Early Cretaceous epoch) from upland sediment sources of the Normanton Formation. The plain, which was once more extensive, has been deeply weathered and lateralised in the highest elevation parts during the Tertiary period, and has subsequently been stripped away in parts leaving today's Donors Plateau as well as exposed older Cretaceous sediments.

2.3 Climate

The mean annual rainfall between 1 September 1890 and 31 August 2022 spatially averaged across the Southern Gulf catchments is 602 mm. Annual rainfall from a selection of stations across the area can be seen in Figure 2-2. Annual rainfall is highest near the coast primarily due to monsoonal activity, which generates considerable rainfall during the wet season, where rainfall totals decline in a southerly direction. Of this rainfall 94% was calculated as falling during the wet season (1 November to 30 April), with the highest median monthly rainfalls occurring during the months of January (138 mm averaged across the catchments) and February (131 mm). The months with the lowest median rainfalls were July and August (less than 1 mm) (Figure 2-2).

Multi-year variability is evident throughout the rainfall record, for example dry periods during the 1930s to 1960s and the late 1980s to late 1990s, with strong wet epochs in between, the 1970s, the 2000s, and the 2010s (Sharmila and Hendon, 2020). These multi-year rainfall variations can have profound impacts on agricultural production and associated business revenues in northern Australia (McKeon et al., 1990). This multi-year variability is likely to be an important factor to consider when considering hypothetical development scenarios and the implications of long-term dry periods.

Morton's areal potential evaporation in the catchments exceeds 1900 mm in most years. All catchments exhibit a strong seasonal pattern in potential evaporation, ranging from 200 mm per month during the build-up (October to December) to about 100 mm per month during the middle of the dry season (June). The difference between annual rainfall and annual potential evaporation is large (~1500 mm) and as a consequence the vast majority (>95%) of the Southern Gulf catchments is classified as semi-arid.

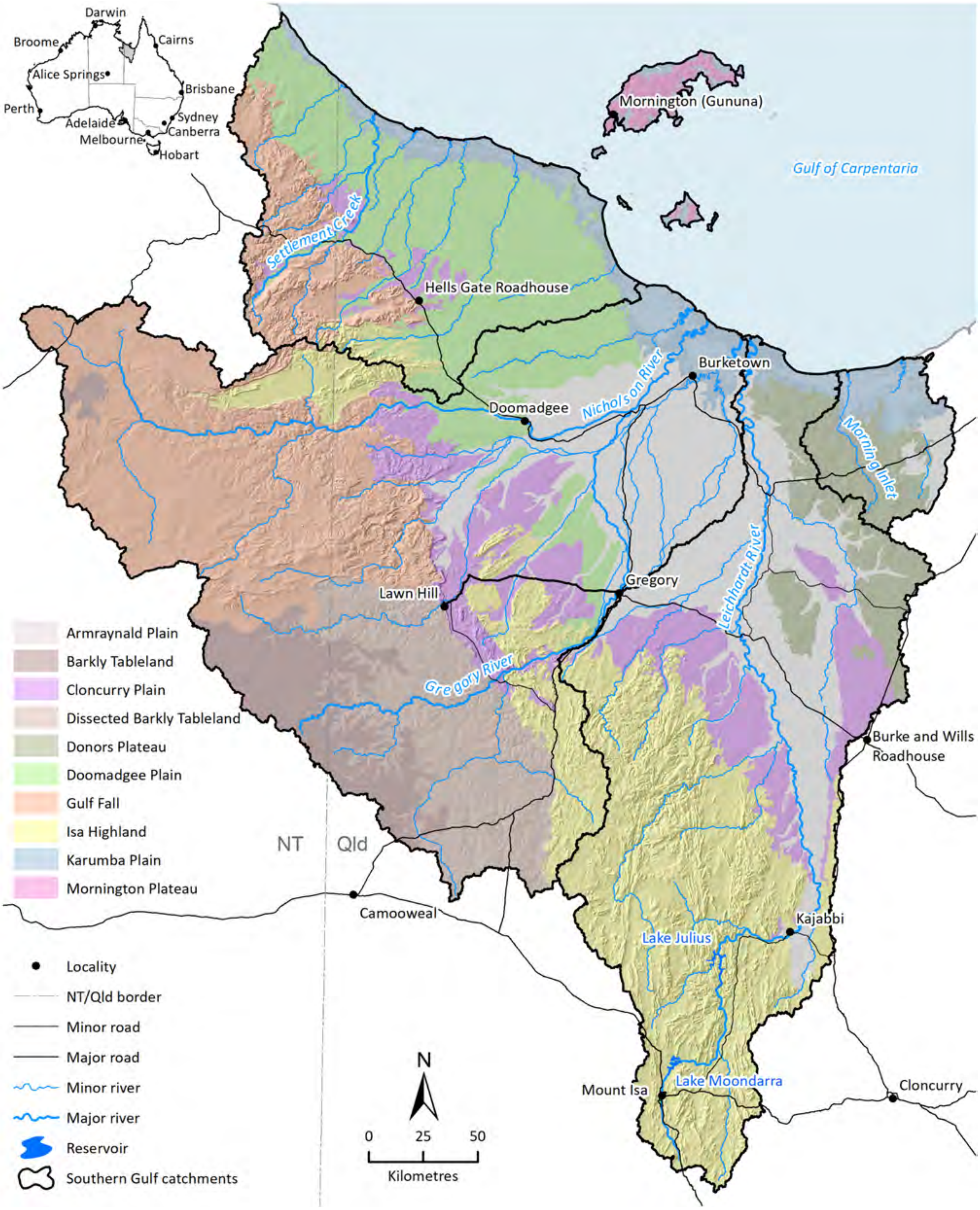

Figure 2-1 Physiographic units in the Assessment area

Source: Thomas et al. (2024)

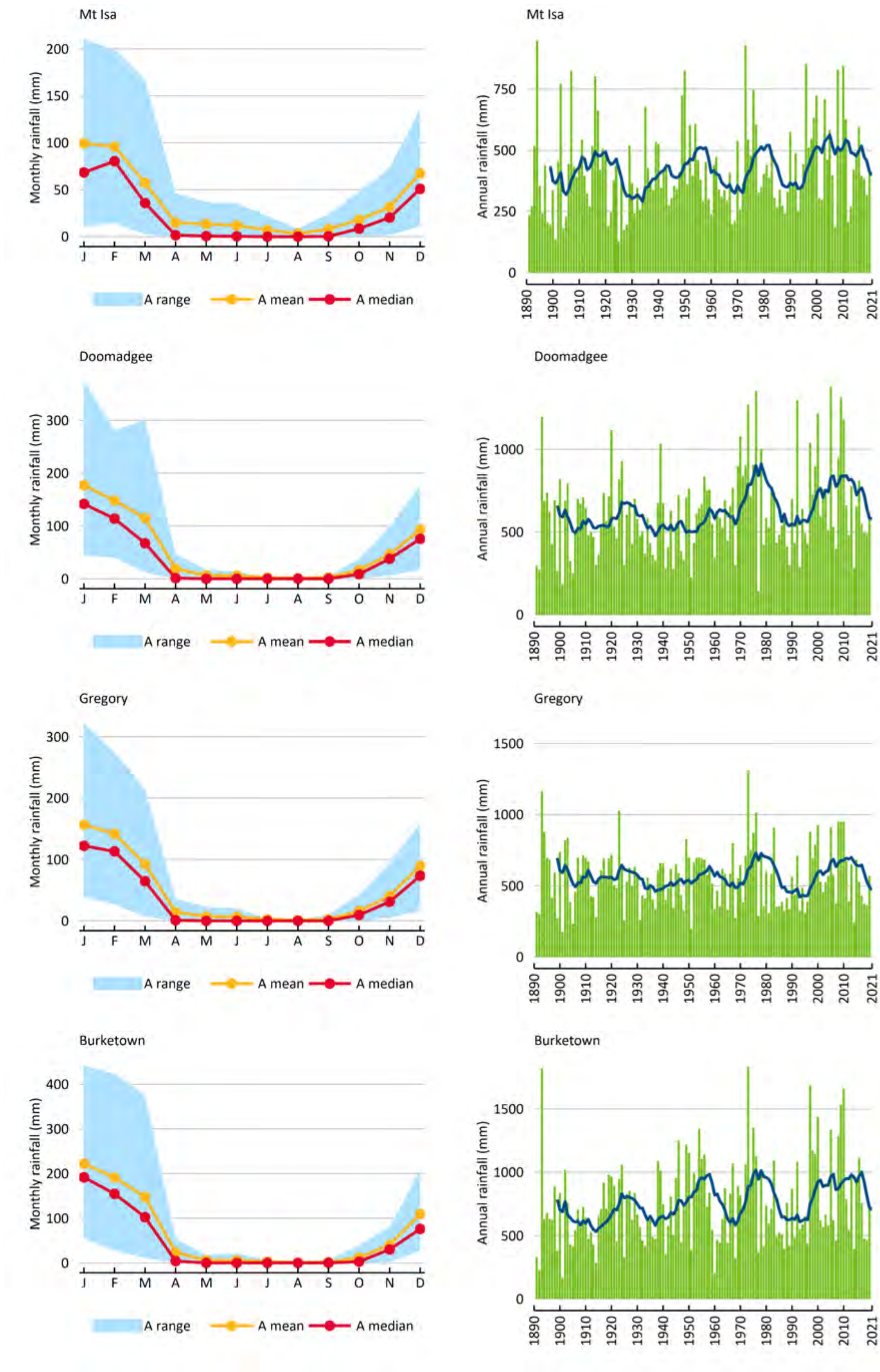

Figure 2-2 Historical rainfall in the Southern Gulf catchments at Mount Isa, Doomadgee, Gregory and Burketown. From McJannet et al. (2023)

Left column shows monthly rainfall, right column shows time series of annual rainfall (A range is the 10th to 90th percentile monthly rainfall).

3 Available data

The quality and quantity of the data available to the modeller has a significant influence on the methods used to estimate streamflow, as well as the potential model applications. The coincidence of climate data and streamflow data in space and time are of particular interest since one without the other means model calibration is not straightforward. To that end, the availability of rainfall data, and the availability of stream gauge data over time was examined for the catchment area to better understand the spatial coincidence of these data (or lack thereof).

3.1 Climate data

Rainfall data used for the Assessment was sourced from the SILO archive (Jeffrey et al., 2001) in two forms: 1) rainfall data availability was analysed based on the 'patched point' dataset, which contains direct observed rainfall time series for individual gauges with no gap-filling or interpolation, and 2) catchment average rainfall used for RR modelling was derived from the gridded rainfall dataset.

For the purpose of assessing rainfall data quality, rain gauge station data were obtained from http://www.longpaddock.qld.gov.au/silo as 'patched point' data (Jeffrey et al., 2001). Only direct observations were utilised for these analyses, while interpolated data were discarded. An exploratory evaluation of the spatial and temporal extent of the available climate data across northern Australia reveals that the Gulf region has some of the best historical coverage of rainfall (Figure 3-1) stations across northern Australia (McJannet et al., 2023). For this reason, as outlined in the companion technical report on climate, McJannet et al. (2023), the adopted reporting period, referred to as Scenario A, was from 1 September 1890 to 31 August 2022. While there is reasonable rainfall station density compared to other catchments across northern Australia, the gauges are still sparse in comparison to other more densely populated parts of Australia, for example the comparably sized Murrumbidgee catchment (~84,000 km^2) in NSW (last panel in Figure 3-1).

Many of the streamflow stations in the study area commence in the late 1960s or early 1970s (see next section). As seen in Figure 3-1 from the 1960s onwards there were multiple rainfall stations in each of the mainland Southern Gulf catchments to support RR model calibration to the observed streamflow data. Not shown in Figure 3-1 is the Mornington Island rainfall station, which commenced in 1914, and the Sweers Island gauge, which was added in 2001. The gauge density is highest for the Leichhardt River catchment with 13 gauges over the 33,430 km^2 producing one gauge every 2572 km^2, on average. The Nicholson River catchment has one extra rainfall station, but over the larger catchment area of 52,239 km^2 results in a lower density of one gauge per 3731 km^2. Notably there is only one gauge over the upper portion of the Nicholson River, with most gauges over the Gregory River and lower reaches of the Nicholson and Albert rivers for this catchment. Rainfall data are sparse for the Settlement Creek and Morning Inlet catchment, however there are no streamflow data for model calibration in these catchments either. Despite a low rainfall gauge density compared to parts of southern Australia, the rainfall data quality is considered suitable for RR modelling, particularly compared to other regions in northern Australia.

The ‘patched point’ data are not used for model calibration and simulation, but rather gridded Data Drill climate data from the same provider. This is an interpolated product but relies upon the same rainfall data that has been reviewed here. Data Drill data are a daily product supplied at 0.05 × 0.05 degree resolution (approximately 5 × 5 km). Observations have been quality checked by the Bureau of Meteorology and the interpolation routines used have been subjected to additional error checking by the Queensland Government (Jeffrey et al., 2001). Data accuracy is expected to be lowest in areas where the observation density is low relative to the climate gradients and where observations are only available for shorter time periods. Data from January 1889 until June 2023 were used as model input, with the first 20 months used as model ‘warm up’, with a model reporting period spanning 1 September 1890 to 31 August 2022.

Data Drill data were bulk downloaded as spatial layers (netCDF format) and aggregated to daily time series for each model subcatchment. As a part of this process Morton’s wet area (Mwet) potential evapotranspiration (ET) was calculated using other Data Drill variables. Mwet is an estimate of potential ET over a large area, assuming an unlimited supply of water. The model assumes upwind effects are negligible and local variations are ignored, so the estimate is an areal average (Wang et al., 2001). Chiew and McMahon (1991) found Mwet is similar to the United Nations Food and Agriculture Organization – Irrigation paper 56 (FAO56) (Allen et al., 1998) in a wet climate but lower than FAO56 in a dry climate. Chiew and Leahy (2003) found that Mwet is similar to FAO56 in the coastal areas of south-eastern and eastern Australia. Morton’s wet area potential ET calculations are detailed in Appendix A, based on Li et al. (2009).

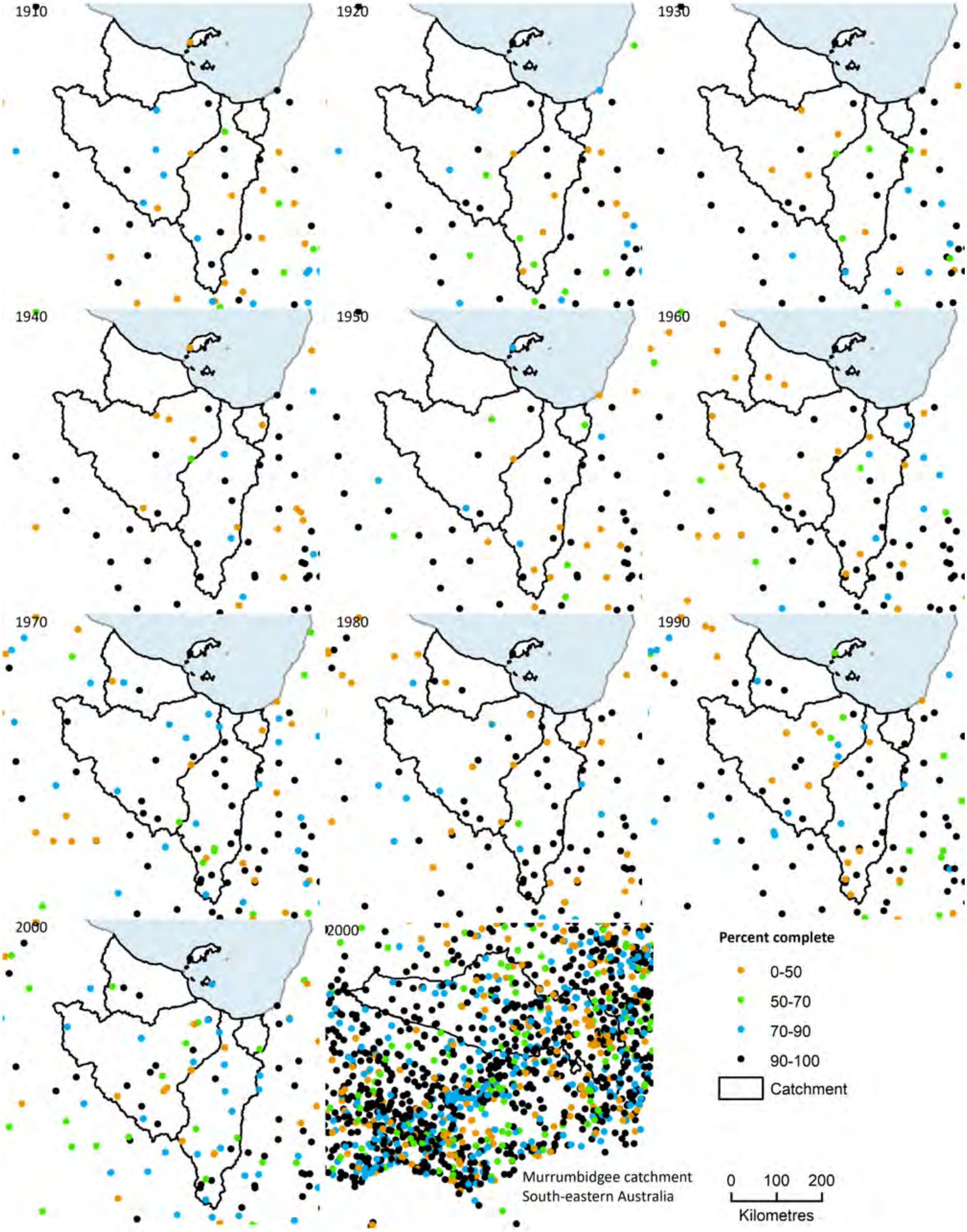

Figure 3-1 Decadal analysis of the location and completeness of Bureau of Meteorology stations in the Southern Gulf catchments measuring daily rainfall used in the SILO database. Reproduced from McJannet et al. (2023)

The decade labelled '1910' is defined from 1 January 1910 to 31 December 1919, and so on. At a station, a decade is 100% complete if there are observations for every day in that decade. The last panel shows the availability of rainfall data in the vicinity of the Murrumbidgee catchment in south-eastern Australia for comparison.

3.2 Stream gauge data

All streamflow data, including gaugings and quality codes, were obtained from the Queensland Department of Regional Development, Manufacturing and Water, with the location of stations presented in Figure 3-2. Data were extracted using the Hydstra application programming interface (API) over a 9 am to 9 am day, to coincide with daily rainfall data records. These data were examined together to determine the suitability of individual gauges for calibration. Quality code information and plots for all stations are provided in Appendix B with an example for the Gregory River at Riversleigh No. 2 station (912105A) shown in Figure 3-3. These plots assist the hydrologist making judgments of the value of stream gauge data at each site.

Gauging period, representation of data quality and the contributing catchment area for monitoring stations in the region, are summarised in Table 3-1. Of the 23 stations with data available, 15 were closed in 1988 as Federal funding for monitoring across Australia reduced. Another site closed in 2019, leaving seven stations currently operating across the Leichhardt and Gregory–Nicholson river catchments. There are no stations outside of these rivers, on the smaller coastal creeks in the Assessment area.

Streamflow gaugings are manual measurements of streamflow that are crucial to developing 'rating curve' relationships between the measured stage and the discharge of interest for water resource assessments. Due to the remoteness of the region and limited accessibility during the wet season, many sites only have dry-season low-flow gaugings. There is significant uncertainty in the discharge calculated from water levels using a rating curve above the maximum gauging as the curve is extrapolated and estimated using other information, typically the cross-section and water surface slope. Over half (12) of the 23 stations have less than 25% of the estimated total volume occurring below the maximum gauged flow, indicating unreliable estimates of most of the flow regime.

The stability of the river cross section is particularly important to the calculation of low flows, where changes in the cross section may change the water level corresponding to the commencement of flow, and the changes to the cross-sectional area have a proportionally large influence on the flow calculated for small changes in water level. Often rock bars across the watercourse are targeted for streamflow station installation, or concrete weirs are constructed, to have a sill level and cross section less likely to change during high flow events. The material of the controlling section at each station is included in Table 3-1. Most stations have a gravel or sand cross section, which has the potential to change over time. It is understood that at one of the few stations that does have a rock control, Gregory River at Riversleigh (912105A), sediment accumulates on top of rock bar during the dry season that changes the sill level of the controlling section, which is then washed away at the start of the wet season, resulting in changes in the relationship between water level and low flow discharge over time. The regular low flow gaugings undertaken at each the station can be used to update rating curves to reflect these changes, however this dynamic behaviour increases the uncertainty in the estimation of low flows at any given point in time.

The only site with a streamflow gauging in the past 35 years and a maximum gauging covering at least 75% of the total volume is the gauge at Gunpowder Creek at Gunpowder (913006A). The streamflow gauging station on the Gregory River at Riversleigh (912105A) also has a relatively high gauging to establish the rating curve, representing over 60% of the total estimated volume. While there is limited information on gaugings used to develop the discharge calculations, flow from Lake Julius is expected to have acceptable accuracy as any flow occurs through a constructed spillway with regular dimensions enabling estimation using weir equations.

Nicholson River at Connolly's Hole (912007A) has gaugings that cover most of the flow regime (86% of the total estimated volume), however this station was closed in 1988. Given the expected reliable rating curve, and this being the only station available on the Nicholson River, it was selected to be used for model calibration.

Most gauges are located toward the southern portion of the Assessment area, in the upper reaches of the catchments (Figure 3-2). The only gauge available in the lower reaches of the Assessment area is Leichhardt River at Floraville Homestead (913007B). This station has a long water level record commencing in 1984, however only has low flow gaugings to convert water level to discharge. To use the data available on the lower plains in the catchment but account for the low confidence in the calculated discharge, the data from this station will be used in a different manner for model calibration compared to data available from the other streamflow stations (see Section 5.5).

There are a number of anabranches on the Gregory River near the gauge at Gregory Downs (912101A). The proportion of flow occurring in each of the flow paths will have an influence on the flow remaining in the Gregory River and ultimately flowing toward the Nicholson River, and the proportion that splits off into Beames Brook and ultimately the Albert River at Burketown. Despite having a relatively low maximum gauging, the gauge at Gregory Downs is used to estimate the anabranch behaviour.

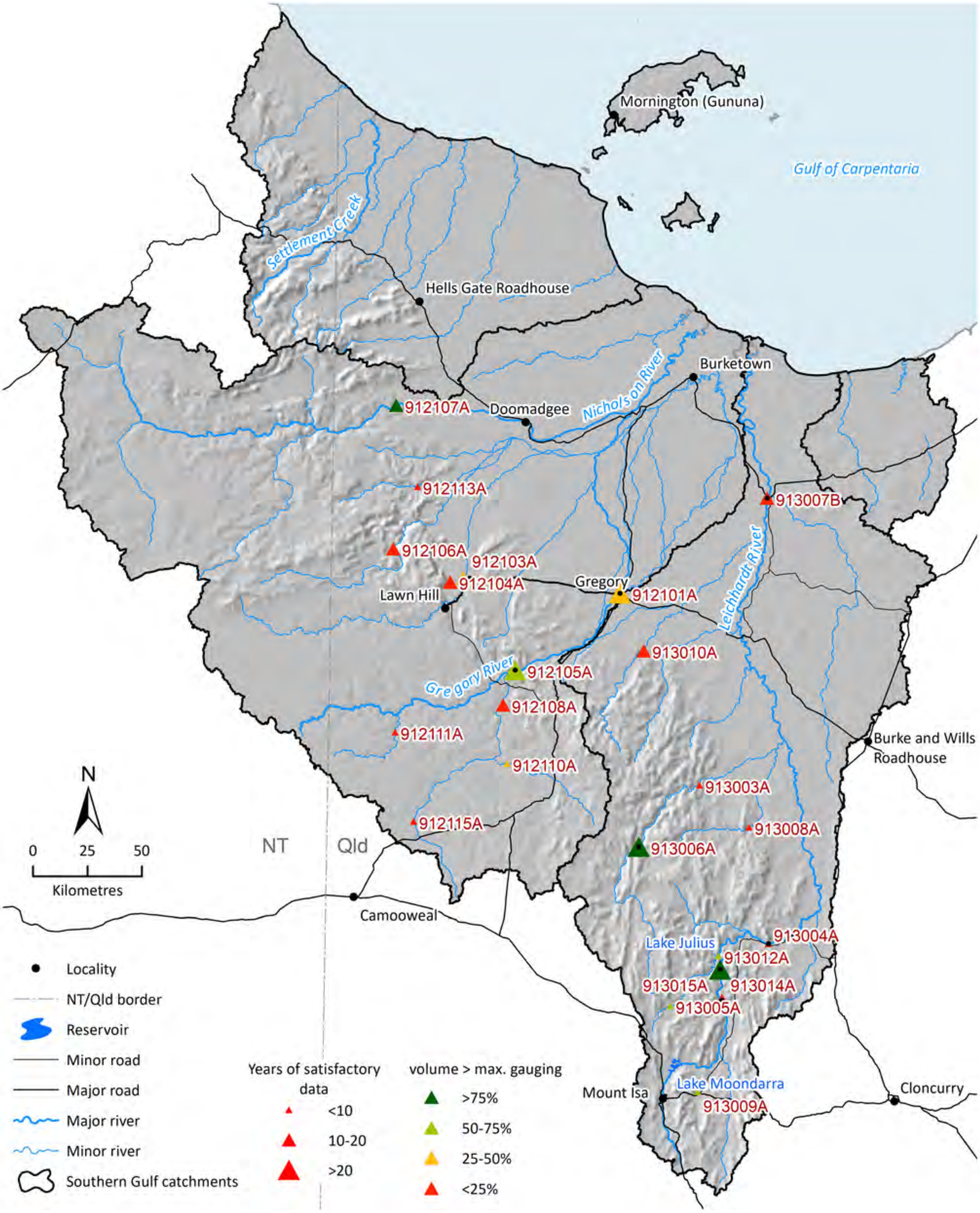

Figure 3-2 Location of streamflow gauges in the Southern Gulf catchments

Colours indicate the proportion of the total estimated volume that occurred below the maximum gauging at the site, with the size of the symbol the years of data with satisfactory data (defined as having a good or fair quality code). Sites that are currently open are indicated by a black dot inside the triangle

Table 3-1 Summary of streamflow stations in the Southern Gulf catchments

Gauges selected for model calibration indicated by * after the station number, with red numbers not meeting the criteria of volume below maximum gauging > 50% and years with good or fair quality code > 10. See section 5.3 for detail on gauge selection

STATION NUMBER	STATION NAME	DURATION			QUALITY CODE		MAX. GAUGED FLOW (m^3/s)	VOL. BELOW MAX. GAUGING (%)	YEARS WITH GOOD+FAIR QUALITY CODE	LOW FLOW CONTROL	CATCHMENT AREA (km^2)
		START	END	YEARS	GOOD (%)	GOOD + FAIR (%)					
912101A	Gregory River at Gregory Downs	1969		54	81	90	89	33	49	Gravel/Rock	12,567
912103A	Lawn Hill Creek at Lawn Hill No. 2	1919	1988	69	26	26	12	28	18	Gravel	4,003
912104A	Widdallion Creek at Lawn Hill	1968	1988	21	69	69	8	19	14	Sand	26
912105A*	Gregory River at Riversleigh No. 2	1968		55	47	87	565	64	48	Rock/Stone	11,382
912106A	Musselbrook Creek at Stockyard Creek	1968	1988	20	52	52	7	3	10	Stones	1,672
912107A*	Nicholson River at Connolly's Hole	1968	1988	20	55	55	1,758	86	11	Gravel	13,875
912108A	O'Shannassy River at 17.7 km	1968	1988	20	74	74	15	17	15	Gravel	5,591
912110A	Thornton River at Rosehill Bore	1970	1988	18	36	36	9	26	6	Gravel	1,716
912111A	Goonooma Creek at Norfolk	1970	1988	18	21	21	6	12	4	Gravel	1,103
912112A	Seymour River at Main Road	1970	1988	18	36	36	8	20	6	Stones	347
912113A	Elizabeth Creek at Mining Camp	1974	1988	14	43	43	5	4	6	Gravel	664
912115A	O'Shannassy River at Morestone	1970	1988	18	13	13	6	5	2	Sand	463
913003A	Gunpowder Creek at White Gorge	1968	1988	20	38	38	9	3	8	Gravel	3,585
913004A	Leichhardt River at Miranda Creek	1968		55	18	37	14	5	20	Gravel	5,959
913005A	Paroo Creek at Damsite	1968	1988	20	37	37	27	56	7	Gravel	304
913006A*	Gunpowder Creek at Gunpowder	1971		52	53	93	699	77	48	Gravel	2,412
913007B*	Leichhardt River at Floraville Homestead	1984		39	41	68	3	0	27	Rock	23,679
913008A	Mistake Creek at White Hills	1970	1988	19	38	38	6	8	7	Gravel	1,178
913009A	Gorge Creek at Flinders Highway	1970	1988	18	36	36	38	68	6	Gravel	250
913010A	Fiery Creek at 16 Mile Waterhole	1972	2019	47	32	91	15	19	43	Gravel	721
913012A	Leichhardt River at Julius Dam Tailwater	1970	1988	18	24	24	308	60	4	Gravel	4,748
913014A	Leichhardt River at Doughboy Creek	1978		45	44	65	19	8	29	Sand/Gravel	3,520
913015A*	Leichhardt River at Julius Dam	1980		42	99	99			42	Dam Spillway	4,748

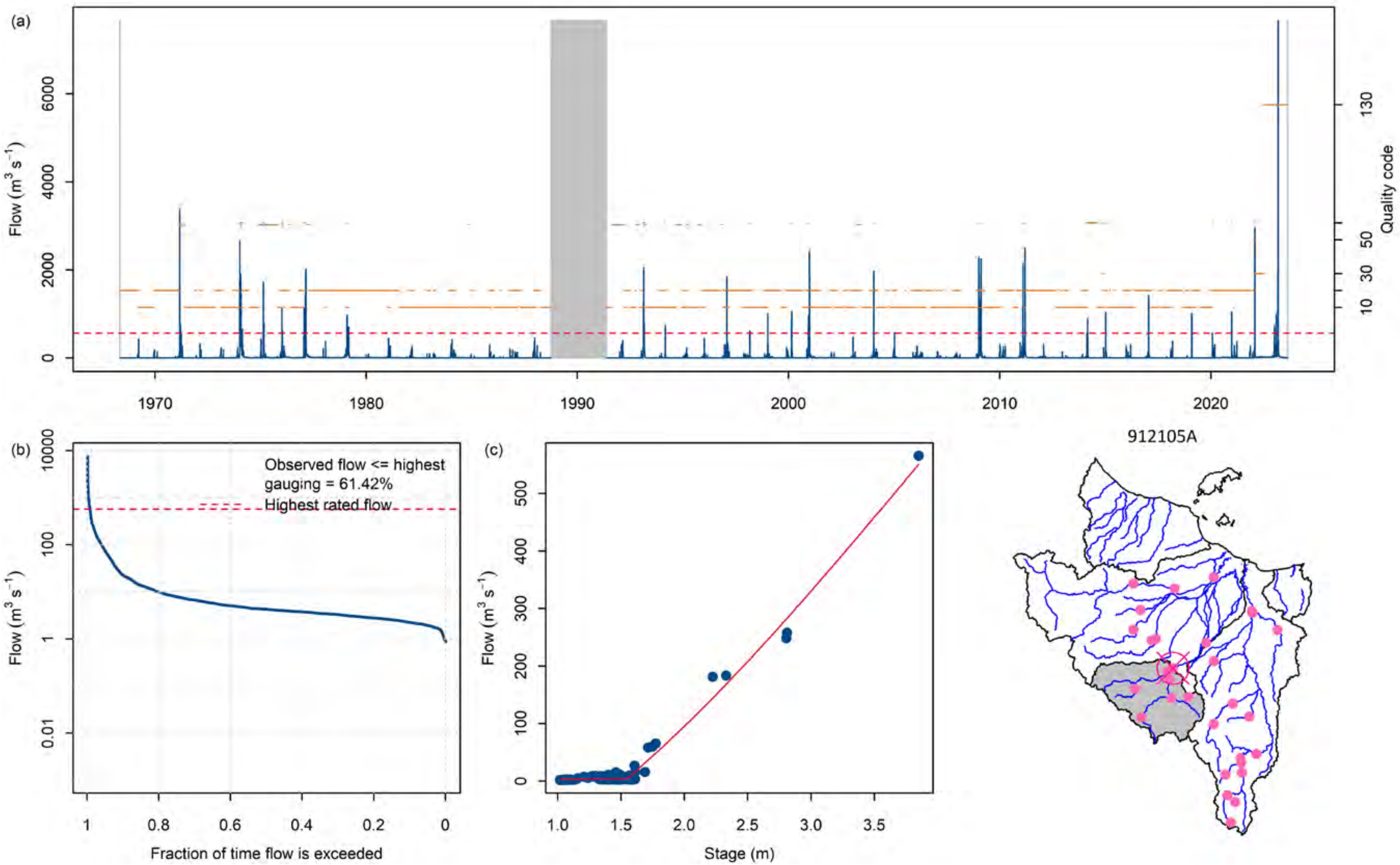

Figure 3-3 Stream gauge data for site 912105A (Gregory River at Riversleigh No. 2)

The dashed red line in plots (a) and (b) indicates highest gauged flow, with the solid red line on plot (c) a loess regression between the manual gaugings available (as opposed to the rating curve for the station). Quality codes are given by orange points in plot (a) and grey areas indicate periods with missing data. Similar figures for other streamflow stations are provided in Appendix B

4 Model software and structure

4.1 River model

The AWRA-R model has been selected for the Assessment. It was selected over eWater Source (a commonly used platform by jurisdictions), largely since it is flexible and has very short run times. AWRA-R is not designed to incorporate complicated operations rules as Source might, although for relatively undeveloped areas such as northern Australia this presents few, if any, simulation difficulties. Rather, the flexibility and short run times allows for extensive sensitivity analyses of hypothetical development scenarios, automated model optimisation and an ability to make the model available to users via a website where simulations can be run 'live' with development parameters of their choosing and accompanying ecosystem analyses.

The AWRA-R model is based upon a series of connected subcatchments that can receive streamflow from upstream nodes, perform various process within each subcatchment, and calculate various fluxes including subcatchment outflow, which may be used as an input to a downstream subcatchment. Outflow points for each subcatchment are generally referred to as a 'node'. Model parameters and time series inputs are required for each subcatchment. The AWRA-R model framework is written in the C language and is used in conjunction with the R language for ease of data processing and access to various functions such as optimisers, goodness-of-fit measures and plotting functions.

A brief summary is provided below, otherwise the reader is directed to the original references of Dutta et al. (2015) and Dutta et al. (2017). Each node in the model requires a configuration vector, a parameter vector, and a time series array as inputs. The standard model output is a time series of model states, including outflow. Where irrigation sub-models are used, these require additional irrigation parameters and configuration vectors, as well as additional time series inputs (e.g. crop coefficient values).

4.1.1 Routing routine

Routing represents the transport of water down a river reach from upstream to downstream. A river channel has capacity to store water in varying degrees, which induces a time lag from inflow to outflow, as well some attenuation and dampening of the hydrograph peak across the reach. These effects were simulated using a lagged Muskingum procedure (Koussis, 1980):

$$\frac{dV}{dt} = I(t - lag) - O \quad (1)$$

and

$$V(t) = K[x * I(t - lag) - O(1 - x)] \quad (2)$$

where *V* is the routing volume (m^3), *I* and *O* are the reach inflow and outflow respectively (m^3/second), and *t* is time. *K* is a calibrated routing parameter, where *x* and *lag* are assumed to be zero.

4.1.2 Loss model

Physically, as water moves along a channel it may experience 'gains' or 'losses' due to exchanges with groundwater or soil water. Transmission losses are very difficult to measure directly, so any loss function that is calibrated jointly with other states (against observed flow) will also implicitly account for gauge error, poor system representation, or overestimates in other model states (e.g. unaccounted runoff). Most model estimates of loss are flow based:

$$l(t) = f(Q(t)) \tag{3}$$

where l is the loss and f is a function describing the flow-based loss. For the Assessment, the loss estimation method developed by Doble et al. (2012) was used. This method is dependent on physical properties of the river bed material, river stage, river length, river width, depth to groundwater and specific water yield of the aquifer. This method is referred to as 'Doble loss'. The river hydraulic conductivity parameter is calibrated jointly with the RR and routing parameters for each reach. Optimal parameter sets are then used for subsequent simulation. The equations for the Doble loss calculations are given below:

$$Q_{gw} = \min(I_{riv}, \Delta S_{riv} + \ q_{riv}) * L \tag{4}$$

$$I_{riv} = Ks_{riv} a_{riv} \left(\frac{h_{riv}}{d_c} + 1\right) \tag{5}$$

$$\Delta S_{riv} = d_{gw} S_y x_w \tag{6}$$

$$q_{riv} = K_{aq} d_{aq} \frac{2h_{riv}}{x_w} \tag{7}$$

where I_{riv} is potential infiltration rate from the river (m^2/second), ΔS_{riv} is total storage available (m^2/second) within the regolith beneath the streambed, q_{riv} is maximum volume of water discharging from the aquifer (m^2/second), L is the length of the reach (m), Ks_{riv} is river bed hydraulic conductivity (m/second), a_{riv} is surface area of the river (m^2) obtained from a flow–area relationship, h_{riv} is depth of river water (m) obtained from a flow–depth relationship, d_{gw} is depth to groundwater (m), d_c is the thickness of the river bed material, S_y is the aquifer-specific water yield (dimensionless), x_w is the width of the river (m) derived from a flow–width relationship, K_{aq} is the aquifer hydraulic conductivity (m/second) and d_{aq} is the aquifer thickness.

In all cases, depth to groundwater information was not available at appropriate spatial and temporal resolution. Accordingly, depth to watertable was assumed static at 5.0 m. The river bed conductivity was calibrated jointly with runoff and routing parameters. Effectively, the Q_{gw} calculations are simplified to an estimation of I_{riv} that is at least partly controlled by the calibrated parameter Ks_{riv}, since Q_{qw} is taken as the minimum of the two terms I_{riv} and $\Delta S_{riv} + Q_{riv}$, and the final two states $\Delta S_{riv} + Q_{riv}$ are likely to be higher due to depth to groundwater assumptions. This method was favoured partly since it is has some physically based constraints (compared to a loss-flow lookup table, for example), but also since it requires only one calibrated parameter and can be applied easily to ungauged locations, requiring an estimate of reach length and assuming the parameters from donor catchments.

4.1.3 Water demands and diversions

Town and mining demands

Existing town water supply and industrial (predominately mining) water demands in the Leichhardt River catchment were represented using constant daily diversions. Given these demands are met from the storages such as Lake Moondarra and Lake Julius, the variations in the pattern of demand over the year are not expected to significantly influence model calibration. Further details on the data sources used to determine existing town and industrial demands are outlined in Section 5.4.

Irrigation demands

The irrigation demand modelling is undertaken using the AWRA-R irrigation demand model (Hughes et al., 2013, 2014). The AWRA-R irrigation model features a soil water store that represents the water balance for an entire irrigation area within individual reaches. Water is extracted from the virtual soil water store according to demand generated from a crop model. Crop demand is based on the FAO56 method (Allen et al., 1998), using crop factors for sown crops and climate data. As the soil water store becomes depleted, increasing volumes of irrigation demand are triggered. Irrigation demand is zero when the soil store is full. One-dimensional demand is converted to volumetric demands via sown crop area. Sown crop area is determined at a series of crop decision days within the irrigation season. Sown crop area can be adjusted depending upon the volume of available water from each of the three sources:

1. surface water licence (managed irrigation district)

2. on-farm storage

3. groundwater licence.

Crop demand for all irrigated crops grown in the reach are determined in the following way:

$$D = (Kc * ET_o * \rho - P * A_a) * A_c / L_t \qquad (8)$$

where D is the total crop demand (m^3/second), K_c is the area weighted crop factor (to include multiple concurrently grown crops), ET_o is the time step potential ET (m), ρ is the soil-dependant crop water stress (dimensionless, range 0–1), P is the time step rainfall (m), A_a is the proportion of the current irrigation area actively growing crops at the current time step, A_c is the current irrigation area, E is irrigation efficiency (dimensionless) and L_t is the time step length (s). Crop demand is supplied via the soil moisture store, which is in turn supplied via irrigation using the following relationships:

$$Irrigation = \begin{cases} I_{max} * A_a * A_c * E / L_t & if \quad \theta_t \leq 0 \\ I_{max} * e^{-\frac{\theta_t^2}{2\sigma^2}} * A_a * A_c * E / L_t & if \quad \theta_t > 0 \end{cases} \qquad (9)$$

and

$$I_{max} = \frac{\gamma}{\sigma\sqrt{2\pi}} \tag{10}$$

where γ and σ are user-defined parameters that are adjusted to suit the soil water-holding capacity of the area of interest, I_{max} is the highest possible rate of irrigation (m) per time step and θ_t is the first estimate of soil water storage for the current time step. When the soil water store is full (say, following rainfall, and $\theta_t = \text{soil capacity}$), no irrigation is triggered.

The model features an on-farm storage module that can extract water from a reach according to user-defined pump parameters, allocation/licence limits and reservoir volumes. Water can then be extracted from the storage as required. Additionally, water can be extracted for irrigation directly from the river, although this feature is more commonly used in larger managed irrigation districts where water is diverted and supplied to irrigators via a channel system. To represent an existing user upstream of one of the calibration gauges in model calibration, the on-farm storage modules were utilised.

4.1.4 Rainfall-runoff model

Rainfall-runoff (RR) models take a 'top-down' approach to estimating runoff, viz., model parameters are adjusted until the model simulation matches streamflow observations to the satisfaction of the hydrologist. This model can then be used to estimate flow at a time outside of the calibration period (assuming inputs, usually daily precipitation and potential ET, are available). In many situations, no streamflow observations are available at a desired location, and parameters must be transposed using other methods.

The calculations within the RR models are influenced by observations of hydrological processes, and hence these models are often termed 'conceptual models'. The ease of use and modest data requirements of these models has seen their widespread application, so much so that these models are applied in a vast array of environments not anticipated (presumably) by the original model authors. Given this, the modeller must take care in their application, especially in environments such as northern Australia. Furthermore, these models are prone to 'overfitting' (i.e. poor predictive performance despite satisfactory representation of observed streamflow during calibration). This is related to the inability of the model to implicitly represent all processes and fitting to any error in input and streamflow observations.

The rainfall-runoff model used for the Assessment was the 13-parameter Sacramento RR model (Burnash et al., 1973; Burnash 1995), successfully used for numerous previous Assessments across northern Australia (Petheram et al., 2012; Hughes et al., 2017; Petheram et al., 2017, 2018a–d).

4.1.5 Reservoir model

Large instream dams have the potential to store water across years and are a means of mitigating the impacts of lower rainfall years on water users. However, disruption to the hydrological characteristics of a stream can also be large, depending upon reservoir operation, with consequences for ecosystems with a dependency on river flows (Pollino et al., 2018).

The reservoir model utilises a water balance equation as follows:

$$V_t = V_{t-1} + Q_l + Q_{in} - D_t - S_t - T_t + (P_t - E_t) * A_t \tag{11}$$

where:

V_t is the reservoir volume at time t

V_{t-1} is the reservoir volume at the previous time step

Q_l is the estimate of local subcatchment streamflow which is, in part, a function of the reservoir surface area

Q_{in} is the estimate of inflow from all other upstream subcatchments into the reservoir

D_t is the diversion out of the reservoir

S_t is the dam spill

T_t is transparent and/or translucent flow released from the reservoir for environmental purposes

P_t is the rainfall on the reservoir surface

E_t is the evaporation on the reservoir surface

A_t is the surface area of the reservoir at time t.

Similar to AWRA-R, the reservoir model was written using C code within an R wrapper.

Time series model inputs are:

1. local climate (rainfall and potential ET)

2. reach inflow (from the river model)

3. local runoff (from the river model)

4. daily diversion out of the reservoir

5. evaporation correction factor.

Additionally, there are various scalar inputs that control such factors as reservoir evaporation adjustment, dam full supply level (FSL) (and height, volume and area relationships for the site) and spillway properties.

The evaporation inputs are calculated using the Morton's wet area algorithm (Morton, 1983). However, these and other typical evaporation estimates have been shown to be different to measured lake evaporation (as shown in Figure 4-1) in some instances, due to variable fetch conditions for example. Accordingly, lake evaporation is estimated using dynamic lake area (A_t) and monthly correction factors based on measured lake evaporation data collected during the project.

Figure 4-1 Floating evaporation pan used to determine water surface evaporation, pictured on Lake Julius on the Leichhardt River

Photo source: Nathan Dyer, CSIRO

4.1.6 Node-link structure

The number and position of river model nodes across a study area is determined by the study's modelling objectives. Increasing the number of nodes increases the flexibility of the model in relation to the number and degree of detail possible within model scenarios; however, increasing the number of nodes also increases the computational burden and model run times. For the Assessment, nodes were assigned to:

1. represent stream gauge positions, allowing for model calibration
2. divide the catchment into reasonably evenly distributed subcatchments and the confluence of large catchment areas
3. existing storages such as Lake Julius and Lake Moondarra
4. existing irrigation and mining demands
5. locations of potential dam sites and water harvesting
6. potential locations of irrigation
7. locations of ecological assets and where reporting on changes may be desired.

The final node and subcatchment structure are shown in the Section 5.

5 River model calibration method

5.1 Model structure

The node-link structure for the AWRA-R model can be seen in Figure 5-1. Initially nodes were located at existing gauges, adopting the node number of the gauge with an additional ‘0’ appended to the number. Additional nodes were located at existing water storages and water users, including the largest dams of Lake Moondarra and Lake Julius, Rifle Creek Dam on Rifle Creek (owned by Mount Isa Mines) and Greenstone Creek Dam (supplies the township of Gunpowder). The East Leichhardt River Dam, understood to not currently be in use, was also included as a node location. Additional nodes were included to subdivide large catchments, particularly to enable streamflow from different tributaries to be represented separately in the model, and to assess locations of interest for dam sites, water harvesting, or changes in streamflow. In total, the Southern Gulf AWRA-R model has 77 simulation nodes.

5.2 Hydrological response units

The Southern Gulf catchments have variable runoff response relationships across the catchments. Most notably, the Gregory River is fed by carbonate aquifers and as such has perennial flow and relatively clear water, in comparison to the other rivers in the area that have some cease-to-flow periods, are more seasonally dependent, and are more turbid. The limited streamflow records available in the catchment do not provide sufficient information to directly calibrate different model parameters in the subcatchments to represent this spatial variability, and a method to regionalise parameters from gauged to ungauged subcatchments in the Assessment area is required.

Spatial proximity alone may not necessarily result in similar functional behaviour (e.g. Ali et al., 2012), and model performance can be improved when applying physically based distance measures (Bárdossy et al., 2005; He et al., 2011; Hrachowitz et al., 2013). Physiographic similarity is commonly used as this distance measure, as a proxy for functional similarity (Arheimer and Brandt, 1998; Parajka et al., 2005; Masih et al., 2010). To account for the different runoff characteristics across the area and provide an approach to regionalise parameter sets to ungauged regions of the Assessment area, a hydrological response unit (HRU) approach based on PUs has been adopted.

The HRU approach assumes that catchments with similar characteristics will have similar RR responses, and hence calibrated model parameters can be transferred to these similar catchments. For this work the PUs identified in Thomas et al. (2024) have been used to determine areas of similar response, defined as a HRU. The ten PUs identified (Figure 2-1) have been grouped into four HRUs (Figure 5-1):

- Gulf Fall unit, occurring in the upper Nicholson River
- Isa Highland, predominately occurring in the upper Leichhardt River but also into the Gregory and Nicholson river catchments

- Dissected Barkly Tableland, representing the perennially flowing catchments of the Gregory River
- the lower plains unit, representing an aggregation of the Armraynald Plain, Cloncurry Plain, Donors Plateau, Doomadgee Plain, Karumba Plain and Mornington Plateau PUs.

The grouping of the lower plain units was partly undertaken to maintain model parsimony, as each HRU introduces an additional 15 parameters to be calibrated, and partly due to a lack of available streamflow data to represent the different PUs separately.

The Barkly Tableland PU, which occurs high in the catchment of the Gregory and Nicholson rivers, was aggregated with the PU surrounding it, either the Dissected Barkly Tableland for the Gregory River or the Gulf Fall for the Nicholson River. The resulting HRUs adopted for model calibration and regionalisation can be seen in Figure 5-1. Subcatchments that contain more than one HRU were separated to have the model parameter for each HRU applied based on the relevant catchment area, and then aggregated to produce the simulated runoff from that subcatchment.

5.3 Streamflow data

Analysis of available gauging stations and associated data quality is outlined in Section 3.2. Stations with more than 50% of the estimated total volume covered by streamflow gaugings and more than 10 years of data with a good or fair quality code were selected as the highest quality stations for calibration of RR and loss model parameters. These stations were:

- 912107A Nicholson River at Connolly's Hole, largely coinciding with the Gulf Fall HRU
- 912105A Gregory River at Riversleigh No. 2, largely coinciding with the Dissected Barkly Tableland HRU
- 913006A Gunpowder Creek at Gunpowder and
- 913015A Leichhardt River at Julius Dam, with both sites having only the Isa Highland HRU upstream

These stations provided observed data to calibrate parameters for three of the four HRUs. There is only one station in the Plains HRU available, 913007B Leichhardt River at Floraville Homestead. This station has less than 1% of the observed volume below the maximum gauging. A different objective function has been used for model calibration at this location to account for the high uncertainty introduced by the extrapolated rating curve used for the majority of streamflow (see Section 5.5).

While not meeting the above criteria with 33% of the estimated volume below the maximum gauging, station 912101A Gregory River at Gregory Downs has a long record of 54 years (48 years with good or fair quality code). This station has been used to develop a relationship to quantify how flow splits at an anabranch upstream of the station.

Unless otherwise stated, data with a quality code worse than fair (value greater than 60) were considered as missing.

Figure 5-1 River model nodes and subcatchment areas. Hydrological response units are based on physiographic units identified for the region

Note that calibration gauge sites were used as simulation nodes and simulation node ID is the same as calibration gauge ID with the addition of a '0'

5.4 Existing storages and demands

Information on existing storages in the Leichhardt River catchment, and water use from these storages, was derived from several sources. The Department of Natural Resources, Mines and Energy (DNRME, 2015) provides storage curves of how volume and area changes with water level for Lake Moondarra and Lake Julius; total storage volume for other dams were sourced from DNRME (2004b). DNRME (2018) reports water extracted from lakes Julius and Moondarra over 2010/11 to 2016/17, which was extended based on SunWater Water Supply Scheme Statistics annual reports (https://www.sunwater.com.au/water-data/report-statistics/). This reporting indicates an overall low level of use compared to entitlements, with the maximum use in a given year from Lake Julius 24% of the total entitlement (48.85 GL) in 2013/14, and for Lake Moondarra a maximum use of 74.1% of the total entitlement (16.3 GL) in 2012/13. A summary of the full supply volume and assumed demand for each storage included in the model is outlined in Table 5-1. The total assumed demand from the upper Leichhardt River (i.e. excluding the demand from Greenstone Creek Dam) is very similar to the total water demand reported in DNRME (2019) of approximately 29 GL/year on average.

Water restrictions to reduce water use from Lake Moondarra and Julius Dam during periods of low storage levels were implemented based on information from DNRME (2019). Time series of storage volume for model calibration for Lake Moondarra and Julius Dam were sourced from Mount Isa Water Board (https://www.mountisawater.qld.gov.au/ourdata/open-data/).

One existing irrigation water user on the Leichhardt River above the monitoring station at Floraville (913007B) was also represented in the model. The irrigation model was configured for a 10,850 ML licence and 8500 ML of on-farm storage assumed to be 4 m deep. A 200 ML/day pump rate was assumed, with a minimum pump threshold of 1 m^3/second discharge in the Leichhardt River required for pumping to occur, over the months from September to June. Based on satellite imagery it was assumed that diversions commenced in 1999 for the calibration scenario with a maximum irrigated area of 450 ha.

Table 5-1 Existing storages represented in the river model and assumed associated demands for model calibration

All existing storages are located in the Leichhardt River catchment. Location of storages are shown on Figure 1-1.

STORAGE	FULL SUPPLY VOLUME (GL)	DEMAND	ALLOCATED (ML/y)	ASSUMED USE (ML/y)	COMMENT
Rifle Creek Dam	9.5	Mount Isa Mines	1,500	1,500	Conservative assumption that all allocation is used
East Leichhardt Dam	12.2	Previous industrial	1,100	0	No current demand (Jacobs, 2018)
Greenstone Creek Dam	14.0	Gunpowder township and industrial	3,953	2,167	Nominal water entitlement (Jacobs, 2018)
Lake Moondarra		Mount Isa town water supply	12,500	6,460	Average value from range in DNRME (2019)
		Industrial	12,500	11,365	Pre-water savings average from DNRME (2019)
	106.8	Distribution losses	1,250	1,250	DNRME (2019)
Lake Julius		SunWater allocation	10,850	4,500	SunWater pipeline, industrial (Ernest Henry Mine) and town (Cloncurry) supply. Assumed total use from Julius Dam based on use reported in SunWater annual reports averaged over 2012/13 – 2020/21.
		Industrial Northwest Queensland Pipeline	15,000	2,975	
		Mount Isa Water Board (MIWB)	21,750	0	MIWB preferentially take from Lake Moondarra (DNRME, 2019). The sum of use from Lake Moondarra is similar to total water supply for MIWB, also suggesting little take from Lake Julius
	107.5	Distribution losses	1,250	1,250	DNRME (2019)
Total			**81,653**	**31,467**	

5.5 Calibration procedure

Each HRU requires 15 parameter values to be calibrated, 13 associated with the Sacramento RR model, the river bed conductivity for the loss model and the *K* parameter related to travel time for the routing model. Hence, in a full system calibration of four HRUs there are 60 parameters to calibrate.

An objective function was determined to enable the suitability of different parameter sets to be compared, and hence optimised. Goodness-of-fit metrics based on commonly used metrics such as percentage difference in total simulated volume (termed 'bias') and Nash–Sutcliff efficiency (NSE) (Nash and Sutcliffe, 1970), were utilised. Given RR models, and models in general, represent a simplification of reality they cannot represent all aspects of the observed conditions perfectly. As such, typically the objective function is specified to focus aspects of the results on aspects that are most important to the application. For example, flood studies require more emphasis on accurate peak-flow representation, while some ecological studies may require more accurate low-flow representation.

The objective function (OF) specified to be used for each gauge, except for 913007B at Floraville, was:

$$OF = \left(2 - NSE(\sqrt{Q})\right)\left(2 - NSE\left(FDC\left(\sqrt{Q}\right)\right)\right)\left(1 + 10Bias_{range}\right) \qquad (12)$$

where:

$NSE(\sqrt{Q})$ is the NSE calculated using square root transformed daily discharge. A number of studies have found a square root transform provides for a more balanced calibration across the flow regime, as opposed to focusing on more uncertain peak discharge (Thirel et al., 2023; Wright et al., 2015).

$NSE\left(FDC\left(\sqrt{Q}\right)\right)$ is the NSE of the flow duration curve, *FDC*, of square root transformed daily discharge, with the flow duration curve calculated between the 10th to 90th flow percentiles at 5% intervals.

$Bias_{range}$ is calculated as:

$$Q_{d,j} = \sum_{i=1}^{j}\left(Q_{s,j} - Q_{o,j}\right) \; for \; j = 1, n \qquad (13)$$

$$Bias_{range} = \frac{\max(Q_d) - \min(Q_d)}{\sum Q_o} \qquad (14)$$

where Q_d is the cumulative sum of the difference between the daily simulated (Q_s) and observed (Q_o) discharge, for *n* time steps, such that Q_d is the same length as Q_o. This is an extension to a traditional total volume bias that calculates the volume difference only at the end of the simulation. This modified version has the advantage of aiming to minimise the largest volume error at any time over the simulation, avoiding the assumption that this largest volume error occurs at the end of the simulation. The $Bias_{range}$ is then multiplied by 10 to prioritise an accurate representation of the volume of water observed at the gauge. Note that $Bias_{range}$ is always positive by definition.

The optimal value for each term in *OF* is 1, as for a perfect representation of the observed discharge *NSE* = 1 and $Bias_{range}$= 0, which when multiplied together gives an optimal value of *OF* = 1 for the minimisation problem.

A different objective function was developed for the Floraville gauge. The maximum gauging at this location occurred in July 2023 for a water level of 1.53 m, 0.62 m above the cease-to-flow level of 0.91 m. This can be compared to the maximum recorded water level, also occurring in 2023, of 11.6 m. Hence, there is low confidence in the calculated discharge over most of the range of water levels, as there are no measured discharge values to determine the relationship between measured water level and calculated discharge.

The objective function for the Floraville site was developed focusing on the components of the flow regime that could be relied on from the recorded water levels, that is the period of time flow exceeded the maximum gauged discharge of 3.91 m^3/second, the period of time with some flow occurring, and the pattern of discharge from day to day. These terms do not provide a way to constrain the total volume simulated however, which is an important factor for water resource assessment.

Several lines of evidence were used to quantify the expected average annual runoff as a ratio of the average annual rainfall (runoff ratio) to constrain the modelled volume:

- Using over 100 gauges across northern Australia, Hughes et al. (2023) developed a relationship to predict the runoff ratio based on the aridity (calculated as potential evapotranspiration/rainfall) and the regolith depth. For the local subcatchment contributing to site 913007B the mean estimate of runoff ratio was 0.058, with a standard deviation of $\sigma = 0.011$. Assuming normally distributed estimates, a 95% confidence interval is then $0.058 \pm 1.96\sigma = 0.058 \pm 0.022$.
- CSIRO MODIS Reflectance-based Scaling evapotranspiration (CMRSET) is a remotely sensed product that scales potential evapotranspiration to estimate actual evapotranspiration (AET) (Guerschman et al., 2022). For the local subcatchment area over the 23 years from the start of the CMRSET record in February 2000 to January 2023, the mean annual AET from CMRSET was 569 mm compared to a mean annual rainfall of 593 mm over the same period. Assuming that that the rainfall that is not estimated to be AET results in runoff, the runoff is estimated to be 24 mm, or a runoff ratio of 0.041.
- In the adjoining catchment to the east the gauge, the Flinders River at Walkers Bend station is known to have a high-quality discharge time series. This catchment has a similar climate, land use and geology and could be expected to have a similar runoff ratio. Over the period from the start of the record in 1970 to 2018 the mean annual rainfall over this catchment was 510 mm and recorded runoff 31.8 mm, producing a runoff ratio of 0.062. If the three years with discharge that exceeded the maximum gauging are excluded, the runoff ratio reduces to 0.047. Both estimates are within the range calculated by Hughes et al. (2023).

Based on the terms outlined above, the objective function used for the Leichhardt River at Floraville site was:

$$OF_{Floraville} = R(Q)(1 + EPD(0.001))(1 + EPD(3.91))(1 + 10Bias_{ratio}) \qquad (15)$$

where:

R is the spearman rank correlation between the observed and simulated discharge (based on all observed data used, not only that coded as good or fair quality).

EPD(X) is the error probability difference (EPD) between the observed flow and simulated flow for a flow of *X* m^3/second. EPD is calculated as the absolute difference in the proportion of time the discharge *X* m^3/second is exceeded in the observed and simulated time series. 0.001 m^3/second is used to represent the period of flowing days (and conversely cease-to-flow days), and 3.91 m^3/second represents the highest flow gauging, where there is high confidence in the calculated observed discharge.

$Bias_{ratio}$ is calculated as $\max(0, abs(RR_s - 0.058) - 0.022)$. That is, if the simulated runoff ratio is outside the 95th percentile estimate from Hughes et al. (2023), a penalty factor is included in the objective function.

Finally, a standard NSE was calculated between the daily simulated and observed storage volumes, *S*, for Lake Moondarra and Julius Dam, with the following objective function used to provide a minimisation problem:

$$OF_{storage} = 1 - NSE(S) \quad (16)$$

To combine the OF values calculated at each site into one value to be minimised, the objective functions for each of the five discharge stations plus two storage volumes were equally weighted and the OF values summed together. The equal weighting was adopted as extensive data review has identified best available datasets to inform the calibration of the model. It is noted that four of the seven datasets used only influence the Isa Highland HRU, which may result in the calibration procedure focusing on the parameters for this HRU. This HRU contains all the town and industrial demands represented in the model, and hence is considered a priority to represent accurately.

All models were calibrated using the differential evolution (DE) algorithm of Mullen et al. (2011). This approach is considered suitable for river model calibration since it is a heuristic method, well suited to uneven or 'rough' optimisation surfaces. The code provides for parallelised processing, thereby speeding up the optimisation process. A population size of 20 times the number of decision variables (i.e. 20 × 60 = 1200) was adopted, double the minimum recommended population size to encourage exploration of the search space. A maximum of 300 iterations were permitted but typically convergence, represented by no improvement in the objective function value for 20 iterations, occurred before this limit. Initial calibration of the sections of the model against each gauge individually was undertaken to identify suitable parameter sets for each HRU to include in the DE initial population, with half of the initial population for the full system calibration constructed from these trial calibrations, and the other half random solutions to promote further exploration of the search space. Five restarts of the DE algorithm were undertaken to test the influence of the initial population and convergence process on the final parameter sets identified.

5.6 Calibration and validation periods

The calibration period considered was from 1/9/1967 to 31/8/2022, with the start date providing a one-year warm-up period before the first observed data for calibration. The observed data for the period from 1/9/2000 to 31/8/2010 was removed from the calibration datasets to provide an independent validation period. This approach allowed the earlier record with data available at the Nicholson River at Connolly's Hole (912107A), as well as the most recent observed data (i.e. data after 31/8/2010) representing current catchment conditions, to influence the model calibration. Statistics of catchment mean annual rainfall are shown in Table 5-2 where the most extreme rainfall years (driest and wettest) are captured in the calibration period to inform the model parameters, with the validation period 18% wetter on average. For model simulation the 'best set' of parameters identified through the calibration process and tested on the validation period were identified (as opposed to recalibrated over the full period), and then used to simulate the full assessment period (1890 to 2022).

Table 5-2 Statistics of catchment mean rainfall (mm/year) for the calibration and validation periods

	CALIBRATION	VALIDATION
Minimum	315	393
75th percentile exceedance	460	516
Median	579	682
Mean	635	771
25th percentile exceedance	754	1048
Maximum	1352	1173

5.7 Uncertainty estimation

The development of river models incorporates a range of uncertainty ranging from measurement errors in spatial data (digital elevation model errors), input data (climate, streamflow data) and hydrological model limitations. In northern Australia, these uncertainties are often larger than in other parts of Australia due to remoteness and extreme climate conditions making it challenging to install and maintain stations (e.g. implications for data paucity and quality). Consequently, it is expected that uncertainty attached to river model simulations may be considerable and is important to report as part of the Assessment. Acknowledging and assessing uncertainty will increase transparency of the modelling process, identify areas for future improvements and better quantify risks for decisions based on the Assessment.

To represent some of this uncertainty a commonly used approach based on the Generalized Likelihood Uncertainty Estimation (GLUE) method (Bevan and Binley, 1992) was adopted. Any set of model parameters that produced an objective function value within 5% of the best solution found across the five DE runs stored and treated as a 'behavioural' set of parameters, used to represent acceptable model performance and indicate the range in plausible streamflow outputs. It should be noted that this approach only represents parametric uncertainty and not other sources of uncertainty, such as input uncertainty introduced by the climate data or structural uncertainty derived from the models adopted. More complex approaches to quantify total predictive (as opposed to only parametric) uncertainty are available (e.g. McInerney et al., 2018), however research questions remain on how to use these approaches in practical applications, for example how to regionalise the error models developed to locations without observed streamflow data.

6 Calibration results

The calibration results have been presented separately depending on the objective functions used for model calibration, where different functions were used for the high-quality streamflow stations compared to the station on the Leichhardt River at Floraville used to calibrate the Plains HRU.

6.1 High quality stations

Figure 6-1 provide a summary of the calibration metrics for the four stations that met the selection criteria: more than 50% of the estimated volume occurring below the maximum gauging and more than 10 years of satisfactory (good or fair) quality data. Any set of model parameter values that produced a combined objective function value within 5% of the best value found across the five optimisation runs is represented by the boxplot for each site, assumed to be equivalent 'behavioural' models as used in the GLUE methodology (Bevan and Binley, 1992). One 'best set' of parameter values was also selected and is represented by the orange dot, identified by comparing metrics across all the stations on both the calibration and validation periods. Results for each station considered presented in Appendix C, and best set of parameter values listed in Appendix D.

The NSE values for the calibration and validation periods, both for original and square root transformed discharge values, are presented on the top row of panels. NSE values across the four stations and two periods were in the range of 0.5 to 0.8. The model has only one set of parameters to match the data from stations 913006 and 913015, as well as the storage level at Lake Moondarra and Lake Julius, which may be a reason for the lower performance metrics for the 913006 gauge. The Kling–Gupta efficiency (KGE) is a metric similar to NSE but was developed to address limitations with NSE and provide a more balanced representation of the terms involved in the metric: the correlation, bias and ratio of variance (Gupta et al., 2009). KGE values tends to be lower than NSE values (e.g. Knoben et al., 2019). However, in this case the KGE values are similar, if not higher, than NSE. These metrics demonstrate good general model performance.

Volume bias across all gauges and both calibration and validation periods is within 20% of the observed volume at each station for both calibration and validation periods (Figure 6-2), with the optimal value for this metric a bias of zero. The exception to this was the flow downstream of Lake Julius (913015) which is underestimated by 25% by the best set (range 22 to 29% over the behavioural parameter sets) in the calibration period, and slightly overestimated (5%) in the validation period.

Metrics in Figure 6-1 and Figure 6-2 are similar, or tend to slightly improve, on the validation period compared to the calibration period. The site on the Nicholson River at Connolly's Hole (912007A) was closed in 1988 and hence there are no results over the 2000 to 2010 validation period for this station. The similar results on both periods suggests that the model can generalise to represent conditions outside of the calibration period. However, the metrics improving on the validation period compared to the calibration period is an unusual result, where typically a model run with inputs not used in parameter calibration (the validation period) will perform worse than when tested using observations also used to calibrate the model (the calibration period). It is expected that this result is because the validation period is wetter than the calibration period (Table 5-2), and therefore easier for the model to represent the rainfall-runoff relationship compared to drier periods. To further test this assumption the model was calibrated to only the valuation period, to see if improved performance could be obtained. The optimisation method aims to minimise the overall objective function, which was 4.41 when applying the best parameter set from the calibration period to the validation period. When the model was recalibrated to the validation period the objective function reduced to 2.76, indicating better overall performance (according to the functions used to calibrate the model) could be obtained by the optimisation process if representing the validation period only was the objective. It should be noted that this model calibrated to only the validation period (2000 to 2010) is expected to be 'overfitted' to this period, and not provide as suitable representation of the extended flow regime the model was originally calibrated to, over the period from 1967 to 2022.

The resulting mean annual volume over the full simulation period at each site can be seen in Figure 6-3. For most stations the box plots are narrow, indicating the volume estimates are similar across the behavioural parameter sets identified. The average and median simulated annual volume is similar to the observed volume for each station (Appendix C), with the results from the best parameter set summarised in Table 6-1. Note that the volumes stated here are based on the good-quality observed streamflow data and are used to compare model performance, as opposed to estimate total volume available at each location.

The storage volume time series for Lake Moondarra and Lake Julius, and exceedance curve of storage volumes, are presented in Appendix C. The results for Lake Moondarra align reasonably well, particularly since the 2000s. The storage volume is underestimated in the 1990s, which may be due to demands based on more recent data overestimating the water use in the earlier period. The simulated filling and drawdown period each year for Lake Julius Dam compares well to the observed volumes, albeit the minimum modelled volume can be higher in some years.

Table 6-1 Summary of annual streamflow volumes at calibration gauges.

STATION	AVERAGE ANNUAL VOLUME			MEDIAN ANNUAL VOLUME		
	OBSERVED (GL)	SIMULATED (GL)	ERROR (%)	OBSERVED (GL)	SIMULATED (GL)	ERROR (%)
912107A	1083	1049	–3	541	505	–7
912105A	659	560	–15	424	407	–4
913015A	260	197	–24	137	96	-30
913006A	153	162	6	76	101	33

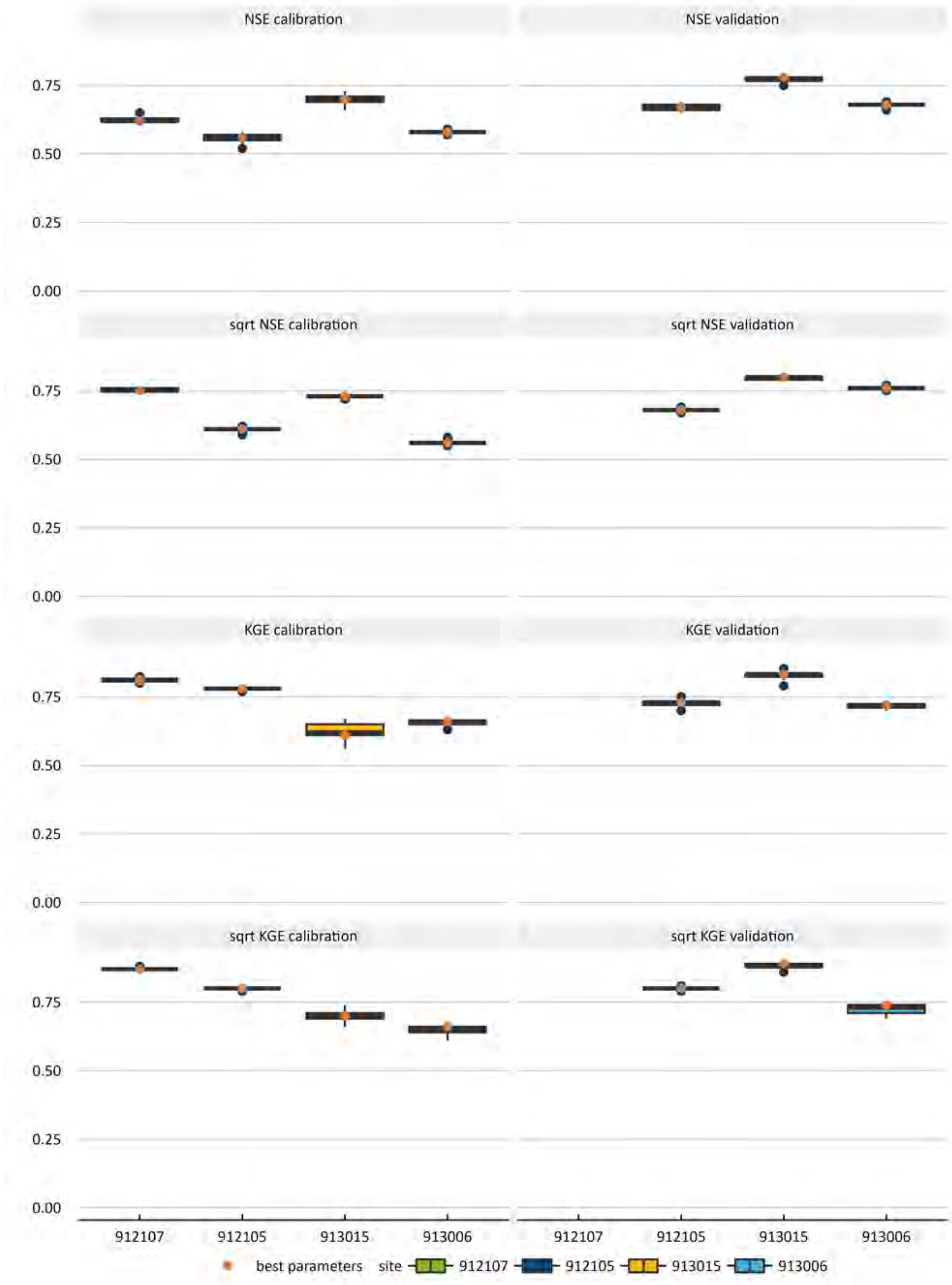

Figure 6-1 Model performance metrics for the four high quality calibration stations over the calibration and validation periods

The range in results for each gauge and metric represents parameter sets with a combined objective function value within 5% of the best value found. The independent validation period was 1/9/2000 to 31/8/2010

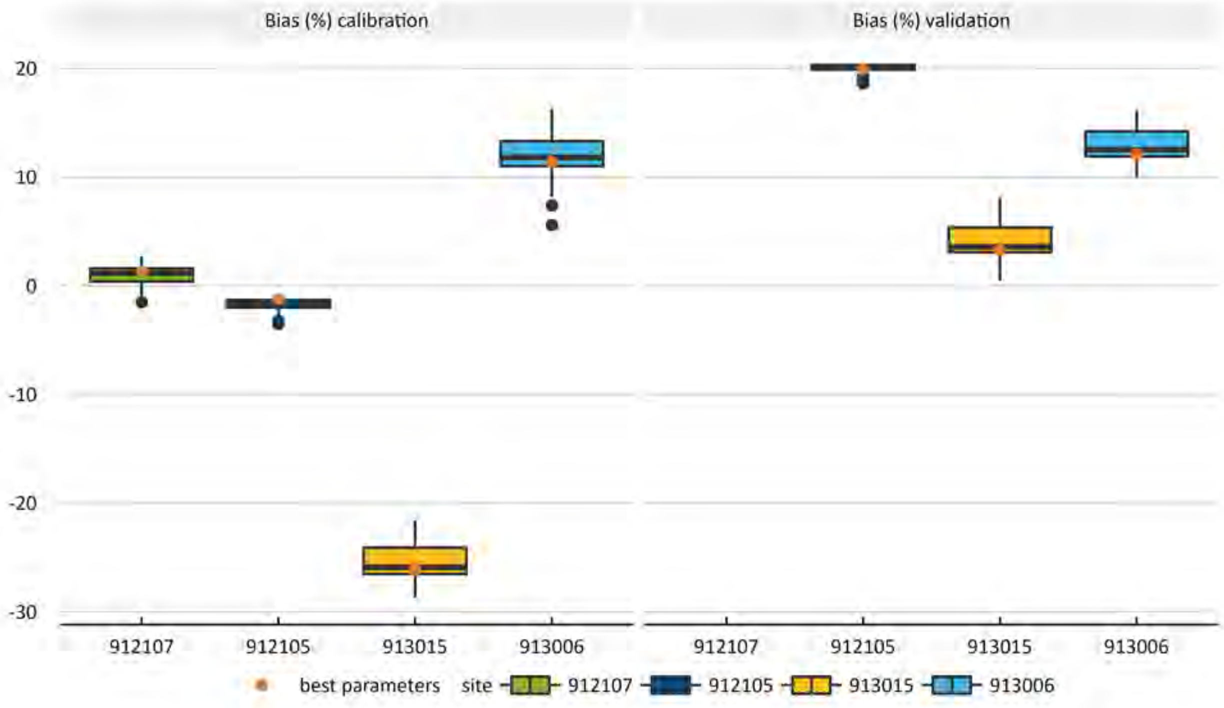

Figure 6-2 Model volume bias for the four high quality calibration stations over the calibration and validation periods

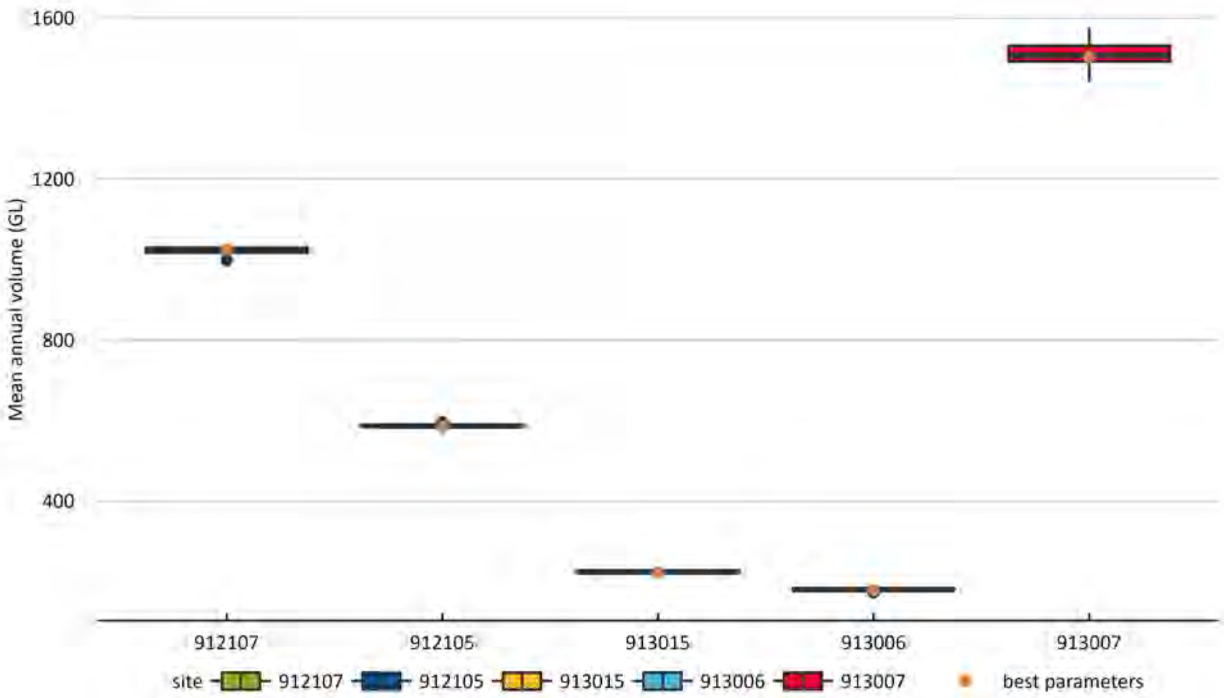

Figure 6-3 Range in simulated mean annual volume at each station based on the behavioural parameter sets

6.2 Leichhardt River at Floraville station

Each component of the objective function used to calibrate to the Leichhardt River at Floraville (912007B) station (Equation 15) is presented in Figure 6-4. The best set of model parameters, and well as the majority of the behavioural set of parameters, produced a rainfall runoff ratio within the range expected based on multiple lines of evidence (Section 5.5), with the 95% range determined by Hughes et al. (2023) represented by the light blue dashed lines. The spearman rank correlation between the observed and simulated streamflow was 0.67 for the best parameter set for the calibration period and 0.61 for the validation period, with other behavioural parameter sets producing higher correlation values (Figure 6-4).

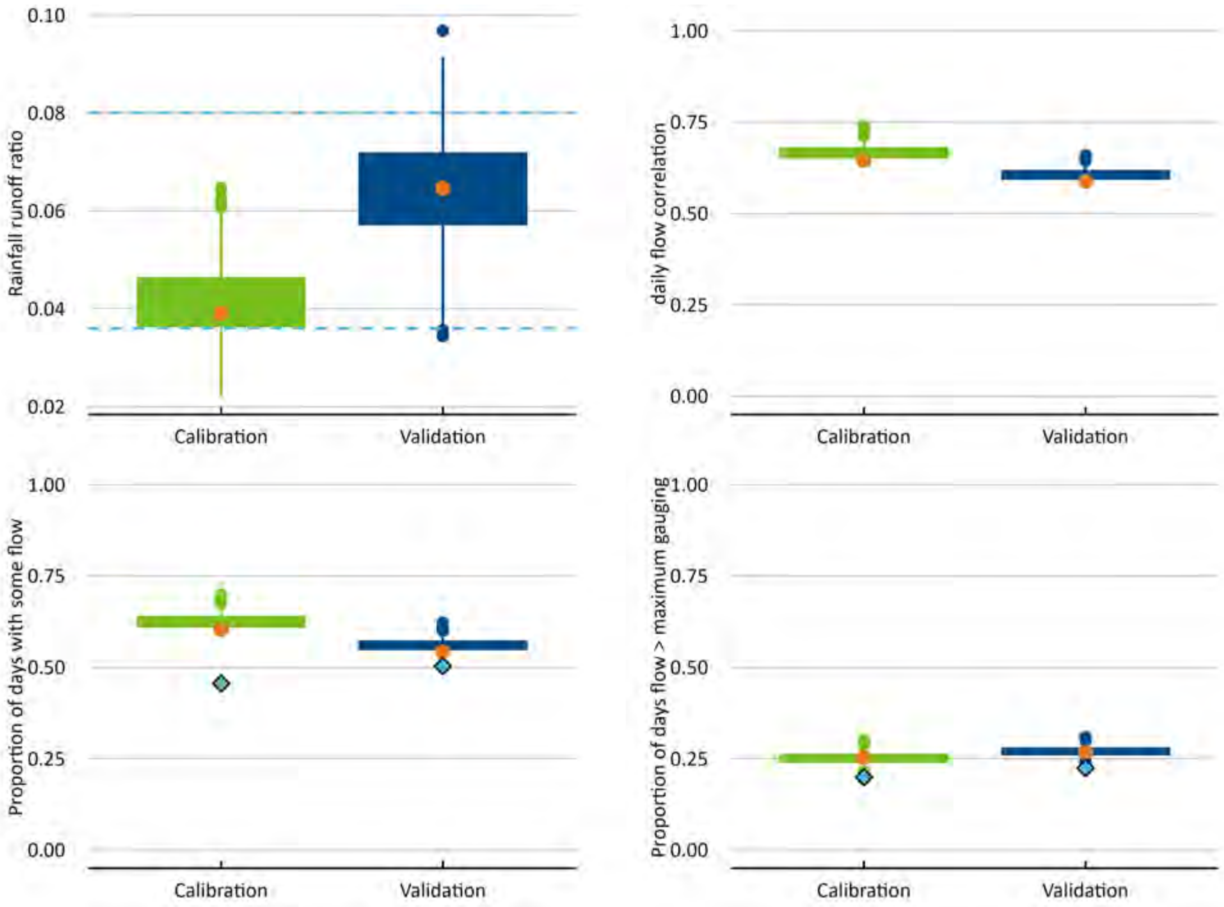

Figure 6-4 Model results on metrics of the flow regime used to calibrate the model to the Leichhardt River at Floraville (912007B) station

Geen and blue boxplots represent the range in results from the behavioural parameter sets, with the best set the orange dot. Light blue results (diamond or dashed lines) indicate the observed values used for calibration

The proportion of days with discharge exceeding the maximum gauging (3.91 m^3/second) was represented accurately by the model. The number of days with some flow was accurately represented particularly in the validation period, however this metric was overestimated in the calibration period (by 15.6% of days). The behavioural parameter sets result in a higher variability in the annual volume simulated at site 913007B compared to the high quality stations (Figure 6-3), expected to be due to the higher uncertainty in the observed data at this site.

Approaches to improve the confidence in the rating curve at this station were considered. For example, the BaRatin software (Le Coz et al., 2014) uses hydraulic information on the channel structure to inform rating curve calibration and associated uncertainty. These uncertain rating curve estimates could then be used to get a quantify the range of uncertainty for the observed discharge. However, further investigation is required to identify and survey the controlling structure(s) at this station, and the location of the control may change for different water levels, between the rock bar immediate downstream of the station, the road crossing for National Highway 1, Leichhardt falls, or the broader channel banks.

Two-dimensional hydraulic modelling may help to identify controlling sections and derive an updated rating curve, and high-resolution LiDAR elevation data has been collected recently as one key input to this type of modelling. However, full bathymetry is not currently available as permanent water prevented the LiDAR from capturing the deepest parts for the river, and there remains limited data available for calibration of other parameters, such as channel roughness. Remotely sensed products such as Digital Earth Australia's Water Observations may help calibrate models such as this for events that create overbank inundation.

Ultimately, additional gaugings at higher flows are required to improve the ability to utilise the long water level record at this location for model development and water resource assessments.

6.3 Gregory River anabranch calibration

To represent the full Southern Gulf Water Resource Assessment area, there are some additional components of the river model to configure. Macadam Creek is an anabranch of the Gregory River occurring between the gauges at Riversleigh and Gregory Downs (Figure 6-5). The creek is dry at low flows, but flow can occur through the anabranch for higher flows. A rating curve to represent this behaviour was calibrated based on the modelled and observed discharge at the Gregory Downs station (912101A), with any simulated flow upstream of the Gregory Downs gauge higher than the recorded flow at the gauge was assumed to have occurred in Macadam Creek. The difference between the modelled and observed time series suggest Macadam Creek flows when discharge in the Gregory River reaches 90 m^3/second. A rating curve of $q = 0.3Q^{0.8}$ was calibrated to this residual flow time series, with Q the discharge in Gregory River above 90 m^3/second, and q the flow into Macadam Creek. The resulting modelled discharge downstream in Gregory River compared to the gauge at Gregory Downs can be seen in Appendix C. All data were used for this model calibration at Gregory Downs, as the calibrated flow split threshold aligns to the maximum gauged flow of 89 m^3/second.

Downstream of the Macadam Creek anabranch the Gregory River also bifurcates at Planet Downs with the Gregory River continuing on toward the Nicholson River, but with a proportion of the flow also splitting into Beames Brook, flowing toward Burketown and the Albert River estuary (Figure 6-5). Gaugings undertaken by the Queensland Government from 1969 to 1976 (N Searle (Supervising Hydrographer, DRDMW), 2022, pers. comm.) were used to determine the proportion of flow in each river at the bifurcation point at Planet Downs (Figure 6-6). Fitting a power curve between the gaugings, a relationship of $q = 0.41Q^{0.87}$ was derived, with q the flow into Beames Brook, and Q the flow upstream of the bifurcation point in the Gregory River. It is possible changes in channel morphology in the past 50 years have changed this relationship, and at discharge rates above the maximum gauging undertaken at 7 m^3/second in the Gregory River upstream of the bifurcation point (a relatively low flow) there is higher uncertainty in the proportion of the Gregory River flow occurring in each downstream river.

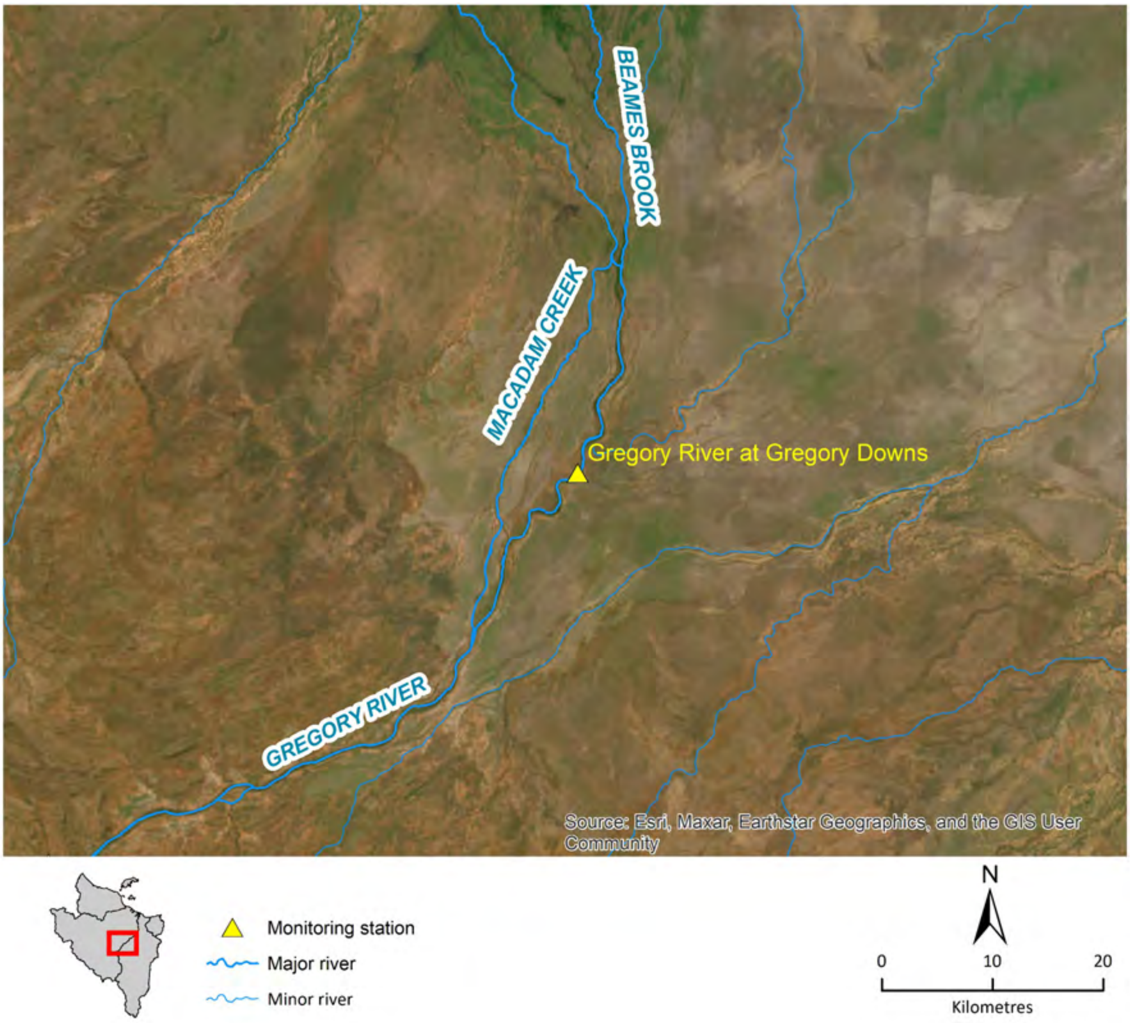

Figure 6-5 Map of Gregory River near Gregory Downs, indicating the anabranch of Macadam Creek and bifurcation into Beames Brook and Gregory River downstream. Direction of flow is from south to north

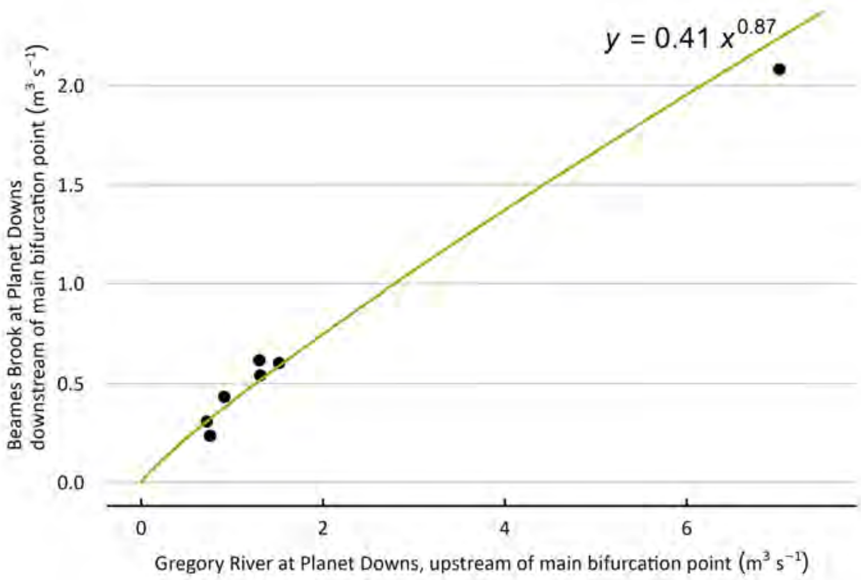

Figure 6-6 Discharge gaugings on the Gregory River and Beames Brook between 1969 and 1976, and relationship used to represent the proportion of flow occurring in Beams Brook

6.4 End-of-system volumes

With calibrated parameter values for each of the HRUs outlined in Section 5.2, streamflow across the Assessment area can be simulated. The end-of-system annual volumes for each of the catchment areas based on the best parameter set are summarised in Table 6-2. The mean annual volume across the full 1890 to 2022 simulation period is substantially higher than the median annual volume, which is a common in systems with a high inter-annual variability of flow. This is also evident by the maximum volume, in the wettest year, much larger than the 10th percentile exceedance largest volume. The 'Total' volume row is based on the annual volumes across the entire Assessment area each year, and as such does not necessarily equal the sum of the rows above. That is, the year with the largest streamflow volume in one catchment does not coincide with the largest streamflow volume in all catchments.

Table 6-2 End-of-system annual volumes (GL/year) based on the best parameter set

Statistics calculated over the full simulation period from 1890 to 2022. The total is based on the total volume in each year, and hence does not necessarily equal the sum of the statistics from the individual catchments.

CATCHMENT	MIN.	90TH PERCENTILE	75TH PERCENTILE	MEDIAN	MEAN	25TH PERCENTILE	10TH PERCENTILE	MAX.
Nicholson–Gregory	189	431	757	1,873	2,476	3,196	4,627	15,602
Settlement	48	291	714	1,304	2,014	2,288	4,442	14,739
Mornington Islands	17	54	116	173	292	371	654	1,865
Leichhardt	65	277	628	1,112	1,733	2,180	3,630	13,120
Morning Inlet	11	50	115	195	307	365	499	2,022
Total	453	1,393	2,453	5,035	6,823	8,268	13,920	40,316

Table 6-2 summarises the temporal variability in volume over time from one set of model parameters. The range in mean annual end-of-system volume produced by the different behavioural parameter sets is summarised in Table 6-3 (model parameter uncertainty). The different parameter sets produce a range in volumes that is much more symmetrical compared to the year to year variability, with the mean of the mean annual flow of the behavioural parameter sets being similar to the median of the mean annual flow of the behavioural parameter sets. While the 'best set' end-of-system volume is higher than the median and average across the behavioural set in Table 6-3, this 'best set' was selected based on performance on the validation period as well as the calibration period. The range between the minimum and maximum volumes is 24% of the average for the total Assessment area, and 17 to 50% on an individual catchment basis.

Table 6-3 Range in mean annual end-of-system volume (GL) produced by the behavioural parameter sets

CATCHMENT	MIN.	MEAN	MEDIAN	MAX.
Nicholson–Gregory	2071	2224	2247	2476
Settlement	1505	1831	1851	2228
Mornington Islands	209	278	283	360
Leichhardt	1468	1568	1574	1733
Morning Inlet	188	242	246	310
Total	5449	6142	6209	6957

7 Discussion and conclusion

The end-of-system volumes presented in the previous section are consistent with previous studies in the region, summarised in Table 1-1. For the Leichhardt River, the end-of-system volume from the best parameter set was very similar (3% lower) to the previous reported value that used river system modelling (CSIRO, 2009a). The end-of-system volume calculated here for the Gregory–Nicholson River is between previous estimates, 11% higher than the National Land and Water Resources Audit (NLWRA) volume and 18% lower than NASY. The difference in volume compared to the NASY study is likely due to assumptions about donor model parameters for the catchments downstream of the observed data on the Nicholson River at Connolly's Hole and on the Gregory River and Riversleigh. This work has used the parameters calibrated to the Leichhardt River at Floraville Station data and the expected RR coefficient based on multiple lines of evidence, where NASY used the more reliable, but more distant, gauge on McArthur River in the NT. For the catchments with no observed streamflow to inform model calibration the mean annual end of system volume from the best parameter set tended to be lower than previous estimates (on average 14% lower), with the NASY estimate for the Morning Inlet AWRC basin and the AWAP estimate for the Mornington Island AWRC basin within the range of volumes from the calibrated behavioural parameter sets derived in this work (Table 1-1 and Table 6-3). It should be noted that the end of system mean annual volumes from the different studies were calculated over different periods of time, which is another source for differences.

It is highlighted that the river models developed as part of this Assessment differ from the one developed by the Queensland Government for the Leichhardt River. The river models developed by Queensland Government in 2004 aimed to support the establishment of statutory water plans with the primary user being state government water policy officers. The river models developed as part of this Assessment are designed to examine hypothetical development scenarios using historical and future climate inputs. These models also need to be accessible to a wide range of stakeholders with varying levels of technical proficiency. As a result, the models (created with a modelling framework that supports different functionalities and levels of accessibility) have different spatial resolutions and were calibrated using different input data and different modelling approaches. Keeping with their overarching modelling objectives, the models were used to report different metrics, for example this work is focused on informing risks both to and from increased development in the catchment, where the previous model was developed to determine water licence volumes over a historical benchmark period.

Recent improvements in streamflow gauging technology provide an opportunity to improve confidence in the discharge calculated from water level measurements. Currently, the remote nature of the Assessment area, difficulty in accessing monitoring stations during the wet season, and the hazard involved in measuring discharge using traditional methods has prevented gauging of flows above the dry-season low flows at many of the stations in the area. Surface velocity techniques based on processing video of river flow is emerging as a promising method to measure discharge remotely without requiring contact with the water. Queensland Government hydrographers have world-leading expertise in this area, including leading the development of the Bureau of Meteorology standard on applying the technique (Bureau of Meteorology, 2021).

Applying this method is highly likely to improve confidence in calculated streamflow time series at existing stations, both in the future as well as existing records based on the historical water level data.

In addition to improving the data available at the current streamflow stations, increased reliability in sensors over recent decades may warrant reinstatement of closed stations. For the Leichhardt River there are four open stations, with 11 more sites that have historical data that are now closed, with two open on the Nicholson River and 12 historical stations closed. There are no streamflow data available in the other Assessment area catchments. Hence, there are six open streamflow stations representing the Assessment area of over 100,000 km^2, a very low gauge density. Increasing the number of stations, and quality of data available at existing stations in the near future, could well be implemented in the Assessment area before the relevant Water Plan (Queensland Government, 2007) is due for review in 2027. If new stations were to be opened in the future, understanding of river model uncertainty in the Assessment area and other bio-physical data collected as part of the Assessment could help inform these decisions.

This work has outlined the model development for the Southern Gulf Water Resource Assessment area, encompassing the Leichhardt and Gregory–Nicholson river catchments, as well as a number of smaller creeks in the Settlement Creek, Morning Inlet and Mornington Island AWRC basins. The model will be used in subsequent work to assess hypothetical water resource development scenarios (i.e. dam yield, reliability of water harvesting) and the modelled changes in streamflow used to evaluate the impacts on existing entitlement holders and used to evaluate the change in flow dependency of water dependent ecological assets in the Assessment area.

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Part II Appendices

Appendix A Morton’s wet area potential ET calculation

C# code of calculation of Morton’s wet area potential ET calculations based on Li et al. (2009).

```
static double CalculateETwp(DateTime today, double Elevation, double Latitude, double tmax,
            double tmin, double eact, double radin, out double RH)
        {
            double height, lat, tavg, esat, pratio, gammap, pdelta,
                   pi, psai, dr, delta, omega, radextra, radinnet, radout, radnet,
                   nNratio, _as, bs, albedo, sigma, term1, term2, term3, fz, ediff, stabfac,
                   Dpfact, vptc, htc, xesat, xtemp, xdelta, tempinc, radnetx, ETpp, ETppx, ETwp,
                   tdiff, esatMax, esatMin, esatMean, ea;

            int julday;

            //psea = 101.3;       //kPa
            pi = 3.1415927;
            _as = 0.25;         // Angstorm formula, regression constant
            bs = 0.50;          // Angstorm formula, regression constant
            albedo = 0.23;
            sigma = 4.903E-9;   // Stefan-Boltzmann constant

            height = Elevation;
            lat = Latitude;

            if (tmax <= -99.0 || tmin <= -99.0 || eact <= -99.0 || radin <= -99.0) // ||  esat <= -99.0 ||
radin == 0 ) //|| sunhrs <= -99.0)
            {
                ETpp = -99.0;
                ETwp = -99.0;
                ea = -99.0;
                RH = -99.0;
                tavg = -99.0;
            }
            else
            {
                tavg = (tmax + tmin) / 2.0;

                //calculate esat

                //formula 35
                esatMax = 0.6108 * Math.Exp(17.27 * tmax / (tmax + 237.3));
```

```
esatMin = 0.6108 * Math.Exp(17.27 * tmin / (tmin + 237.3));
esatMean = 0.6108 * Math.Exp(17.27 * tavg / (tavg + 237.3));

//formula 43
ea = 0.25 * esatMax + 0.5 * esatMean + 0.25 * esatMin;
esat = ea;

if (esat <= 0.0) esat = 0.0001;
if (eact <= 0.0) eact = 0.0001;
if (eact > esat) eact = esat;

RH = eact / esat;

//     Calculate ratio of atmospheric at the station to that at the sea level (Pstn/Psea)
pratio = Math.Pow((293.0 - 0.0065 * height) / 293.0, 5.26);

//     Calculate psychrometric constant (kPa/C)
if (tavg >= 0.0)
    gammap = 0.066 * pratio;
else
    gammap = 0.0574 * pratio;


//     Calculate slope of saturation vapour pressure/temperature curve (kPa/C)

if (tavg >= 0.0)
    pdelta = (4098.0 * esat) / Math.Pow((tavg + 237.3), 2);
else
    pdelta = (5809.0 * esat) / Math.Pow((tavg + 265.5), 2);


//     Calculate extraterrestrial radiation (Ra=radextra)   (MJ/m2/day)

psai = (lat / 180.0) * pi;

julday = today.DayOfYear;
dr = 1.0 + 0.033 * Math.Cos(0.0172 * Convert.ToDouble(julday));
delta = 0.409 * Math.Sin(0.0172 * Convert.ToDouble(julday) - 1.39);
omega = Math.Acos(-1.0 * Math.Tan(psai) * Math.Tan(delta));
radextra = (118.1 / pi) * dr * (omega * Math.Sin(psai) * Math.Sin(delta) + Math.Cos(psai)
* Math.Cos(delta) *Math.Sin(omega));

// Calculate nNratio based on radin

nNratio = (radin / radextra - _as) / bs;

//     Calculate NET incoming solar radiation (Rns=radinnet)
```

```
radinnet = (1.0 - albedo) * radin;

//     Calculate net outgoing longwave radiation (Rnl=radout)

term1 = (Math.Pow((tmax + 273.16), 4) + Math.Pow((tmin + 273.16), 4)) / 2.0;
term2 = (0.34 - 0.14 * Math.Sqrt(eact)) * (0.10 + 0.9 * nNratio);
radout = sigma * term1 * term2;
if (radout < 0.0) radout = 0.0;

//     Calculate net radiation (Rn) : if negative set it to zero

radnet = radinnet - radout;
if (radnet < 0.0) radnet = 0.0;

//     Calculate stability factor(stabfac), vapour pressure transfer
//    coefficient(fa=vptc)and heat transfer coeffieient(lamda=htc)

if (tavg >= 0.0)
    fz = 24.19;
else
    fz = 27.82;



ediff = esat - eact;
if (ediff <= 0.0) ediff = 0.0001;
term3 = gammap * (Math.Sqrt(1.0 / pratio)) * fz * ediff; //
term3=gammap*((1.0/pratio)**0.5)*fz*ediff !!!can be wrong because of Jai
stabfac = 1.0 / (0.28 * (1.0 + eact / esat) + pdelta * radnet / term3);
if (stabfac < 1.0) stabfac = 1.0;               //!!!!! MODIFICATION

vptc = (Math.Sqrt(1.0 / pratio)) * fz / stabfac;  //vptc=((1.0/pratio)**0.5)*fz/stabfac
htc = gammap + (1.804E-8 * Math.Pow((tavg + 273.0), 3)) / vptc; //htc=gammap+(1.804E-
8*(tavg+273.0)**3)/vptc;

//     Carryout iterative procedure to satisfy the energy balance and obtain
//     equlibrium quantities

xesat = esat;
xtemp = tavg;
xdelta = pdelta;

do
{
    tempinc = (radnet / vptc + eact + htc * (tavg - xtemp) - xesat) / (xdelta + htc);
    tdiff = Math.Abs(tempinc);
    if (tdiff < 0.01)
        break;
    else
```

```
            {
                xtemp = xtemp + tempinc;
                if (xtemp >= 0.0)
                    xesat = 0.6108 * Math.Exp((17.27 * xtemp) / (xtemp + 237.3));
                else
                    xesat = 0.6108 * Math.Exp((21.88 * xtemp) / (xtemp + 265.5));


                if (xtemp >= 0.0)
                    xdelta = (4098.0 * xesat) / Math.Pow((xtemp + 237.3), 2);
                else
                    xdelta = (5809.0 * xesat) / Math.Pow((xtemp + 265.5), 2);
            }

        } while (true);


        ETppx = radnet - htc * vptc * (xtemp - tavg);
        ETpp = ETppx * 0.408;
        if (ETpp < 0.0) ETpp = 0.0;

        //     Calculate Morton Wet Environment Areal Potential Evapotranspiration. ETwp

        radnetx = ETppx + gammap * vptc * (xtemp - tavg);
        Dpfact = xdelta / (gammap + xdelta);
        ETwp = 0.408 * (1.2096 + 1.2 * Dpfact * radnetx);
    }

    return ETwp;
}
```

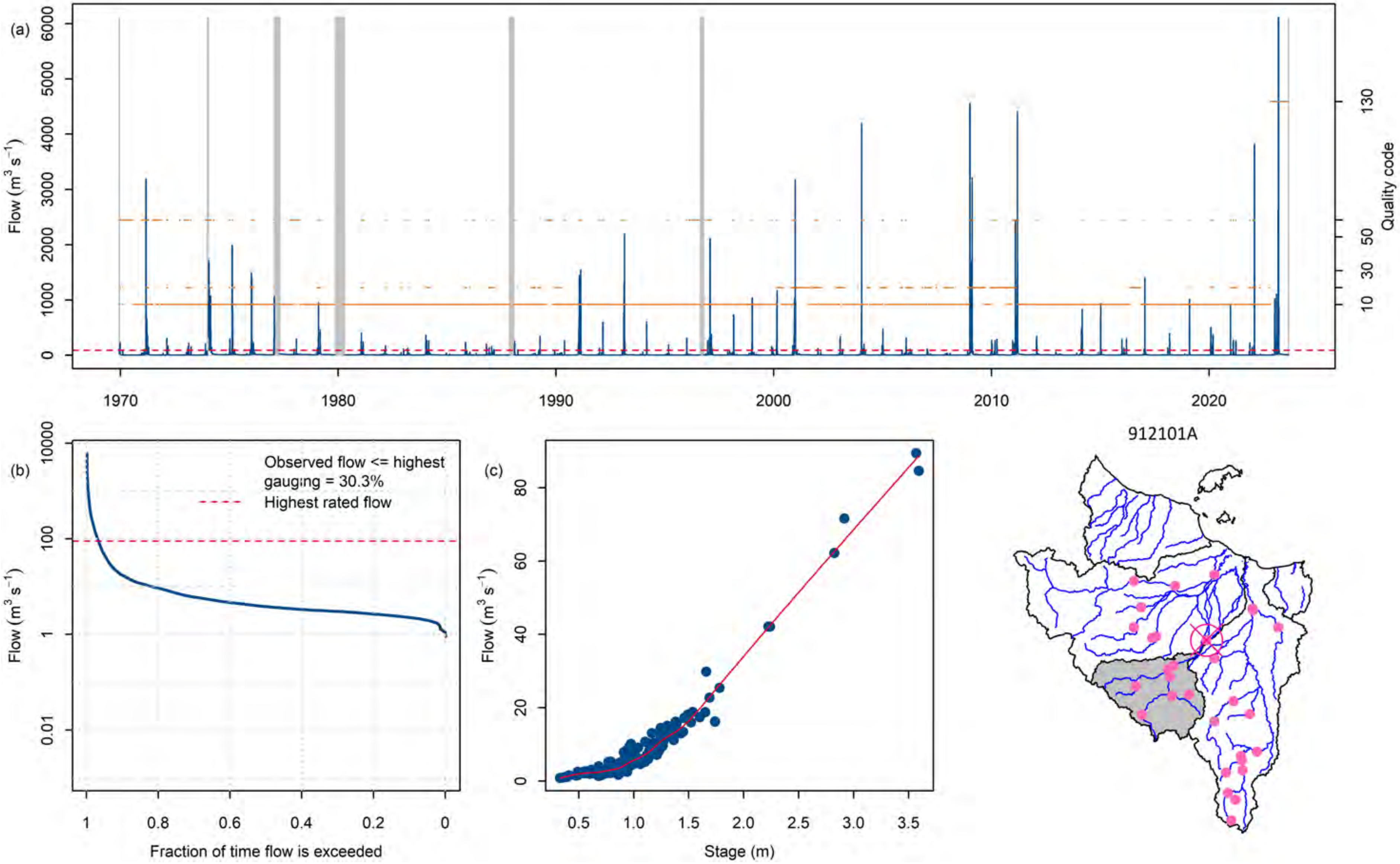
Appendix B Stream gauge data in the Southern Gulf catchments

Apx Table B-1 Streamflow quality codes

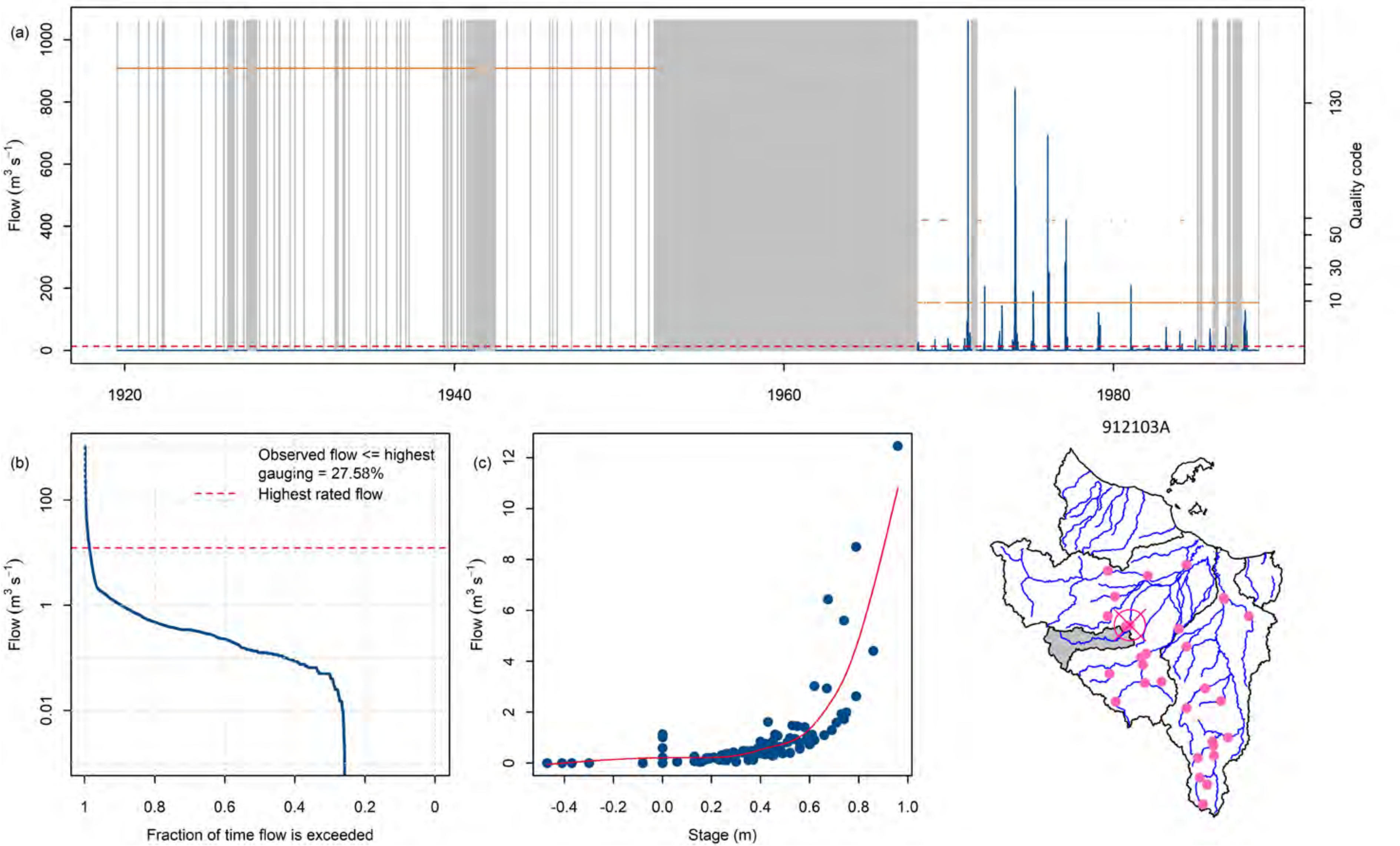
Reproduced from https://water-monitoring.information.qld.gov.au/wini/documents/webglossary.pdf.

CODE	DESCRIPTION
9	Historical data code (CITEC data – normal reading)
10	Verified 10
15	No flow (water level below threshold)
20	Verified 20
30	Verified 30
50	Theoretical calculation
59	Derived height (CITEC data)
60	Estimate
69	Derived discharge (CITEC data)
130	Not coded (unvalidated data)
151, 160, 180, 200, 201, 255	Unreported data/missing

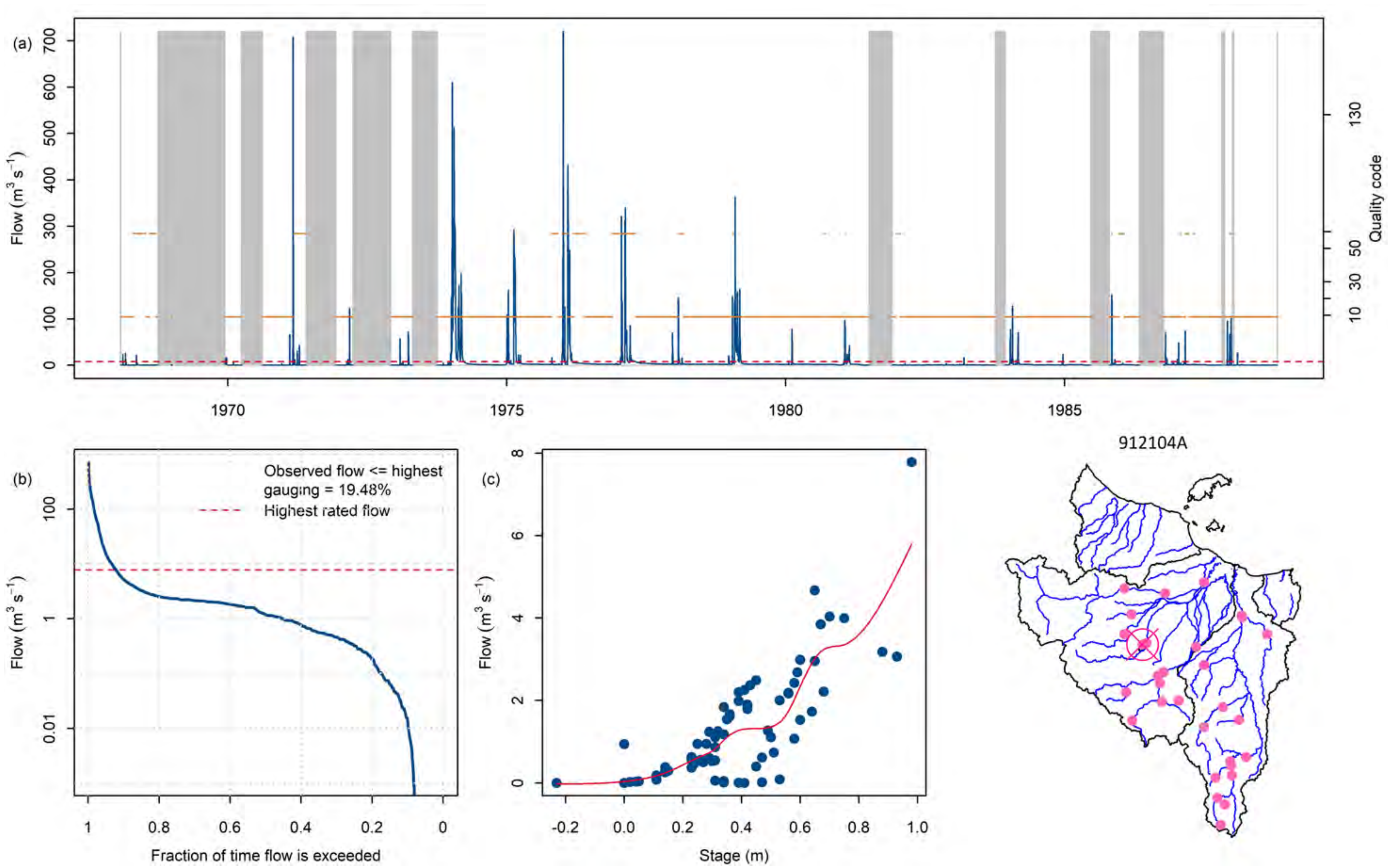
Note: CITEC = Queensland Government Data Centre Services



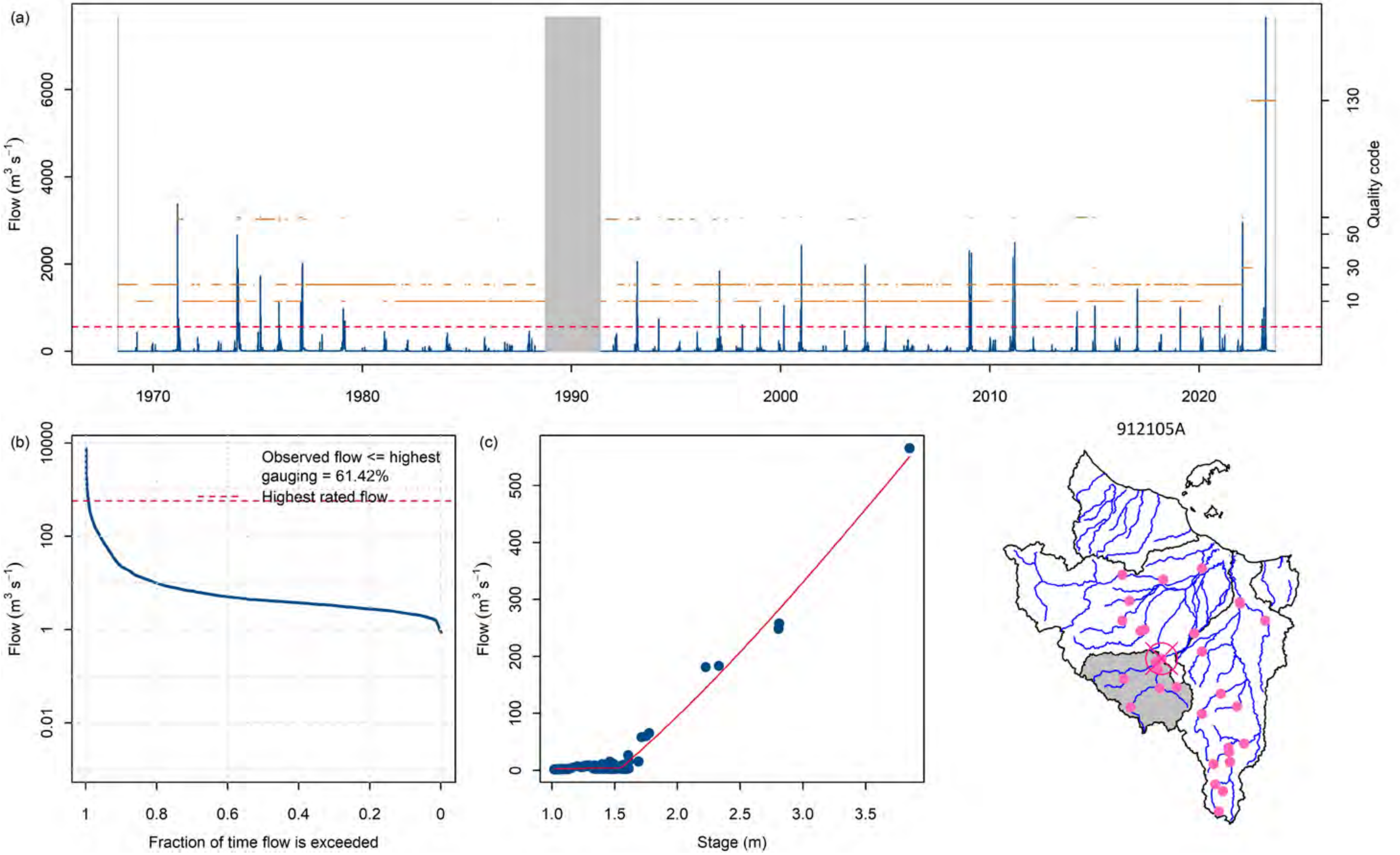
Apx Figure B-1 Stream gauge data for site 912101A (Gregory River at Gregory Downs). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings available



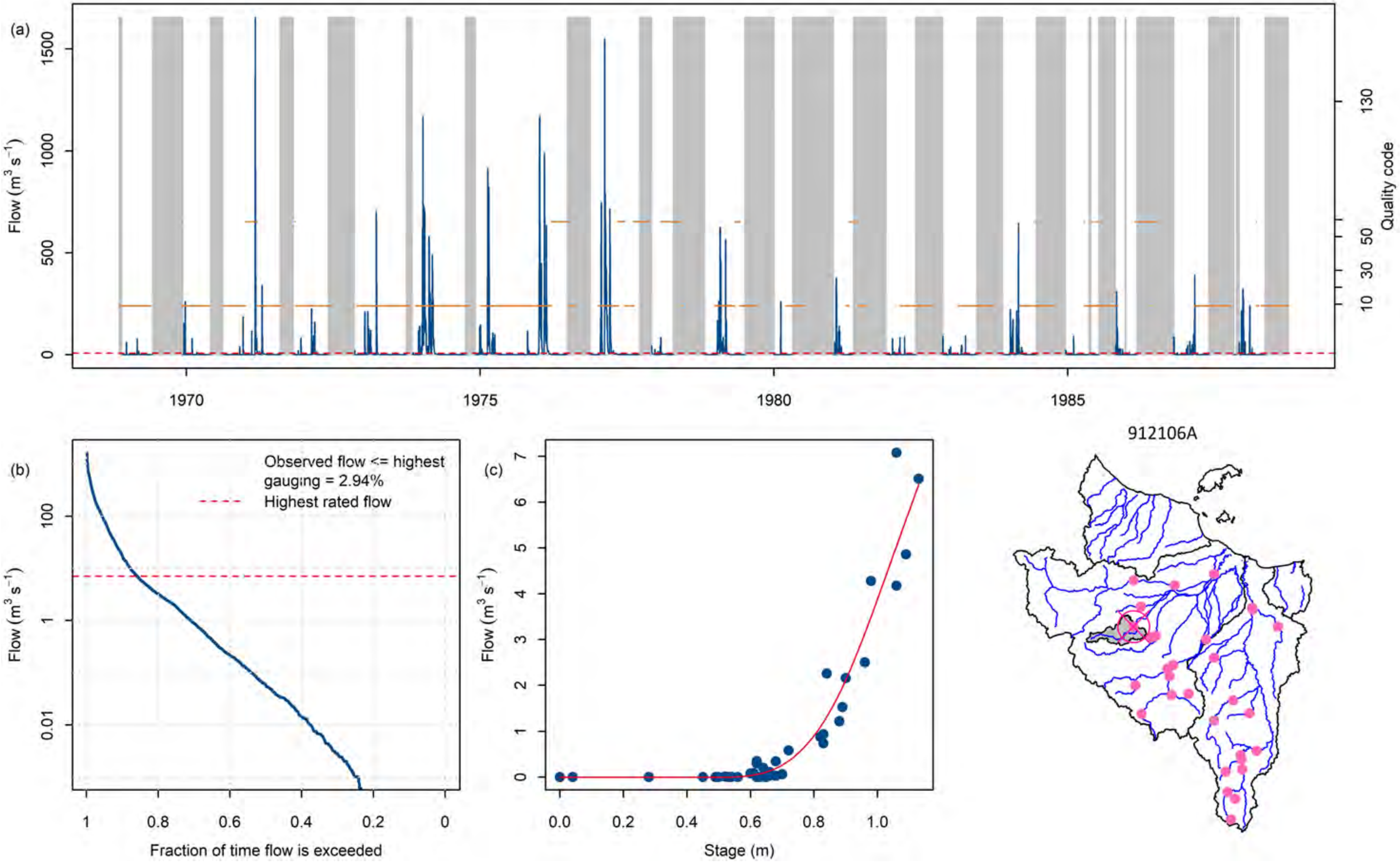
Apx Figure B-2 Stream gauge data for site 912103A (Lawn Hill Creek at Lawn Hill No. 2). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings available



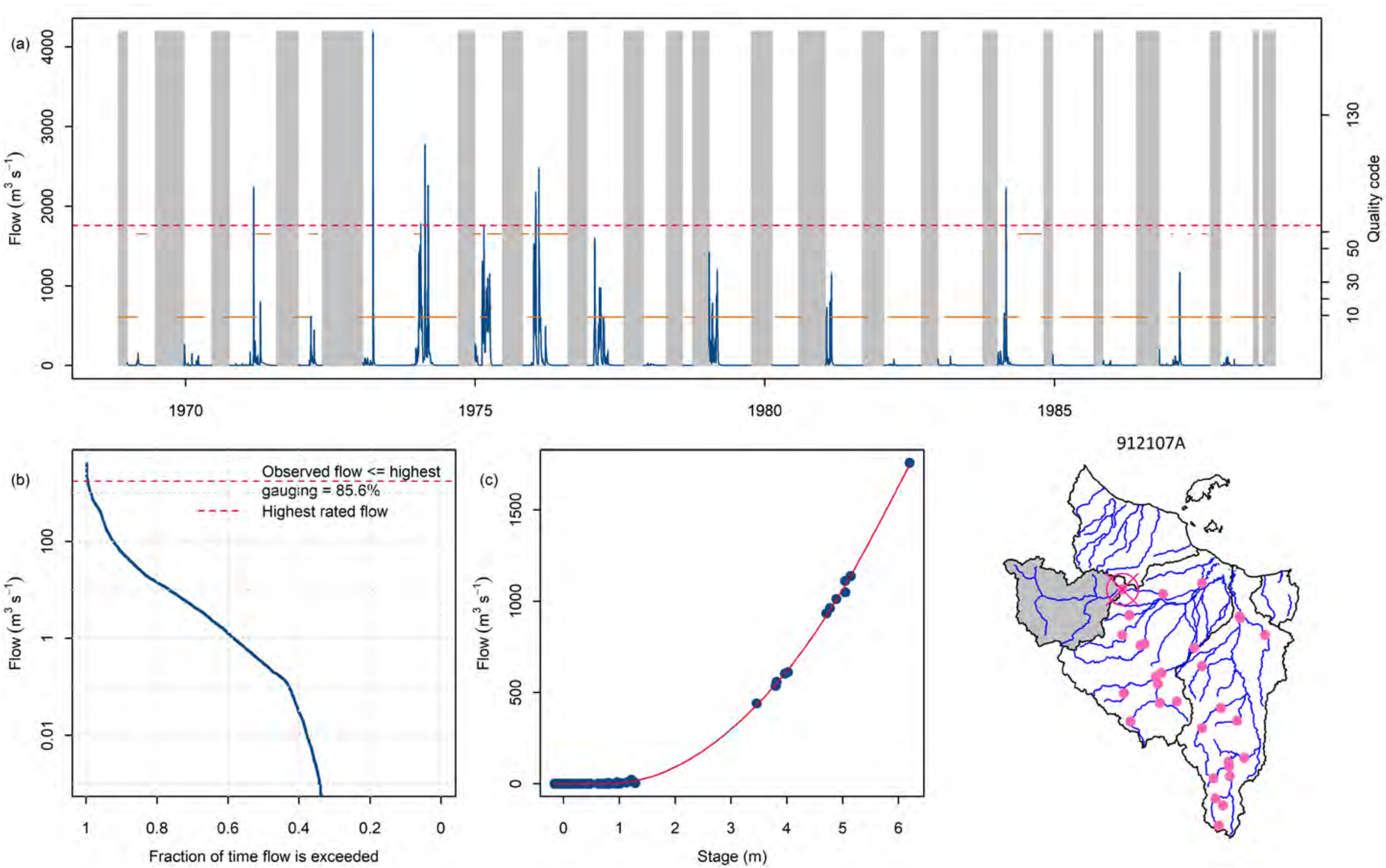
Apx Figure B-3 Stream gauge data for site 912104A (Widdallion Creek at Lawn Hill). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings available



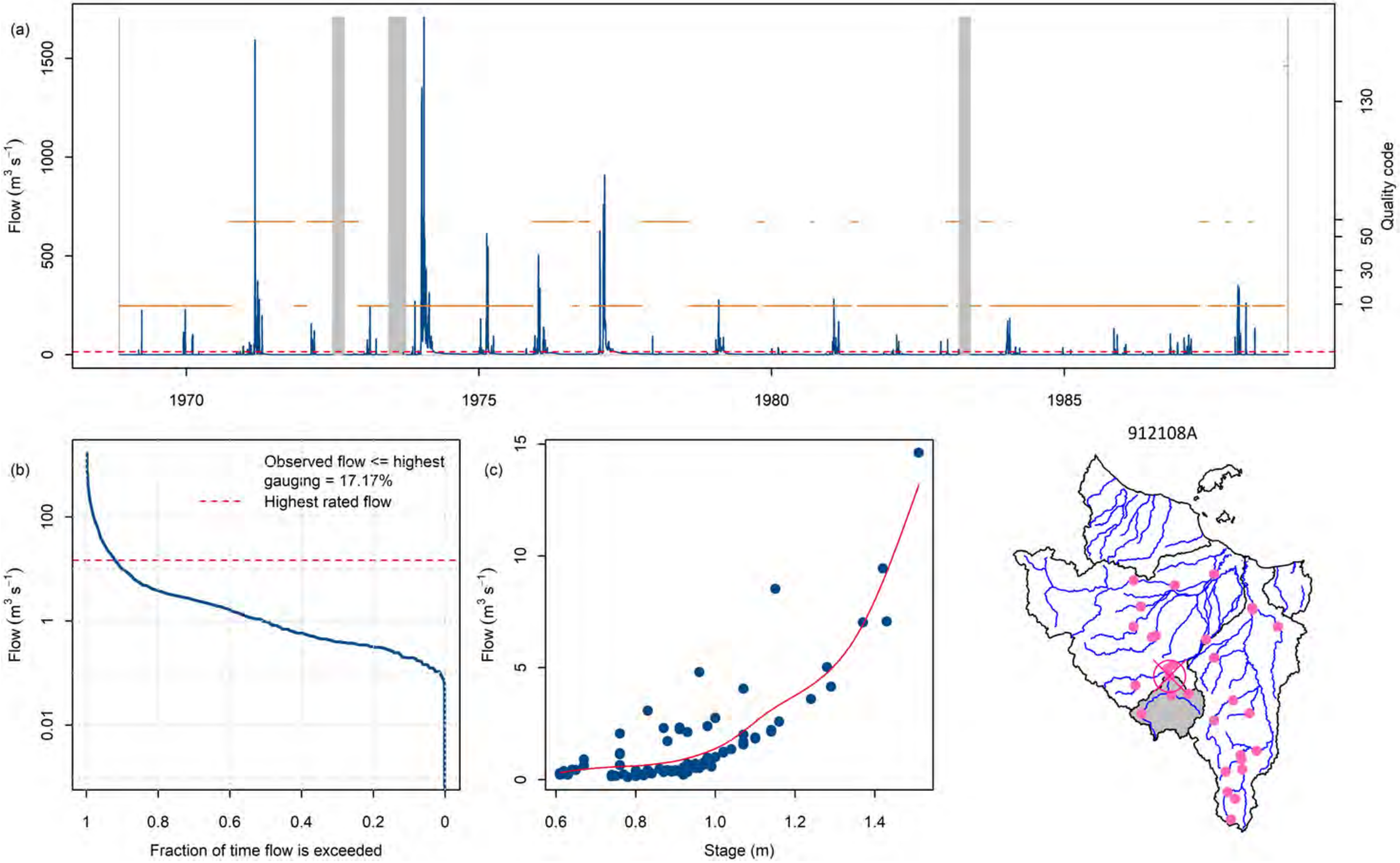
Apx Figure B-4 Stream gauge data for site 912105A (Gregory River at Riversleigh No. 2). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings available



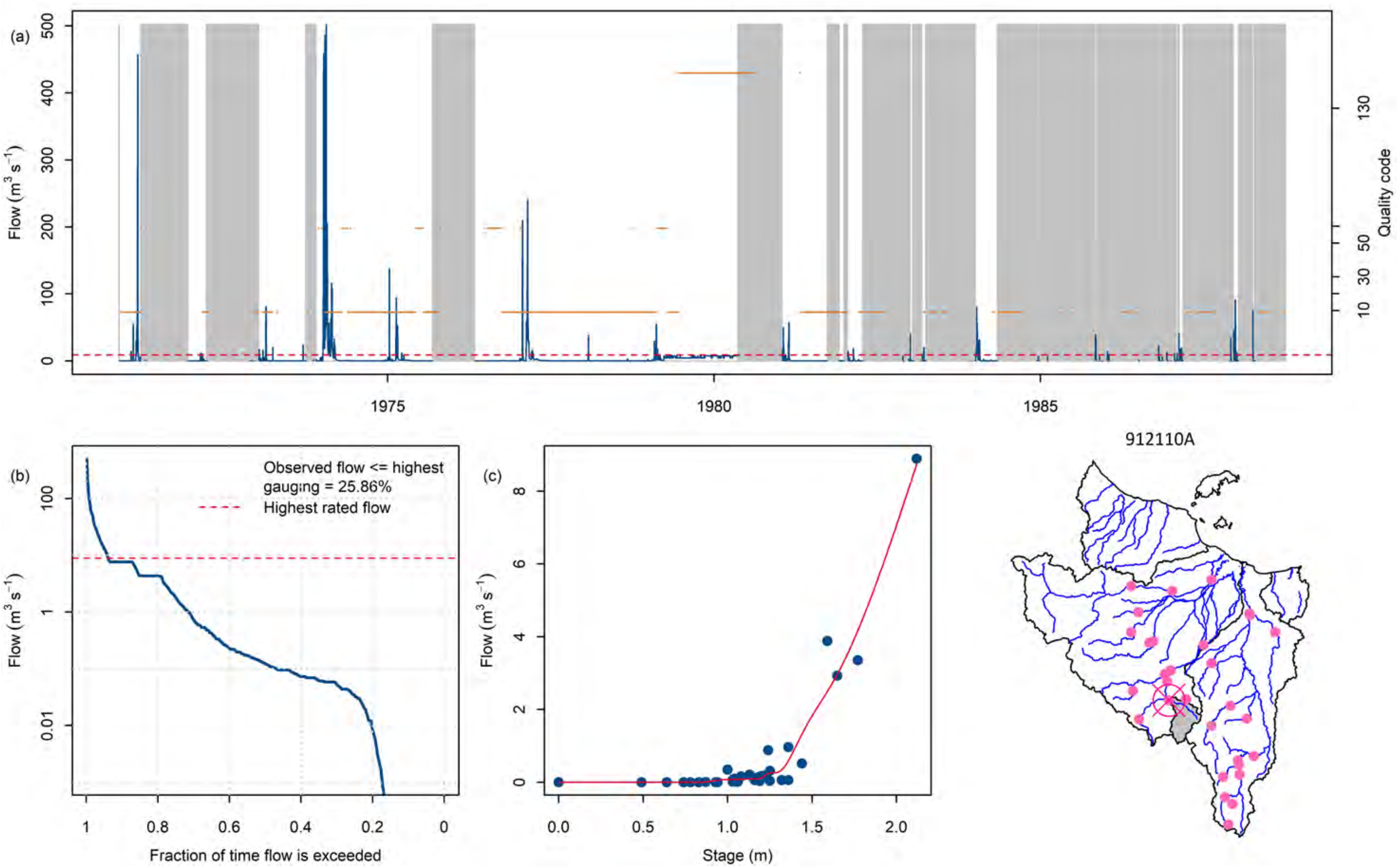
Apx Figure B-5 Stream gauge data for site 912106A (Musselbrook Creek at Stockyard Creek). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings



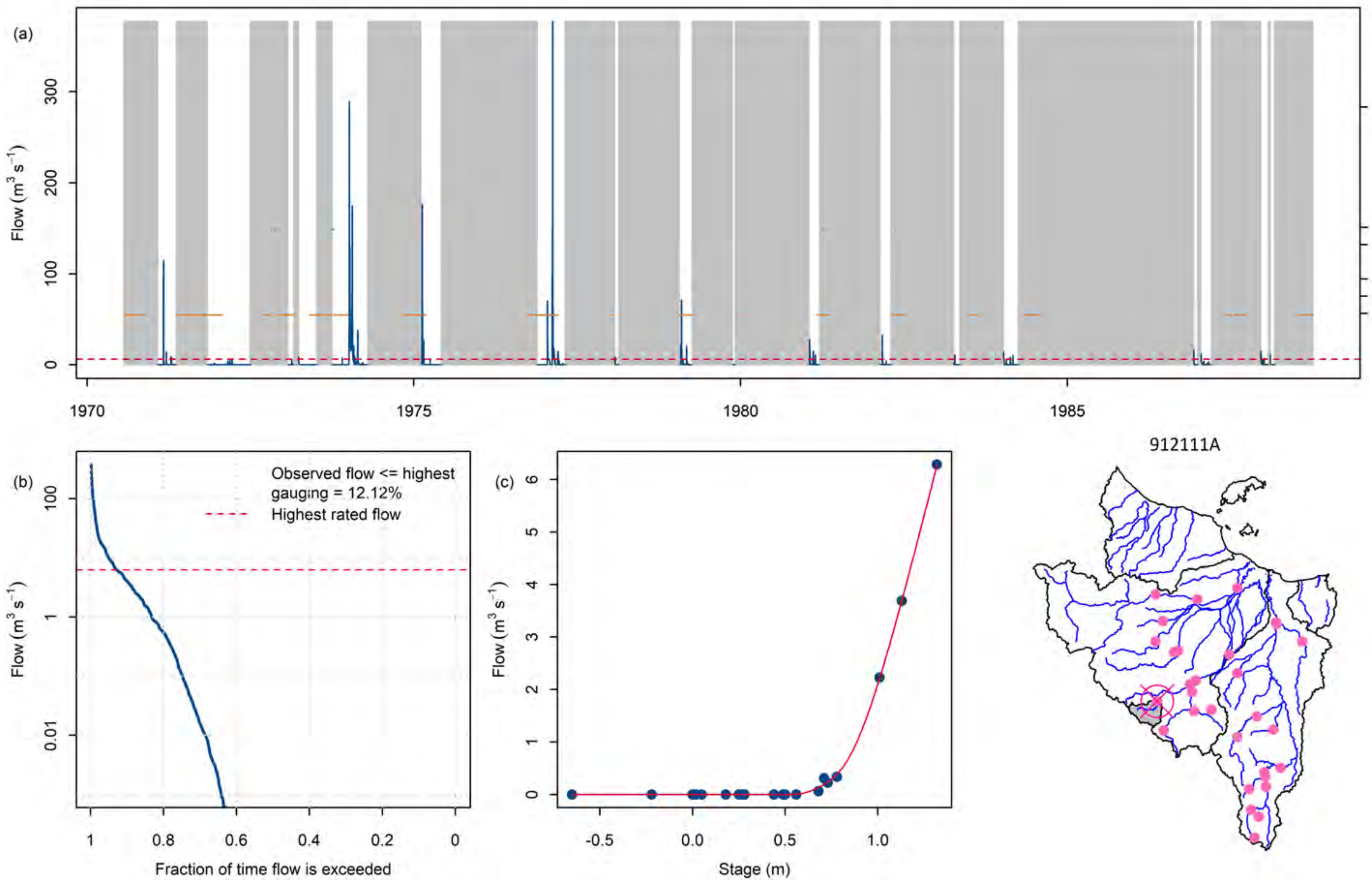
Apx Figure B-6 Stream gauge data for site 912107A (Nicholson River at Connolly's Hole). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings available



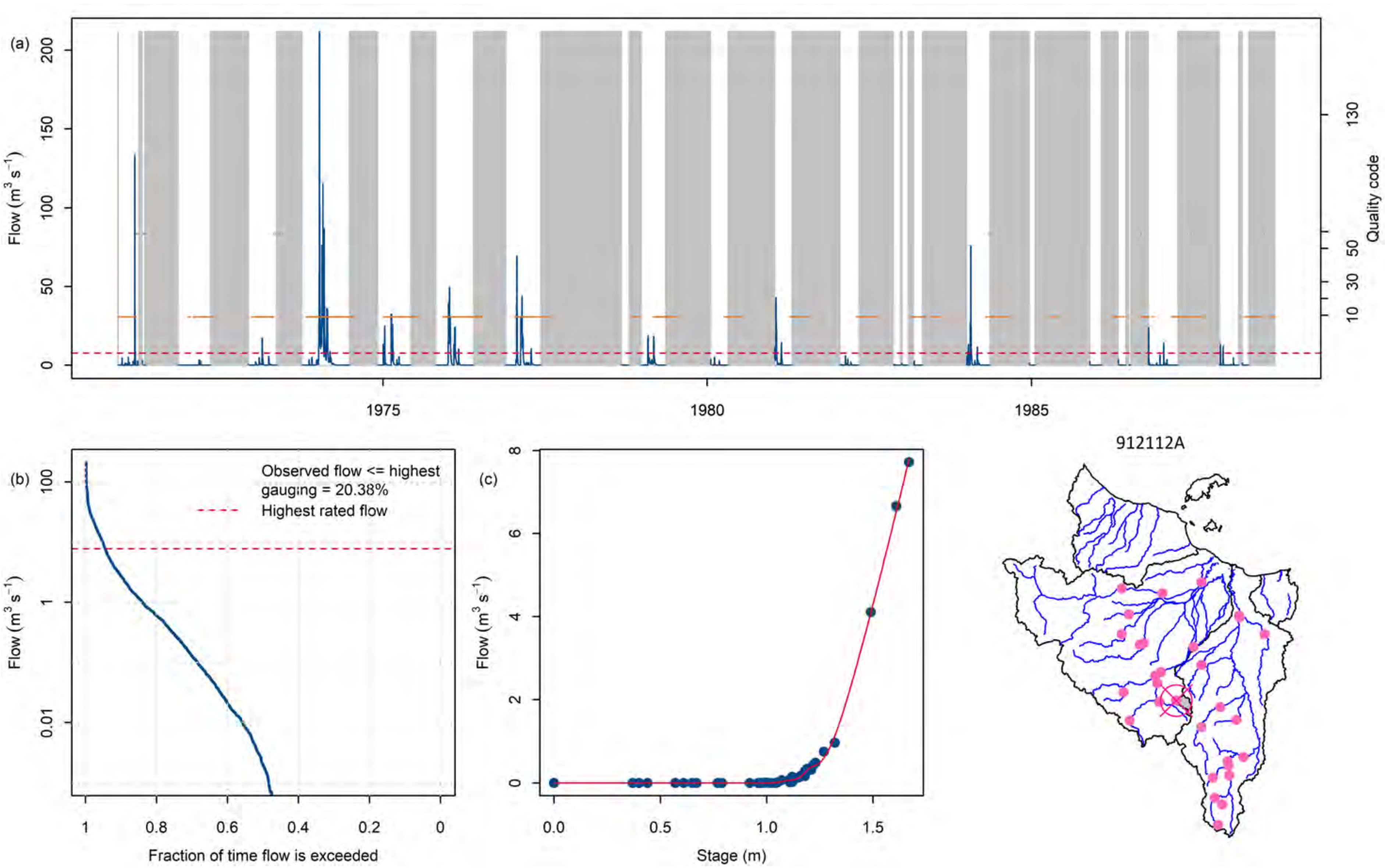
Apx Figure B-7 Stream gauge data for site 912108A (O'Shannassy River at 17.7 km). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings available



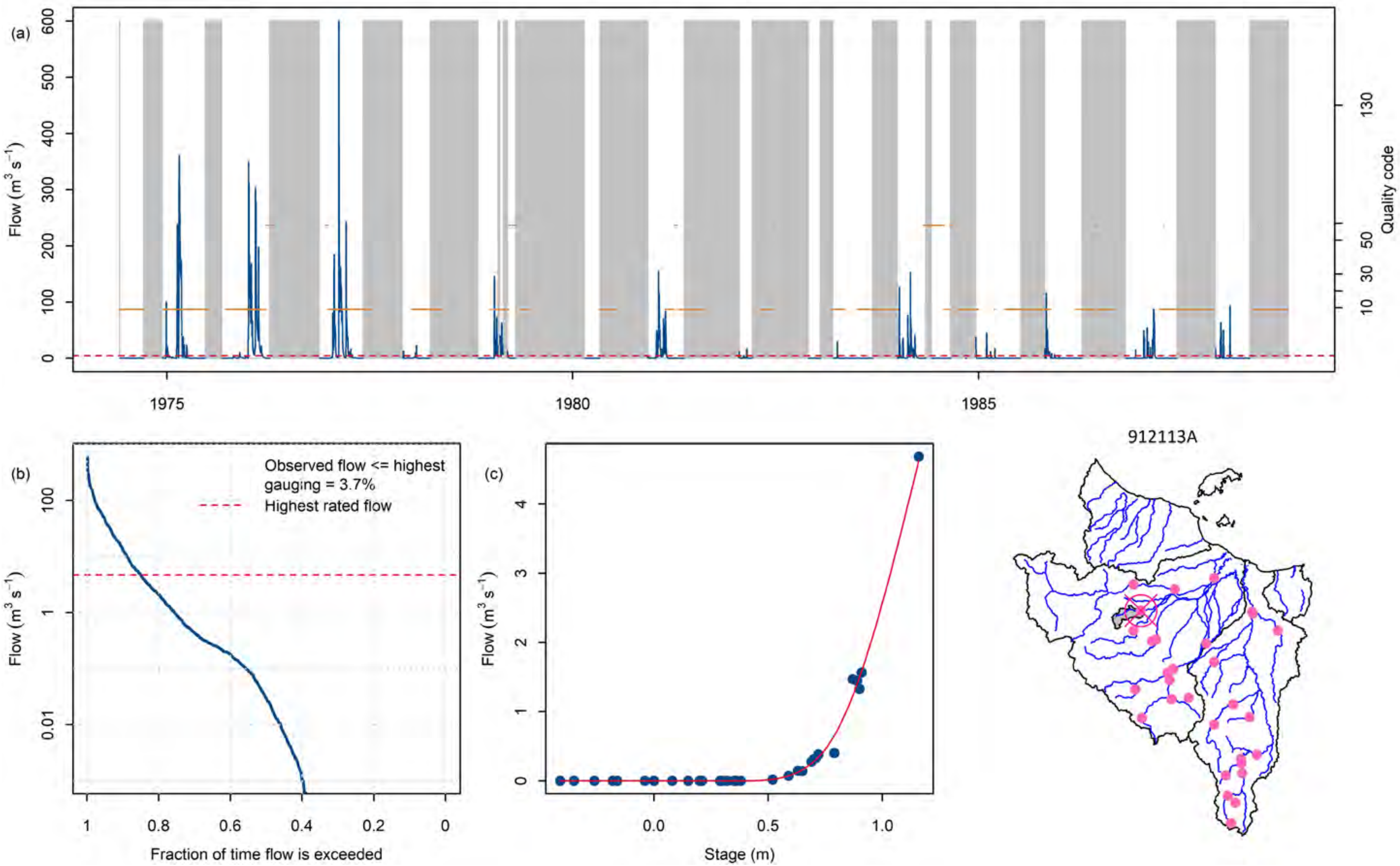
Apx Figure B-8 Stream gauge data for site 912110A (Thornton River at Rosehill Bore). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings available



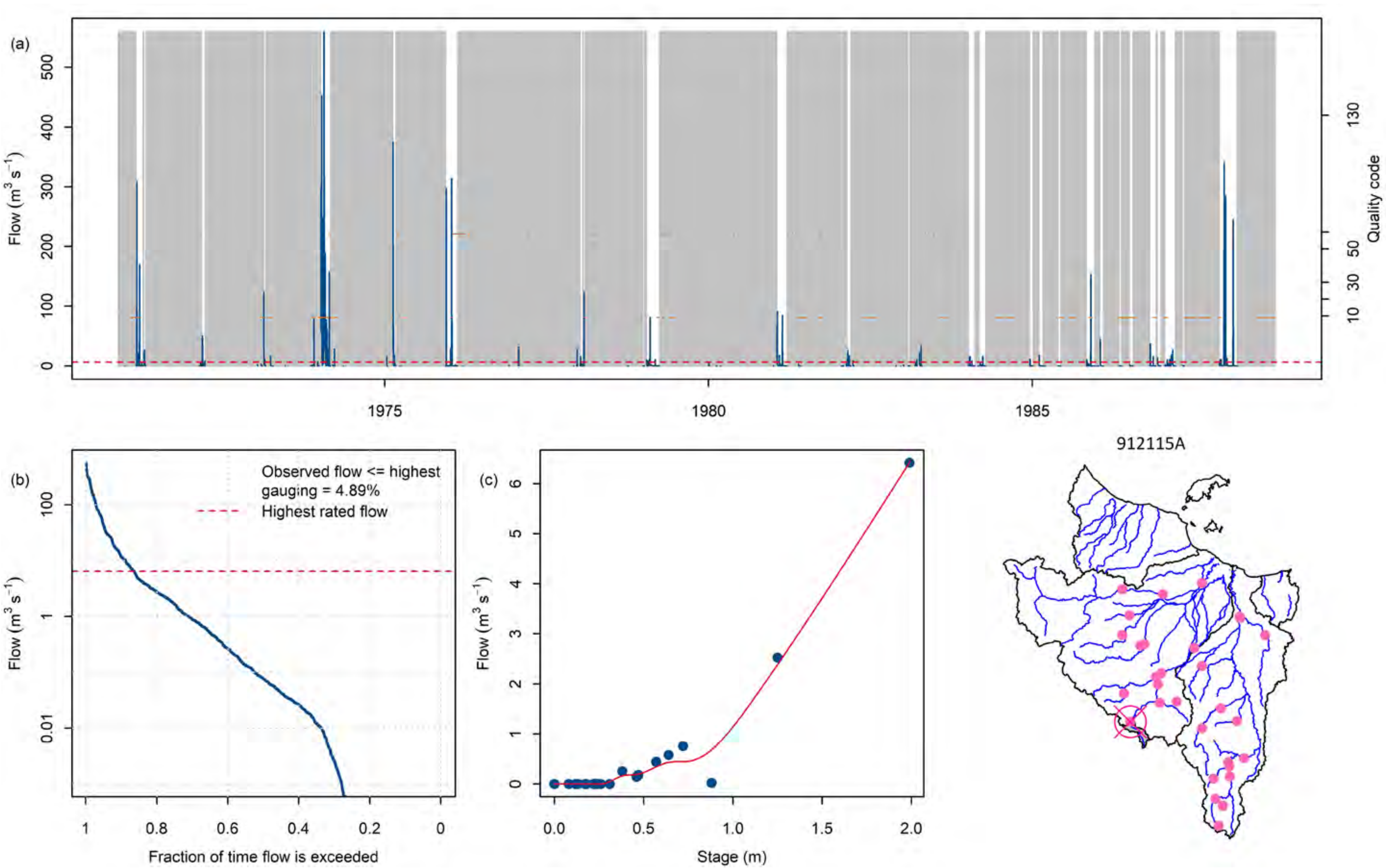
Apx Figure B-9 Stream gauge data for site 912111A (Goonooma Creek at Norfolk). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings available



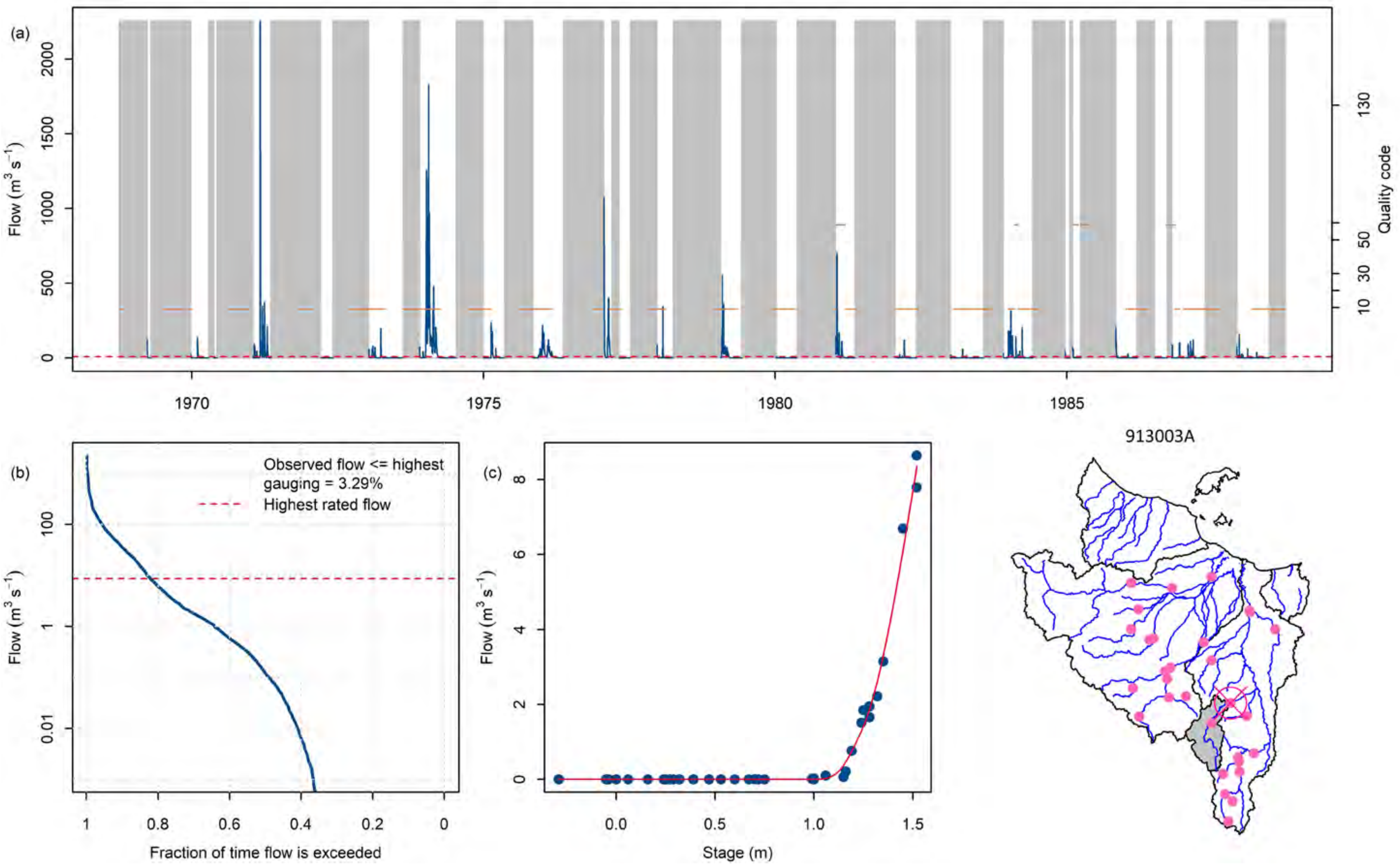
Apx Figure B-10 Stream gauge data for site 912112A (Seymour River at Main Road). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings available



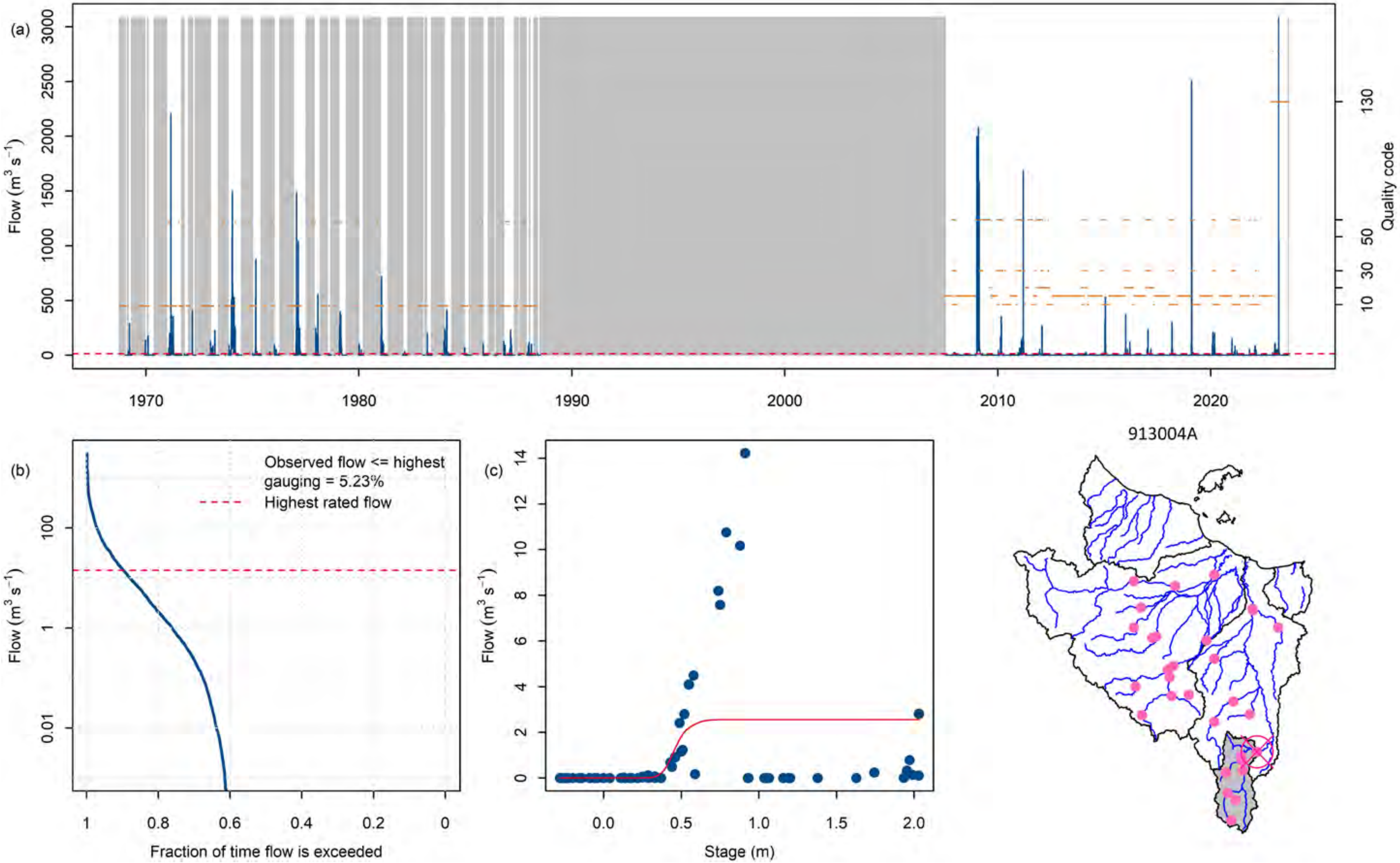
Apx Figure B-11 Stream gauge data for site 912113A (Elizabeth Creek at Mining Camp). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings available



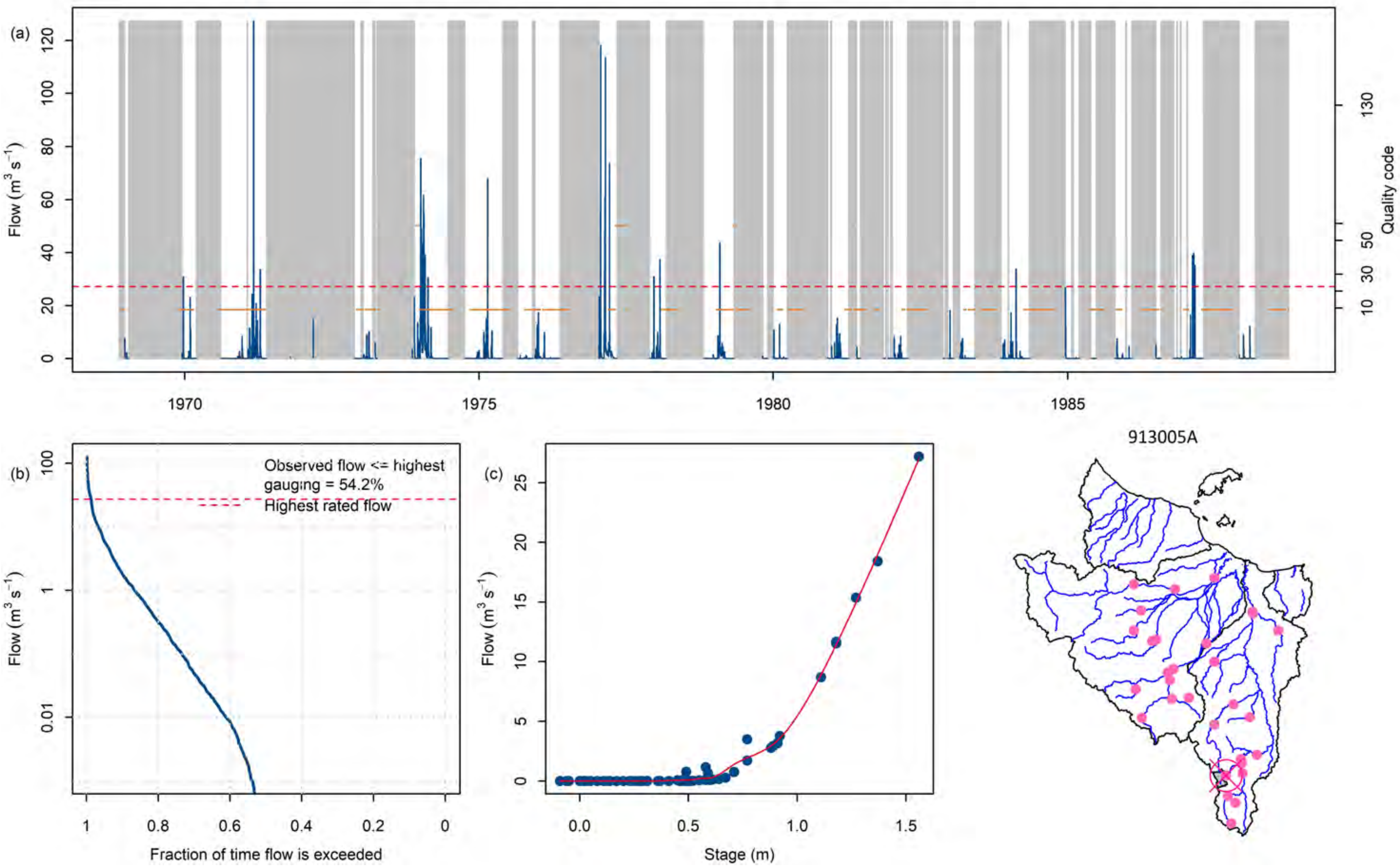
Apx Figure B-12 Stream gauge data for site 912115A (O'Shannassy River at Morestone). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings available



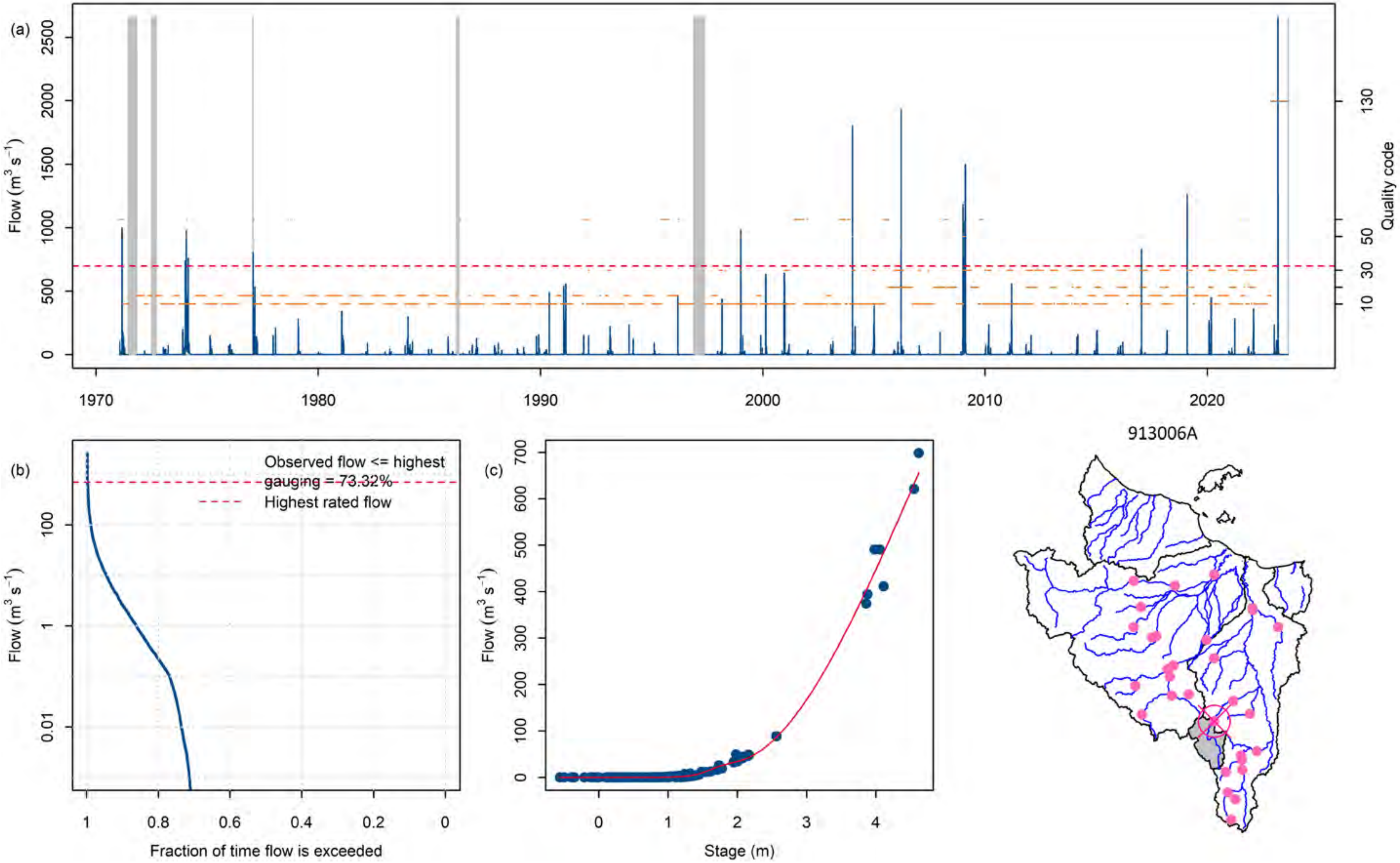
Apx Figure B-13 Stream gauge data for site 913003A (Gunpowder Creek at White Gorge). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings available



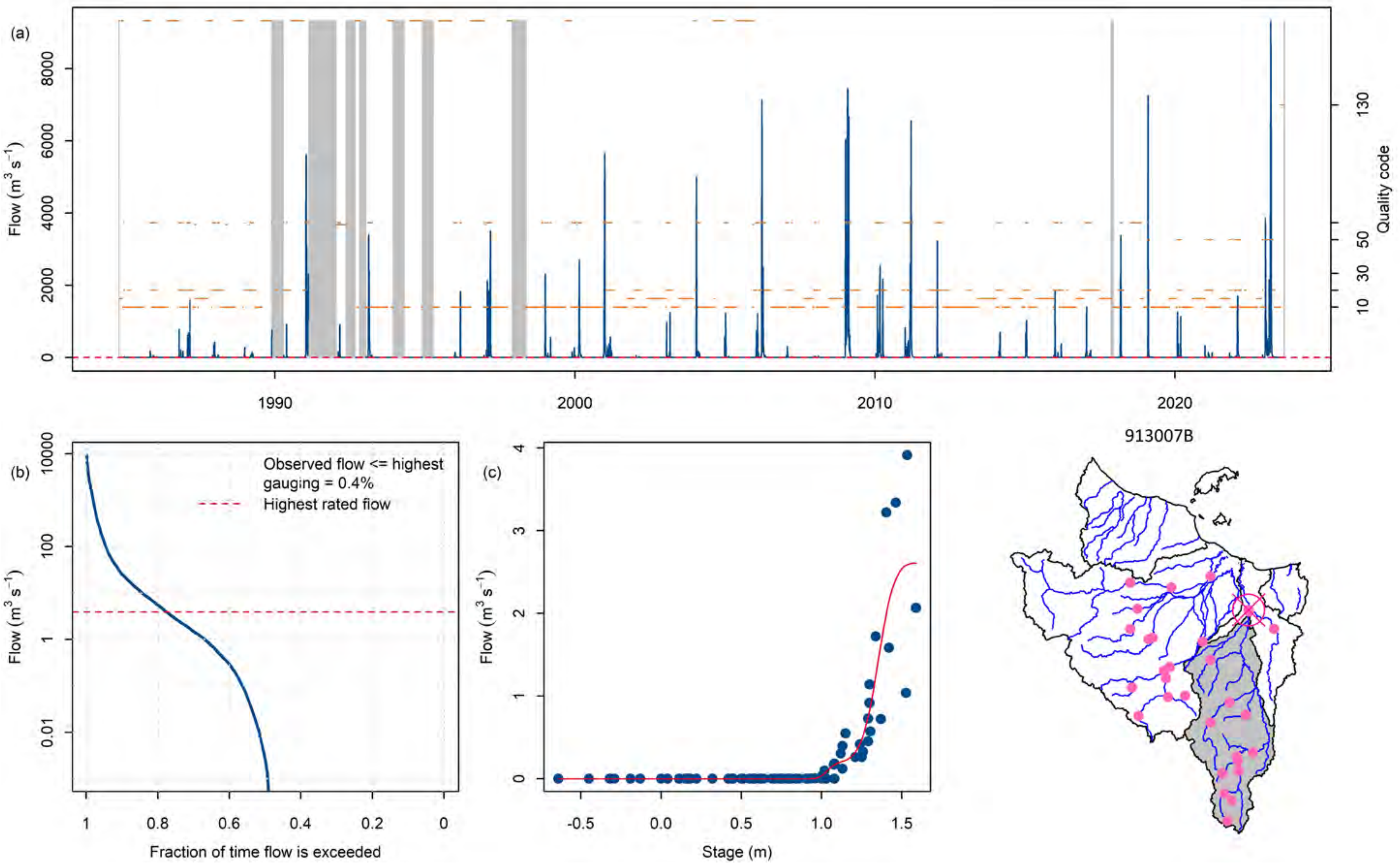
Apx Figure B-14 Stream gauge data for site 913004A (Leichhardt River at Miranda Creek). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings available



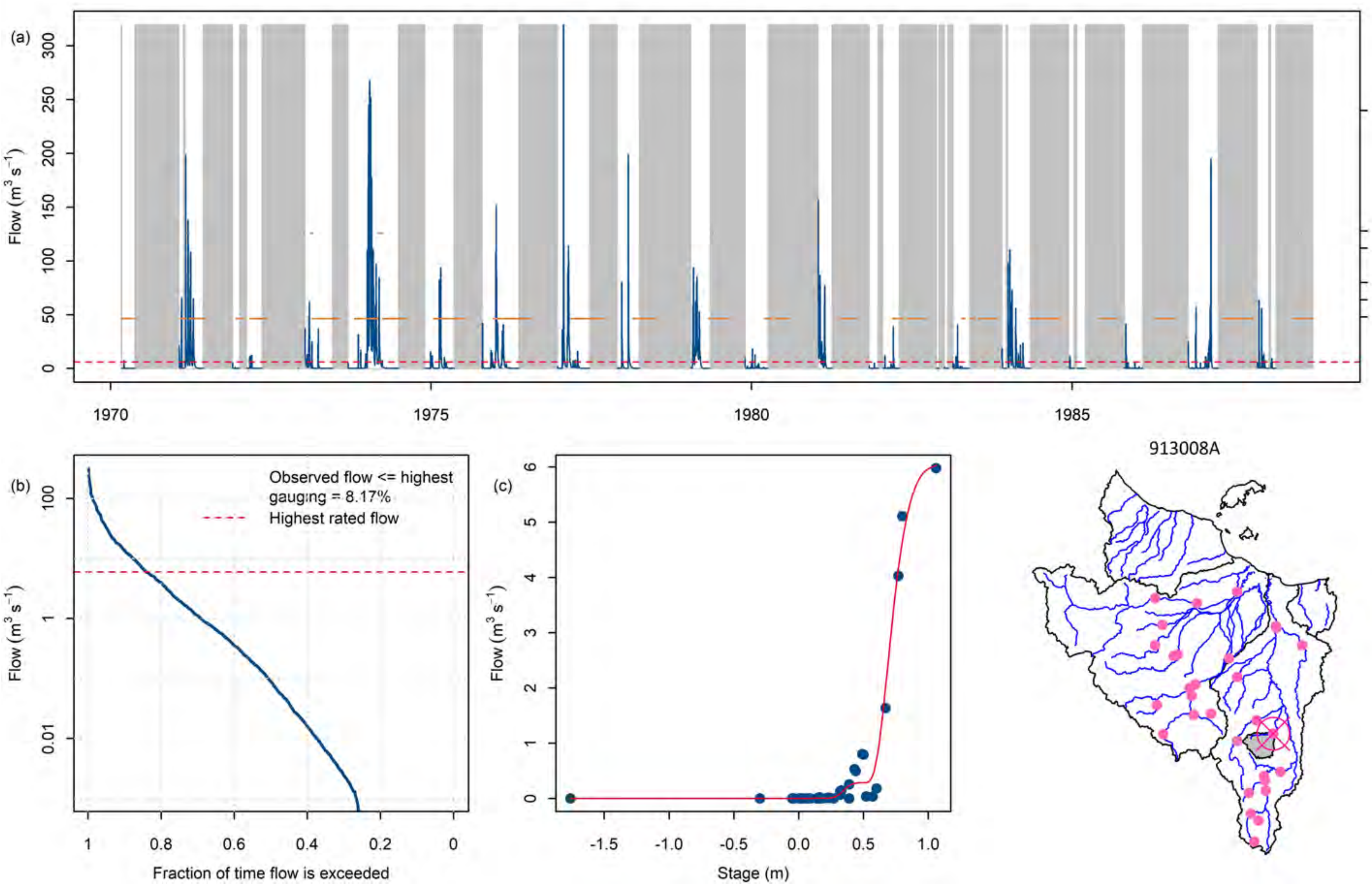
Apx Figure B-15 Stream gauge data for site 913005A (Paroo Creek at Damsite). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings available



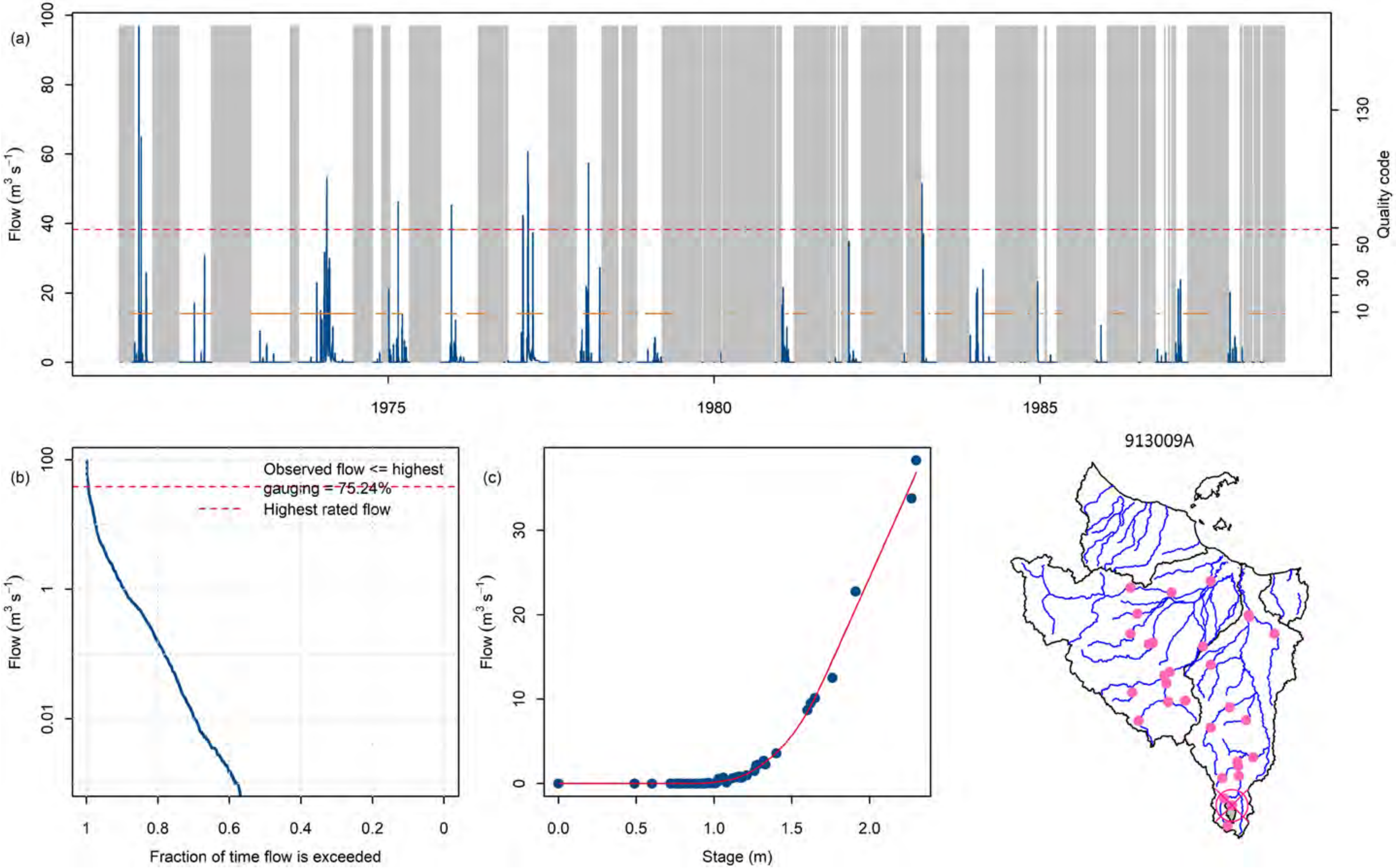
Apx Figure B-16 Stream gauge data for site 913006A (Gunpowder Creek at Gunpowder). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings available



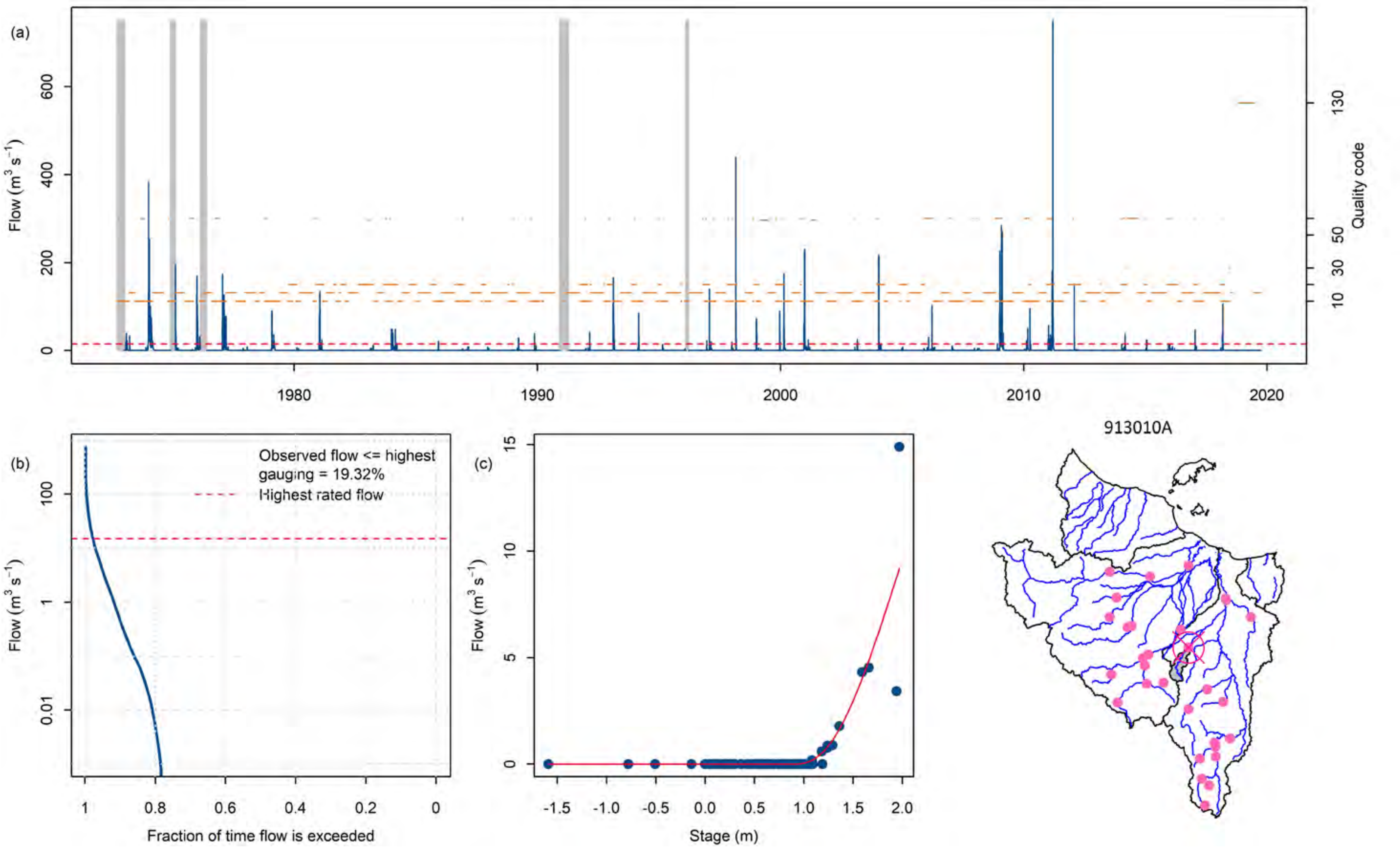
Apx Figure B-17 Stream gauge data for site 913007B (Leichhardt River at Floraville Homestead). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings



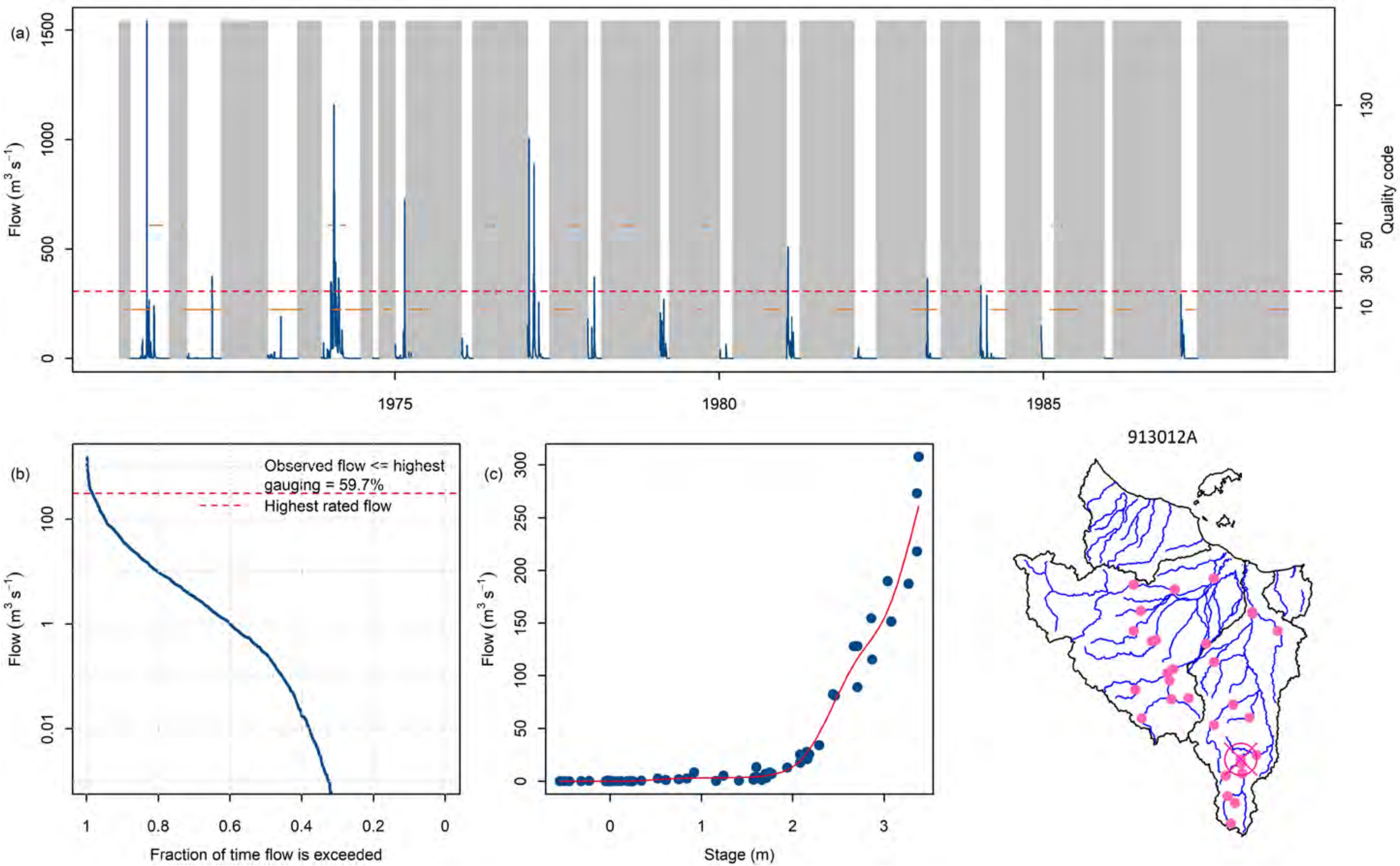
Apx Figure B-18 Stream gauge data for site 913008A (Mistake Creek at White Hills). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings available



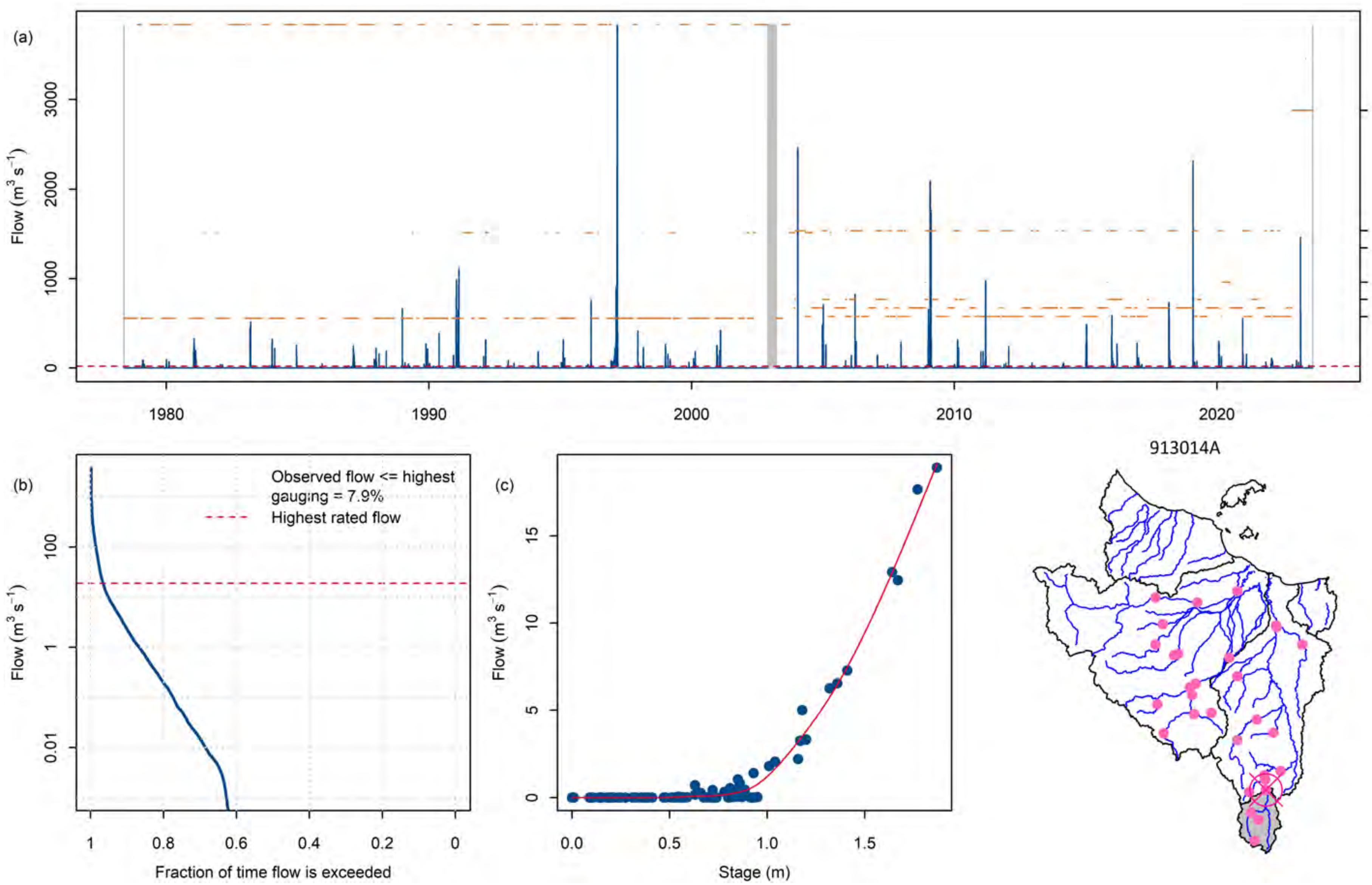
Apx Figure B-19 Stream gauge data for site 913009A (Gorge Creek at Flinders Highway). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings available



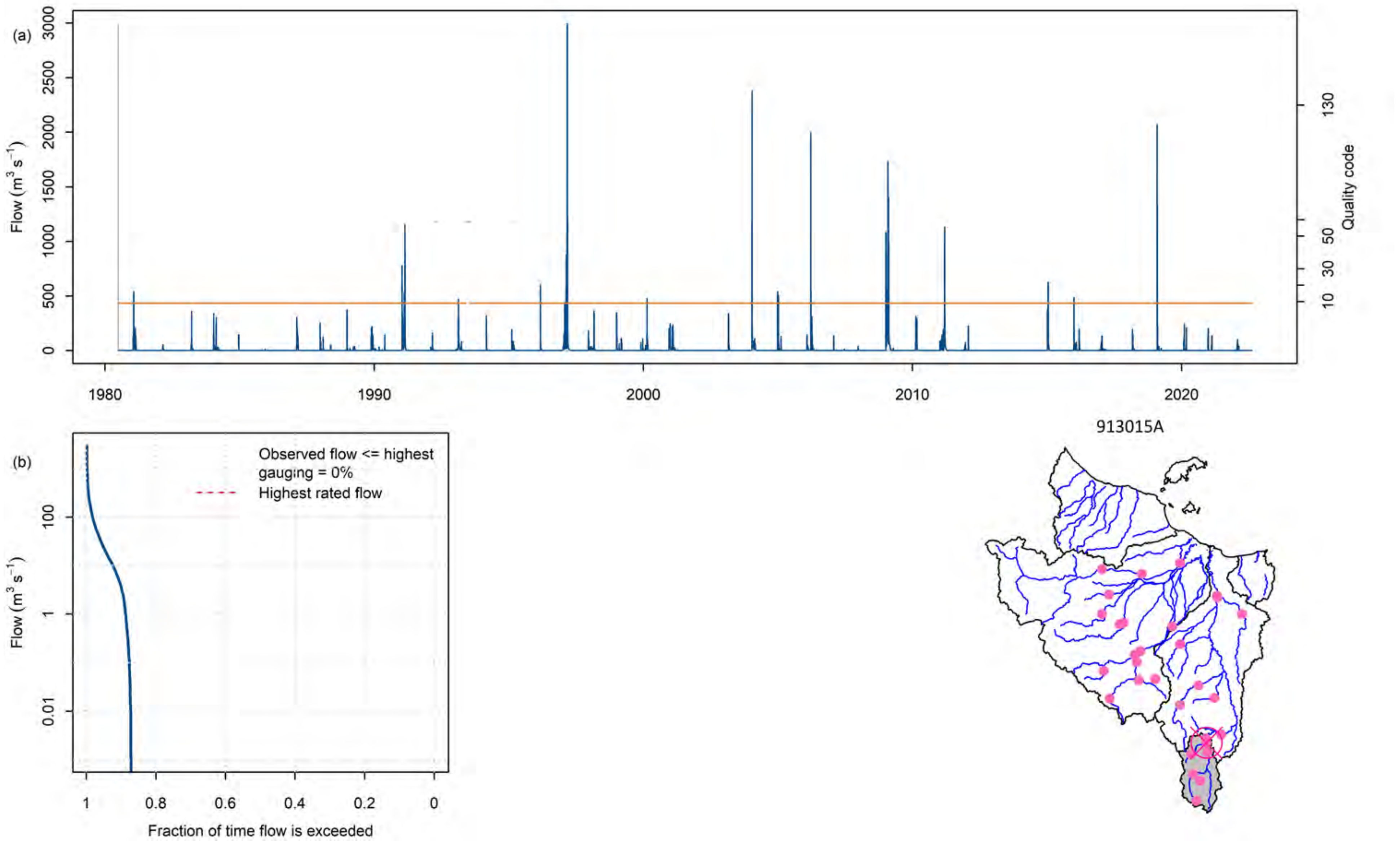
Apx Figure B-20 Stream gauge data for site 913010A (Fiery Creek at 16 Mile Waterhole). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings available



Apx Figure B-21 Stream gauge data for site 913012A (Leichhardt River at Julius Dam Tailwater). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings



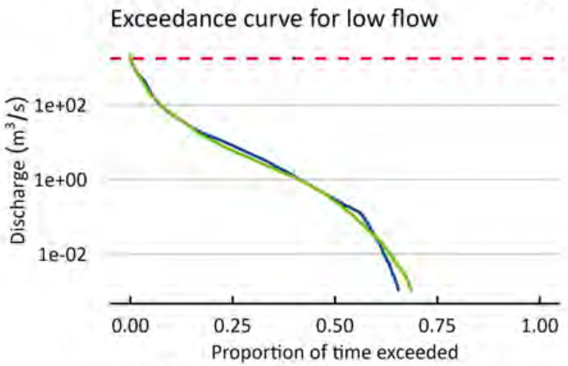
Apx Figure B-22 Stream gauge data for site 913014A (Leichhardt River at Doughboy Creek). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. Stage–flow relationship is a loess regression through the gaugings

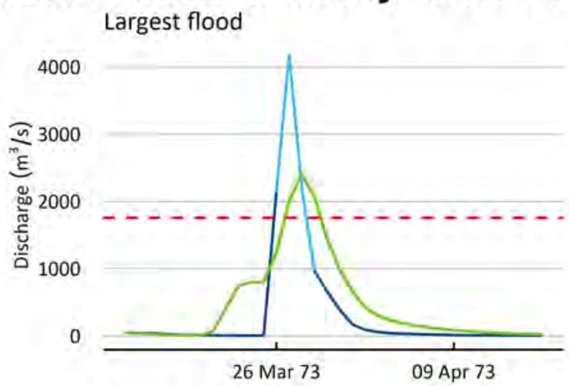


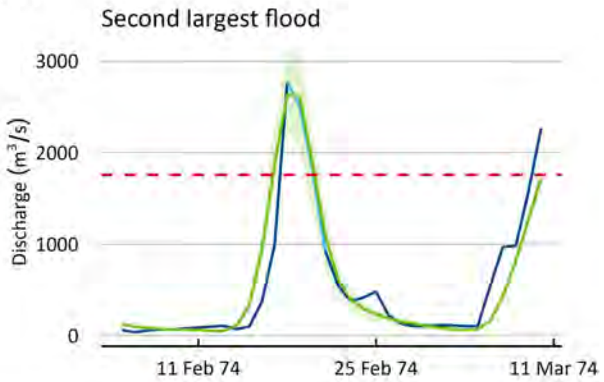
Apx Figure B-23 Stream gauge data for site 913015A (Leichhardt River at Julius Dam). The dashed red line in the top and bottom left panel shows highest gauged point. Quality codes are given by yellow points in the top panel, while grey vertical lines indicate missing data. No gaugings were identified for this site

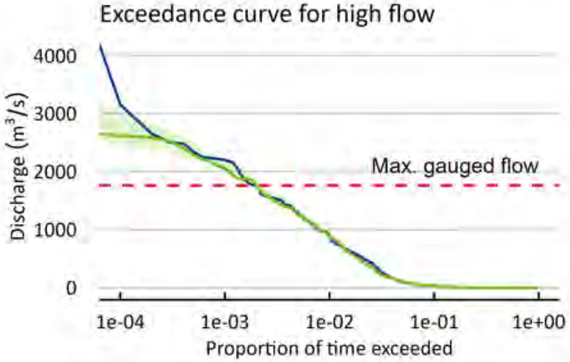
Appendix C River model benchmark plots

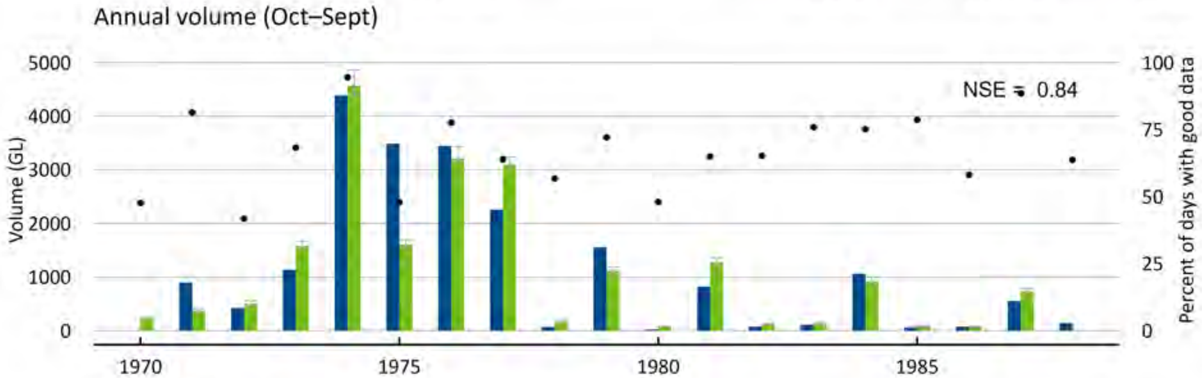
Nicholson River at Connollys Hole 912107A





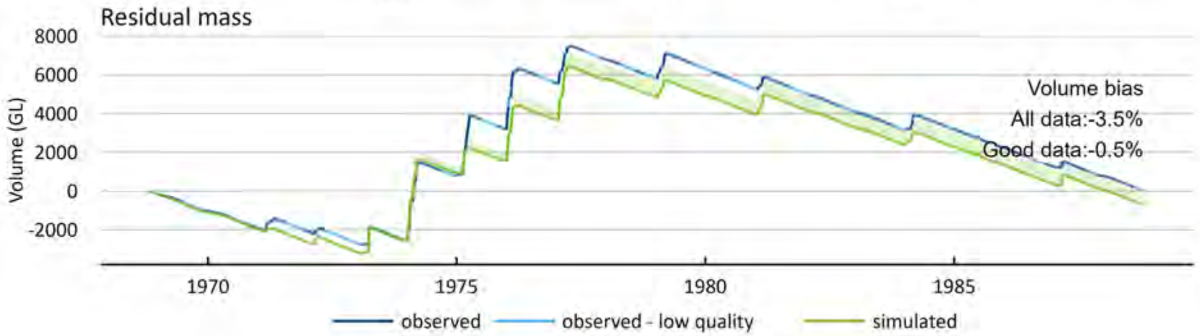




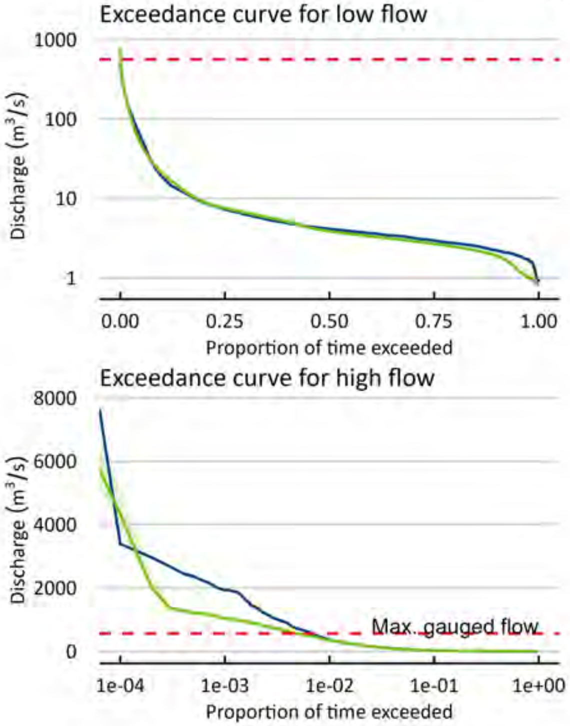


statistic	observed	simulated
Days with flow (%)	65	69
Mean (GL/y)	1083	1049
Median (GL/y)	541	505

metric	calibration	validation
Daily NSE	0.65	NA
Daily sqrt NSE	0.76	NA
Bias (%)	-1.40	NA

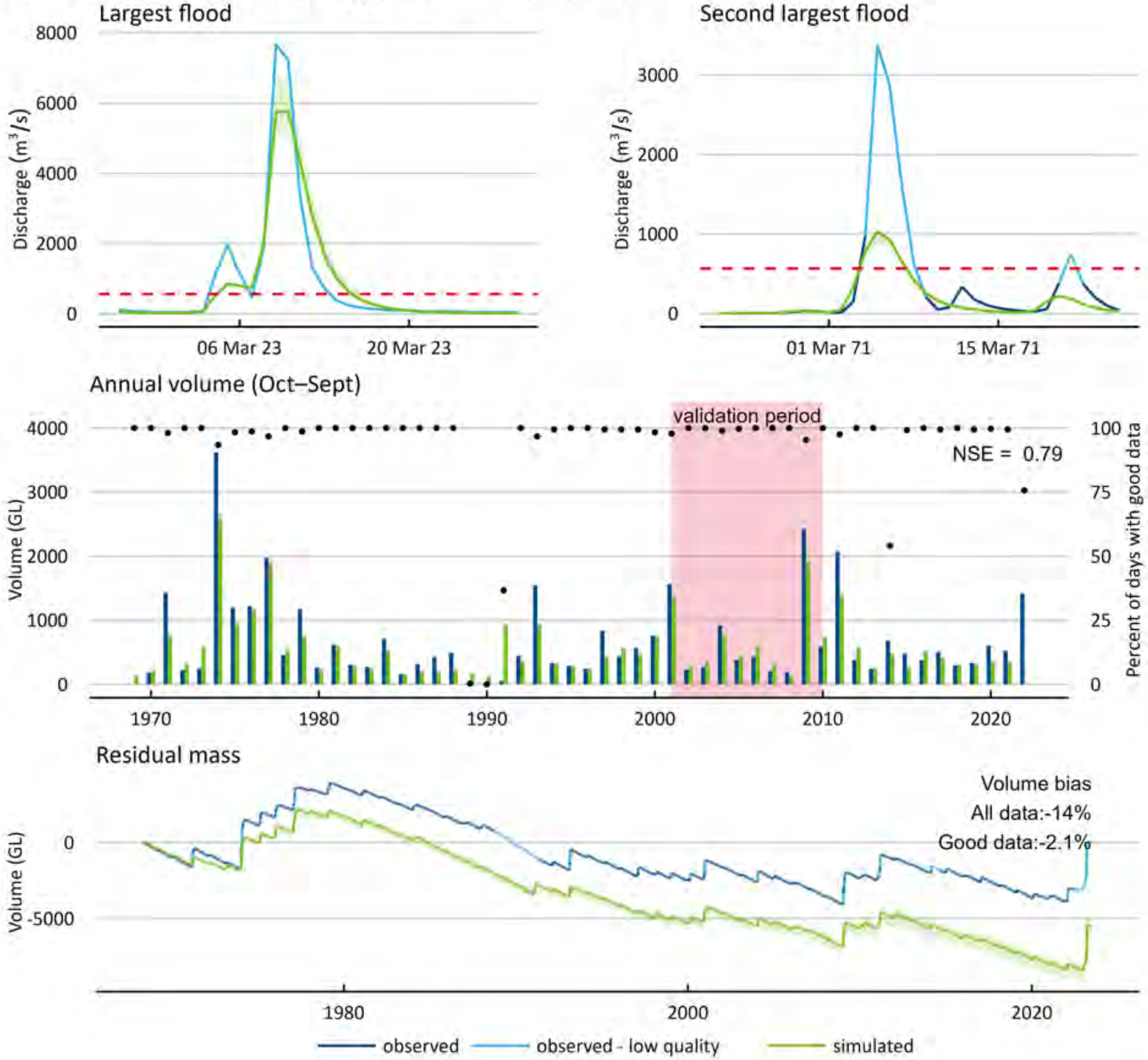


Gregory River at Riversleigh No.2 912105A

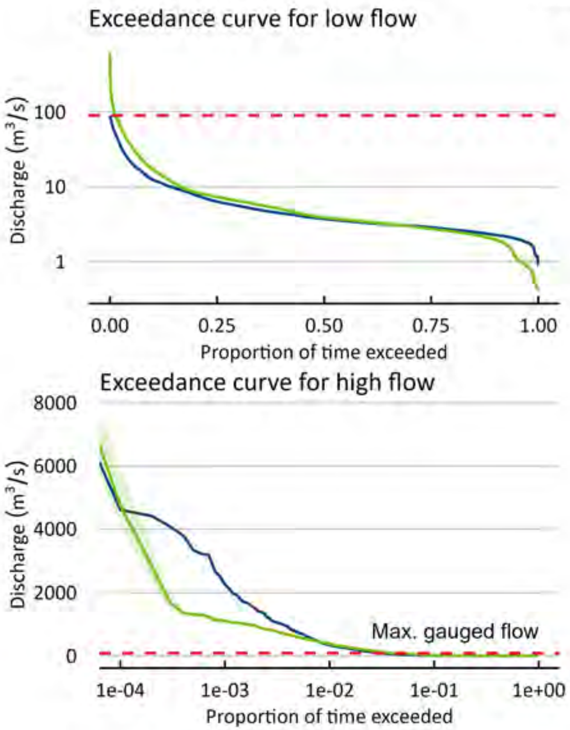


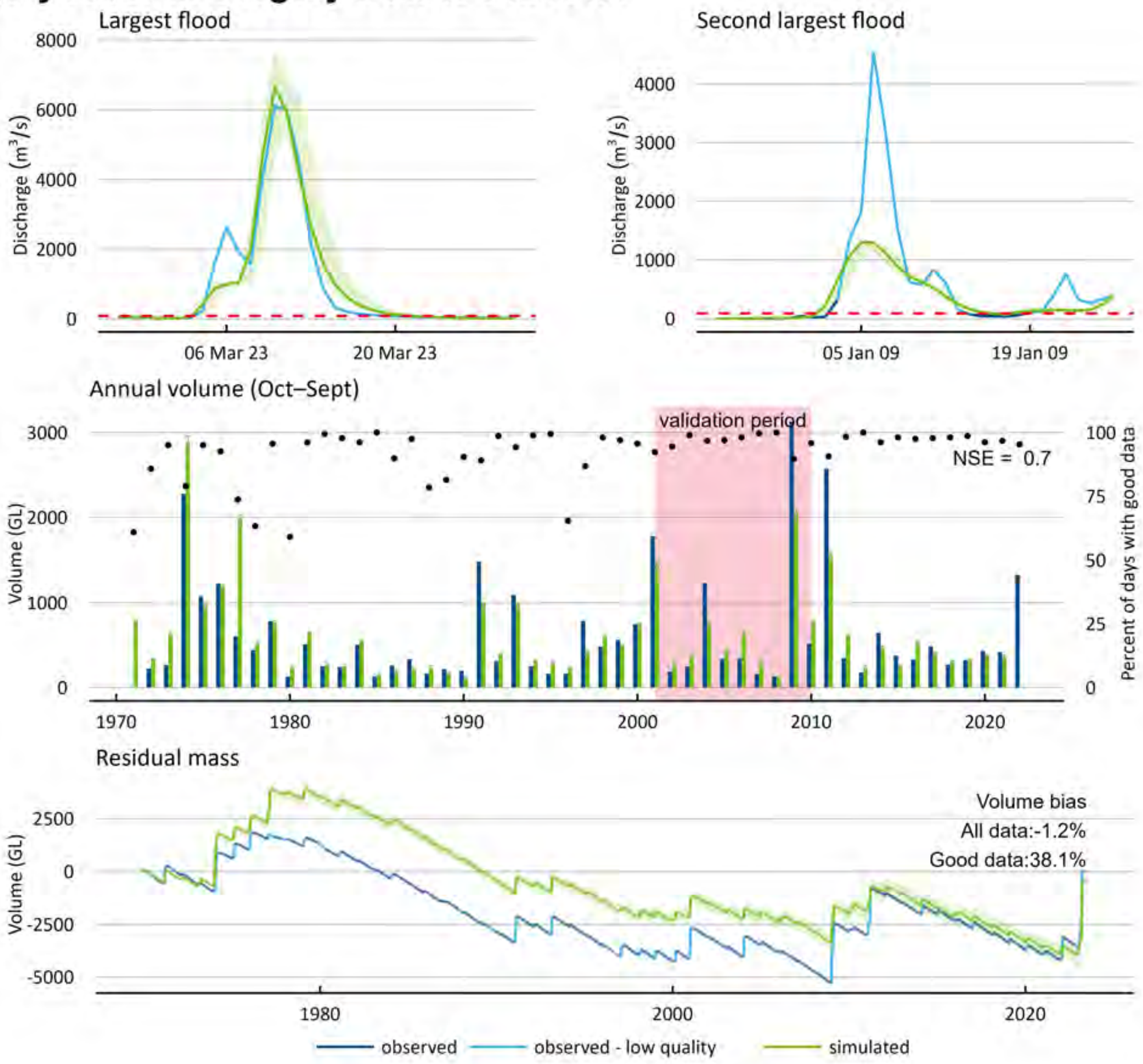
statistic	observed	simulated
Days with flow (%)	100	100
Mean (GL/y)	659	560
Median (GL/y)	424	407

metric	calibration	validation
Daily NSE	0.53	0.65
Daily sqrt NSE	0.60	0.68
Bias (%)	-3.30	20.00



Gregory River at Gregory Downs 912101A



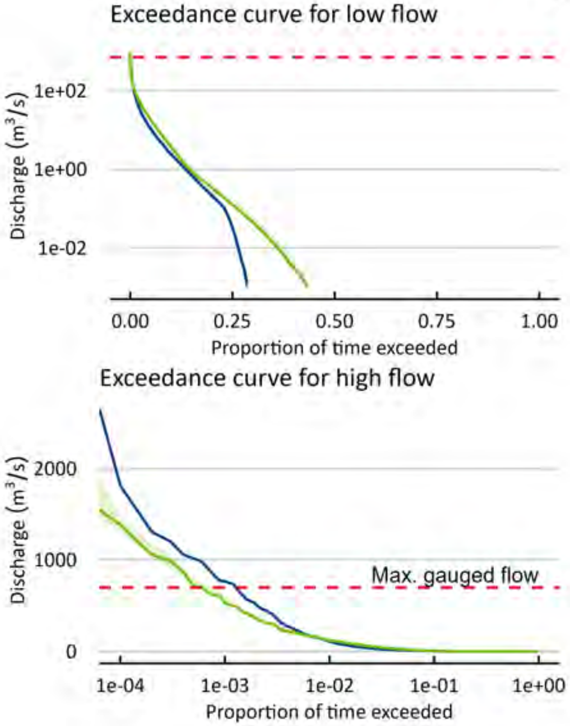


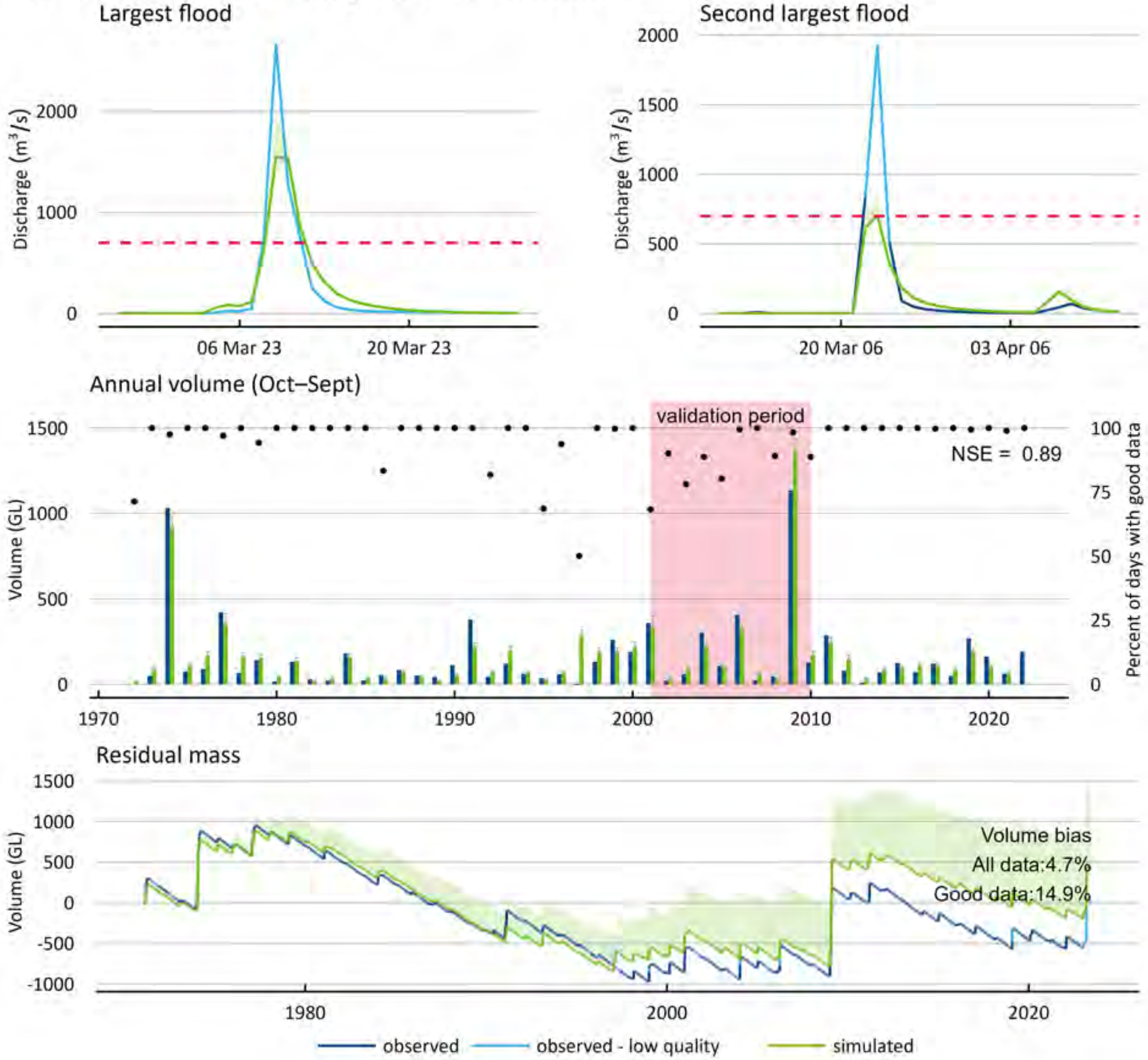
statistic	observed	simulated
Days with flow (%)	100	100
Mean (GL/y)	623	614
Median (GL/y)	355	430

metric	calibration	validation
Daily NSE	0.66	0.78
Daily sqrt NSE	0.56	0.61
Bias (%)	1.10	-9.50

Note: These statistics are based on all data available as anabranch connections occur at a similar level to the maximum gauged flow, as opposed to only good-quality data for other sites.

Gunpowder Creek at Gunpowder 913006A

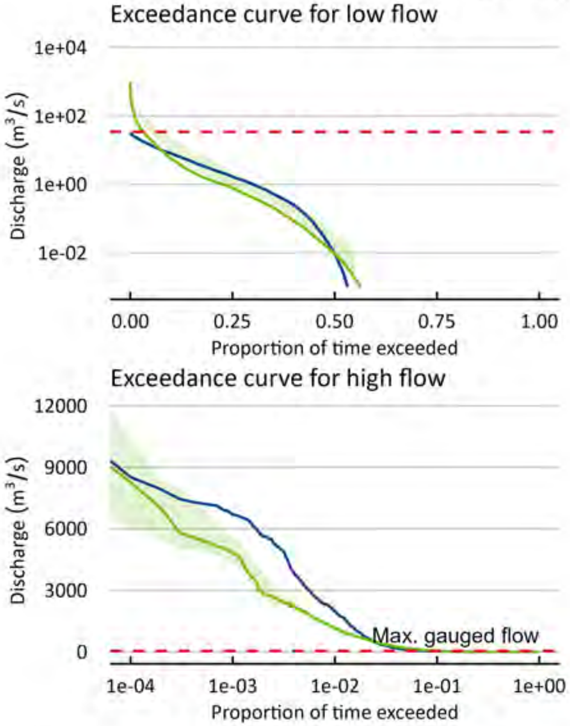


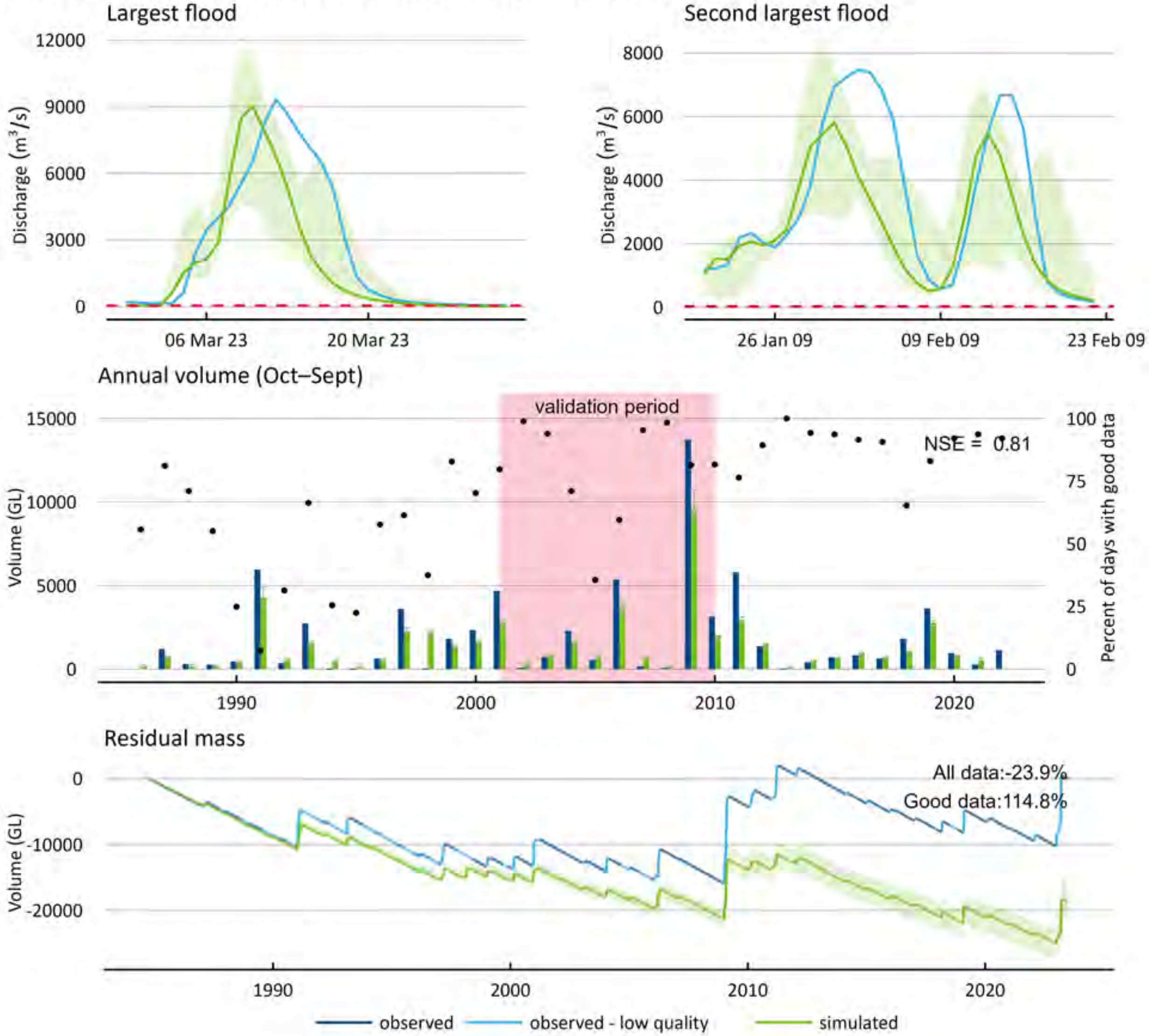


statistic	observed	simulated
Days with flow (%)	29	43
Mean (GL/y)	153	162
Median (GL/y)	76	101

metric	calibration	validation
Daily NSE	0.58	0.67
Daily sqrt NSE	0.59	0.77
Bias (%)	3.20	6.80

Leichhardt River at Floraville Homestead 913007B



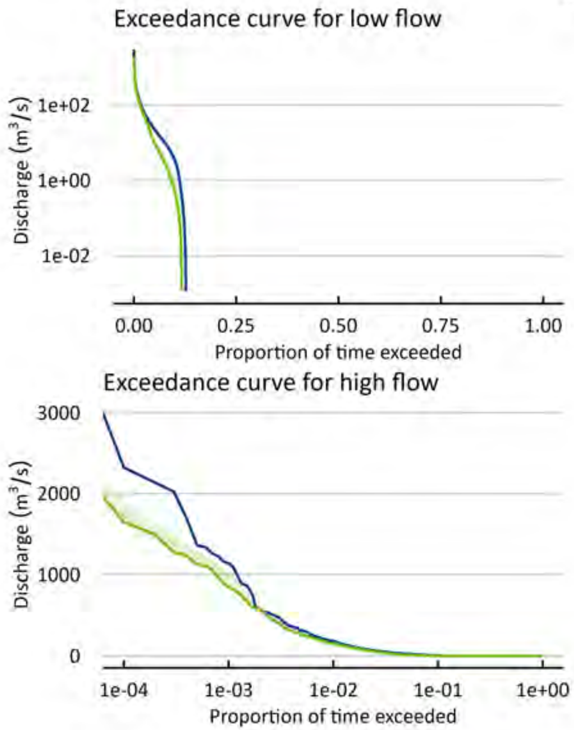


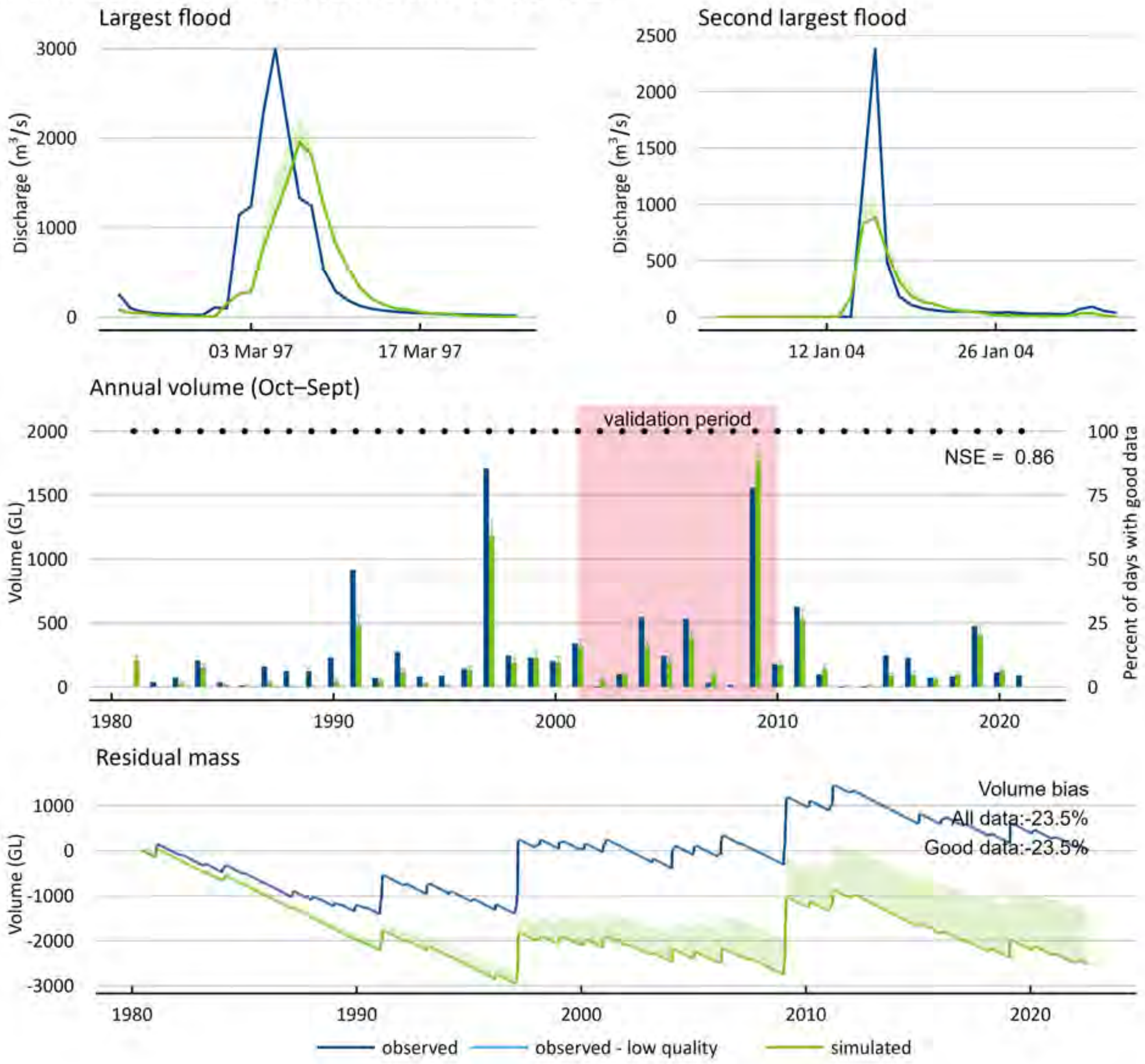
statistic	observed	simulated
Days with flow (%)	53	56
Mean (GL/y)	1815	1412
Median (GL/y)	693	802

metric	calibration	validation
Daily NSE	0.60	0.69
Daily sqrt NSE	0.78	0.81
Bias (%)	-30.60	-27.10

Note: Due to the low maximum gauging (see exceedance curve for high flow panel), there is low confidence in the calculated discharge for most of the flow range, and hence volume estimates at this location.

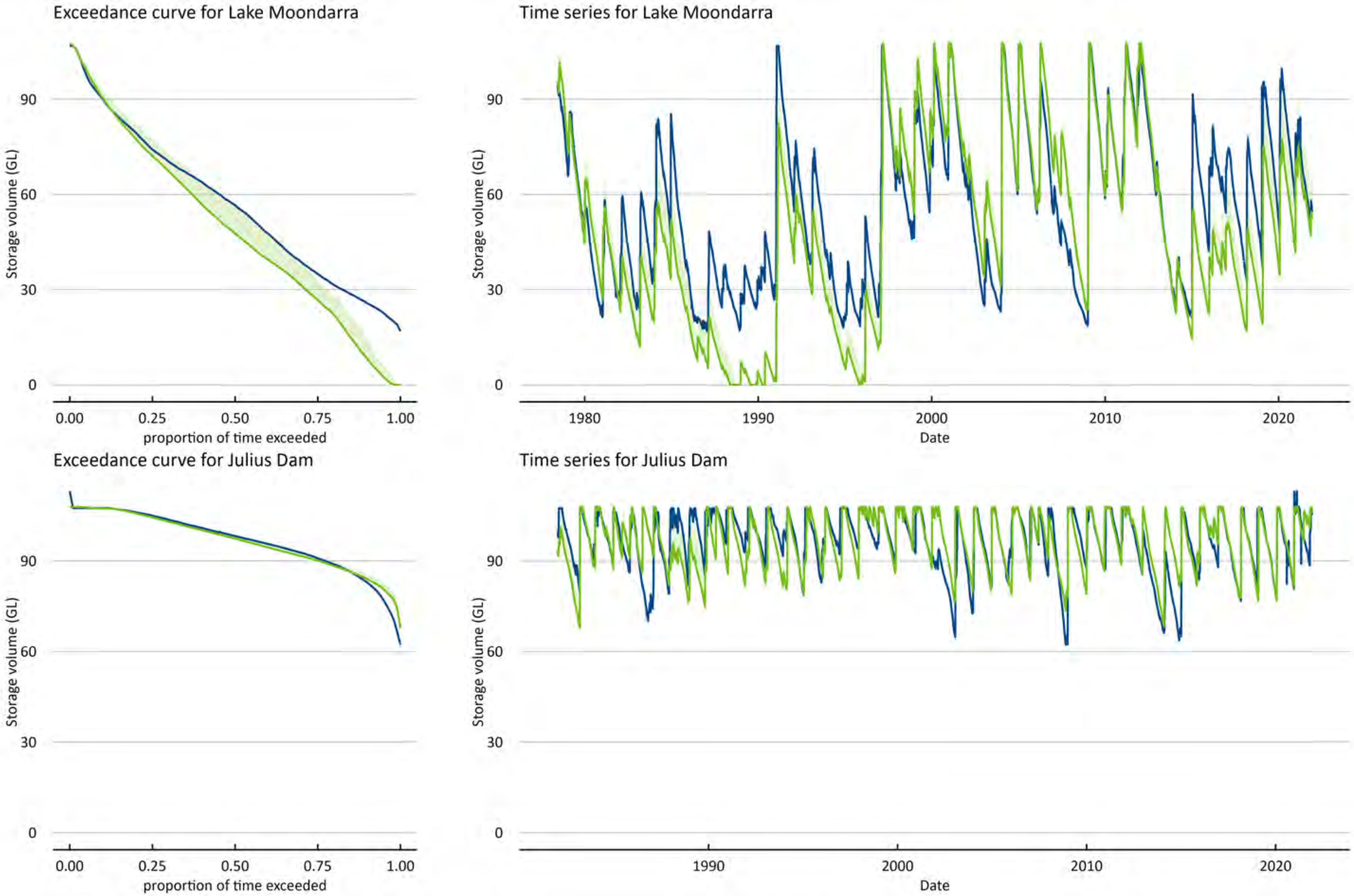
Leichhardt River at Julius Dam 913015B





statistic	observed	simulated
Days with flow (%)	13	12
Mean (GL/y)	260	197
Median (GL/y)	137	96

metric	calibration	validation
Daily NSE	0.66	0.76
Daily sqrt NSE	0.72	0.81
Bias (%)	-33.30	-3.30



Apx Figure C-1 Results for the two major storages in the Leichhardt River system that have observed storage level information available. Green is simulated, blue observed

Appendix D Calibrated model parameter values

Apx Table D-1 'Best set' of model parameter values adopted for each hydrological response unit

PARAMETER	HYDROLOGICAL RESPONSE UNIT			
	BARKLY TABLELAND	ISA HIGHLAND	GULF FALL	PLAINS
proK	0	0	0	0
uztwm	68.18	27.94	147.3	52.9
uzfwm	13.62	89.4	117.1	51.1
uzk	0.4803	0.2094	0.4451	0.669
pctim	0.02571	0.001848	0.01079	0.003
adimp	0.02866	0.1204	0.1489	0.0199
zperc	314.9	40.73	6.487	138
rexp	5.792	5.653	2.368	2.53
lztwm	473.4	254.5	217.2	467
lzfsm	152.1	250.6	105.1	97.5
lzfpm	227.8	223.6	120	293
lzsk	0.00122	0.6715	0.1673	0.636
lzpk	0.3936	0.2449	0.722	0.519
pfree	0.3245	0.2882	0.4263	0.241
K (routing)	1.381	1.091	2.789	0.682
river conductivity (10^x)	–9.184	–6.866	–10.32	-8.66

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