Appendix 4: Details of methods

Data checking and integrity

1. Before any analysis could be undertaken, it was necessary to collate, systematise and validate all of the disparate survey records dating back to 1979. All survey data were transcribed into a purpose-designed geospatial database, including records that had no positional data.

Summary of survey data collected

2. A comprehensive summary was created of all identifiable surveys conducted between 1979 and 2019. These were extracted from all available internal and external departmental reports, archival records, and published papers (Messel 1981a; Taplin 1987; 1988a; 1988b; Taplin et al. 1989; Read 1998a; 1998b; 1999a; 1999b; 1999c; 2001; 2007; Read et al. 2004; Kofron and Smith 2001; Britton 2008; 2009, 2012; Sullivan et al. 2010) This was used to cross-check the GIS database and resolve uncertainties and ambiguities in reported survey dates. Details pertaining to the data from each survey period now follow.

Survey data 1979

3. Records from surveys in 1979 were available, for the most part, only as published in Messel et al (1981a) where data was tabulated and graphed in 5km intervals for large waterways and, for smaller waterways, into 'whole-of-tributary' counts, 'all –tributaries-combined' counts, or some mix of the two. Sightings were recorded in terms of distance from the river mouth in km.
4. Raw data sheets with sighting and waypoint locations recorded were available for the 1979 surveys of Port Musgrave. These were converted to newly-created and more accurate GIS-derived river layers developed for the current survey program, and the locations transformed to latitudes and longitudes.

Survey data 1980s

5. Survey data from the 1980s were referenced originally, in the absence of affordable GPS equipment, to river maps on which river km were marked using Messel's methods. Messel's published maps were used for the seven river systems his teams surveyed in 1979. New river maps were created as required. For this review, sighting data were assigned locations based on GIS-derived river km as well as latitudes and longitudes.

Survey data 1990s-2000s

6. GPS was used for the first time to record survey transects and locations during the 1990s. Some early records were affected by positional inaccuracy and, in some cases, use of only intermittent waypoint data, between which crocodile sightings were recorded without either km locations or GPS positions. The vast majority of sightings could be converted to latitude and longitudes. Where this was not possible, transects were identified and counts by size class compiled and assigned in the GIS to the midpoint of each transect. A small amount of data proved unusable.
7. GPS records from the later 1990s and 2000s were generally more accurate and reliable and tied to every individual sighting and waypoint. Many of these records were imported from electronic spreadsheets created close to the time of survey from paper records.

Survey data 2016-2019

8. The 2016-19 surveys integrated GPS technology into data collection. Sightings were recorded directly in the GPS and downloaded into the GIS database without risk of transcription errors. GPS positional accuracy was much improved over earlier surveys. Paper records with all sightings, size class estimates, waypoints and survey metadata were also created in the field and archived electronically.

Checking and correction of locational data

9. The GIS database was subsequently checked against paper records recovered from DES filing systems. The paper data provided much additional metadata (dates and times of surveys, survey start- and end-points, personnel details and field notes) that was incorporated into the GIS.

10. Records for every survey were examined for consistency, corrected wherever possible, or marked to be excluded from analysis where they could not be corrected with confidence or where reliable transect start- and end-points could not be identified.

11. Some historical geocoded records mapped far away from the known survey transects. Most of these errors were clearly attributable to transcription errors and readily corrected by a simple transposition or insertion of a numeral in the latitude, longitude or both. Some were also derived from differences in the output formats of positional data from GPS units that had been overlooked during transcription.

12. The appropriateness of each correction could be judged by its consequent alignment with other survey data such as the sequence numbers of consecutive sightings/waypoints, recording times of survey points, and the alignment of data points along the waterway. A handful of sightings could not be corrected and the surveys affected were marked as unsuitable for analysis.

13. A number of survey records showed a displacement of about 200m to the south-west for all sightings and waypoints. This survey-wide misalignment was attributed to incorrect translation of GPS data to the appropriate datum for mapping. These were corrected mechanically by re-aligning survey data to the identifiable transect.

14. Some individual GPS records were misaligned with transects by tens or scores of metres, placing sightings on dry land. In most instances, the available records and knowledge of the waterways allowed confident assignment of data points to identifiable transects. Latitudes and longitudes of this particular class of data points were not changed in the database as survey results could be calculated regardless.

Measuring transect distances

15. Surveys in the 1980s relied principally on river maps traced from 1:100,000 AUSLIG topography maps with distances measured using a mechanical map measurer. Sightings and waypoints were recorded in the field by referring to their mid-stream distances from the river mouth in km. Later surveys recorded locations as latitudes and longitudes, but still required transect distances to be measured to estimate population density. River km distances are a more intuitive way to define transects for between-year comparisons of sighting numbers on a consistent like-for-like basis.

16. No suitable spatial layers were found online that mapped river centre-lines with precision sufficient for our purpose. River lines were therefore digitised manually from 1:100,000 maps. This was an approximation given the limitations of the topographical mapping but allowed continuity with the older survey records. GIS-generated distance markers were

constructed for all waterways and the locations of sightings and waypoints in km from each river line's origin were used to bring pre- and post-GPS data from every survey onto a common spatial basis. Pre-GPS km locations were converted to the new GIS-generated km. In some instances, where digitisation of small side-creeks from topographic maps were markedly inaccurate, river lines and km distances were updated from recent satellite imagery.

17. High accuracy digitisation was not essential given 1970s/80s inaccuracies in estimating sighting locations at night from paper maps. In those early surveys, sightings close to identifiable features could be quite precisely located, while sightings on broad-sweeping bends of large rivers were less accurate. Night navigation was enhanced using reflective tags placed during the day at 5km intervals.

Resolving start- and end-point uncertainty

18. There were many instances in which waypoints marking the start and end of transects were not available from DES records, sometimes because the field datasheets could not be found and in other cases because they had not been recorded. Omissions were more prevalent in wildlife management surveys, for which record keeping and datasheet formats changed over time and the focus of the survey was on immediate management needs. Nonetheless, these surveys contain valuable data that has been used here wherever possible.

19. Where start- or end-waypoints were not found, they were estimated conservatively based on the evidence available. In some instances, surveys encompassed known and/or frequently used start- and or end-points, such as boat-ramps. Where there was adequate corroborative information, the survey start-point was taken to be the known boat-ramp, and the start-point for tributaries to be their junction with the higher-level waterway.

20. Rather than discard valuable data, transect start- and end-points that were otherwise undefined were taken to be the mid-point of the last two sightings recorded. Counts for such transects excluded the first or last animal sighted so as not to bias the density estimate. Where only one or two crocodiles were sighted on a transect, the end-point was taken to be the first km mark encountered after the last sighting.[1]

Systematisation

21. As conventions for naming Australian waterways differ, the survey records included many instances where local or colloquial names were used. In addition, large tributaries have often been treated as separate survey entities for multi-year comparisons, when they are better considered tributaries of a larger river system. Queensland-wide compilation of data required systematisation of watercourse name conventions. The procedures used for hierarchical naming are set out in Appendix 3.

Off-transect and return-trip sightings

22. About 1% of the imported data (some 250 sightings) proved unusable. Some of these lay outside the boundaries of any waypoint-defined transect because erroneous positional data could not be corrected unambiguously. More common were sightings recorded during return travel along a transect but had not been separated from valid transect counts. These data were marked in the database and excluded from all analyses.

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[1] Estimated waypoints are identified with the descriptor ESTWPT in the sightings database, to distinguish them from definitively located waypoints, marked WPT.

Scoring 'data quality' based on tidal conditions

23. The Bureau of Meteorology (BOM) provided hourly reconstructions of tide heights for the period 1979-2009 for a large number of tide stations around the Queensland coastline from Mornington Island (southern Gulf), through Weipa in north-west Cape York Peninsula and south to Maryborough, at the southern extent of incidental sightings of estuarine crocodiles in Queensland. Having identified the dates (and, where recorded, the exact times) of each survey, the survey window was plotted over the tide chart. Tide times had to be adjusted from standard port locations to distant river mouth locations, based on BOM information and detailed field observations from the 1980s and 2016-19. Tide timings also had to be adjusted for distance upstream, again based on analysis of tidal lags from field observations – typically in the order of 3-6 minutes per km.

24. It was also necessary to identify the highest surveyable tide (in cm measured at the standard tide station) that would ensure >60cm EB in particular rivers. This measure varied considerably around the state from 1.1m in some rivers to over 2m in others.[2] The maximum surveyable tide was overlaid on the tide graph and survey window.

25. This reconstruction could provide only an estimate of conditions during historical surveys. Actual tide heights can differ considerably from predicted heights, even at the standard stations. Meteorogical conditions can have significant local and regional effects not reflected in annual tide tables. Prolonged onshore winds can push tide heights higher than predictions while offshore winds may do the opposite.

    25.1. Some historical data on actual tide heights is available online for selected Queensland stations (https://www.msq.qld.gov.au/Tides/Open-data). This was used where available to examine surveys that were particularly important to the analysis but had seemingly marginal sighting conditions. Data quality assessments for a few surveys were modified after plotting survey windows against actual rather than predicted tides.

26. Despite these limitations, it was essential to rank the surveys to distinguish those done during very high and clearly unsuitable tides from those that would meet the Messel 1979, QNPWS 1980s and DES 2016-19 survey standards. Every survey was given a rank reflecting tide suitability (Table 1).

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[2] The maximum surveyable tide is related to, but different from, the rule-of-thumb used for planning surveys. For example, the rule-of-thumb says that a low tide of <0.7m at Karumba should provide a suitable survey window on any river between the Flinders River in the southern Gulf and the Mitchell River on western CYP. Karumba is the only long-term tide recording station between Mornington Island and Weipa, so has to be used for planning purposes. However, tides on western CYP lead the Karumba tide by up to 3h and differ considerably in peak height. So the maximum surveyable tide on the Mitchell River has to be derived from field observations of the actual tide lag relative to Karumba experienced at slack low or slack high tide, the state of the tide during surveys (typically recorded as rising or falling quarter tides), and the corresponding exposed bank records.

Table 1: Data quality scores assigned to surveys based on the assessed state of the tide on the date and at the known or likely time of day the survey was conducted.

Rank	Meaning	Explanation
G	Good	Unequivocally good tides at time of survey
GQ	Good qualified	Good tides available during the survey window, but no survey times available to confirm that the appropriate tide was exploited. In many instances it would have been possible to work a good or marginal/bad tide depending on precisely when the survey started.
G(AT)	Good – against tide	Good tides available for survey but records indicate survey direction was against the run of the tide. This can compromise counts because, instead of following a good tide as it moves upstream with EB fairly constant, a 4-5h survey can pass through a low tide, across a rising and then high tide, and back into a favourable tide on the next cycle far downstream.
M	Marginal	Tide marginal at best for sight-ability during survey. Survey times were available to precisely define the window exploited.
MQ	Marginal qualified	Tide likely to have been marginal at best for sight-ability during the survey. No times were available to determine whether the marginal tide was exploited. If it was not, then sighting conditions would usually tend towards bad rather than good – but this is a function of whether the exploitable tide was on the rising or falling leg of tide.
B	Bad	An unqualified bad tide, insofar as tide height was above the maximum surveyable tide throughout the survey window, or survey timing was recorded and showed that a bad tide was exploited.
BQ	Bad Qualified	As for bad tides (above), but no survey times available to confirm whether the bad tide was actually exploited. Tide times indicate that it was highly likely the survey would have been done when tide was Bad rather than Marginal, or possibly Good.
NR	Not relevant	Survey in non-tidal reach. Sighting conditions are fixed by the riverine habitat and largely invariant except in the case of heavy rainfall and floods.

Mapping the extent and distribution of estuarine crocodile habitat

Sampling regime for helicopter survey of the estuarine and upstream reaches of the Mitchell River

27. Design of a sampling regime commenced by mapping polygons in the GIS for all waterholes over 10m long within ~5km either side of the Mitchell, Alice and Palmer River mainstreams. Late dry season satellite imagery was used to ensure only waterholes liable to persist through the dry season were mapped. Mapping extended to some 580km on the Mitchell River mainstream (refer Figure 1b) and far enough along the Alice and Palmer Rivers (refer Appendix 1, Mitchell River) to capture waterholes near their junctions with the Mitchell River proper. Waterholes were classified as mainstream waterholes, floodplain waterholes, saltpan waterholes, and side-channel waterholes. The first three are self-explanatory, the last category was used for waterholes lying away from the mainstream, usually in channels that flow only during the wet season/floods but retain water late into the dry.

28. In total 2075 waterholes were mapped, ranging in length from 0.01 – 5.7km, and in area from 44 m^2 to 0.52 km^2, of which 875 were associated with the Mitchell River proper rather than the Alice and Palmer Rivers.

29. To ensure sampling of the various habitat types along the river was not coloured by preconceptions about what constituted good and bad crocodile habitat, a balancing act was required between sampling widely enough that some unoccupied habitat would be covered (to confirm it was indeed unoccupied) and, at the same time, maximising return on effort expended.

30. As it was impractical to survey all waterholes and the mainstream proper, the river was subdivided into four broad zones based on physiography: the delta from 0-200km, mid-reaches from 200-350km, central highland reaches from 350-500km and high plateau reaches beyond 500km (Figure 1a). Sample blocks 5km long were defined along the entire river, relatively narrow in the Midreaches, Central Highland and Upstream zones because waterholes were concentrated close to mainstream and wider in the Delta zone because more waterholes existed at greater distances from the mainstream.

31. A random sample, weighted by the total area of waterholes in each block, was selected for survey (Figure 1b). The transects eventually flown differed in minor ways from the design to accommodate changes in waterholes and mainstream channels and to avoid a mustering helicopter working in one sample block.

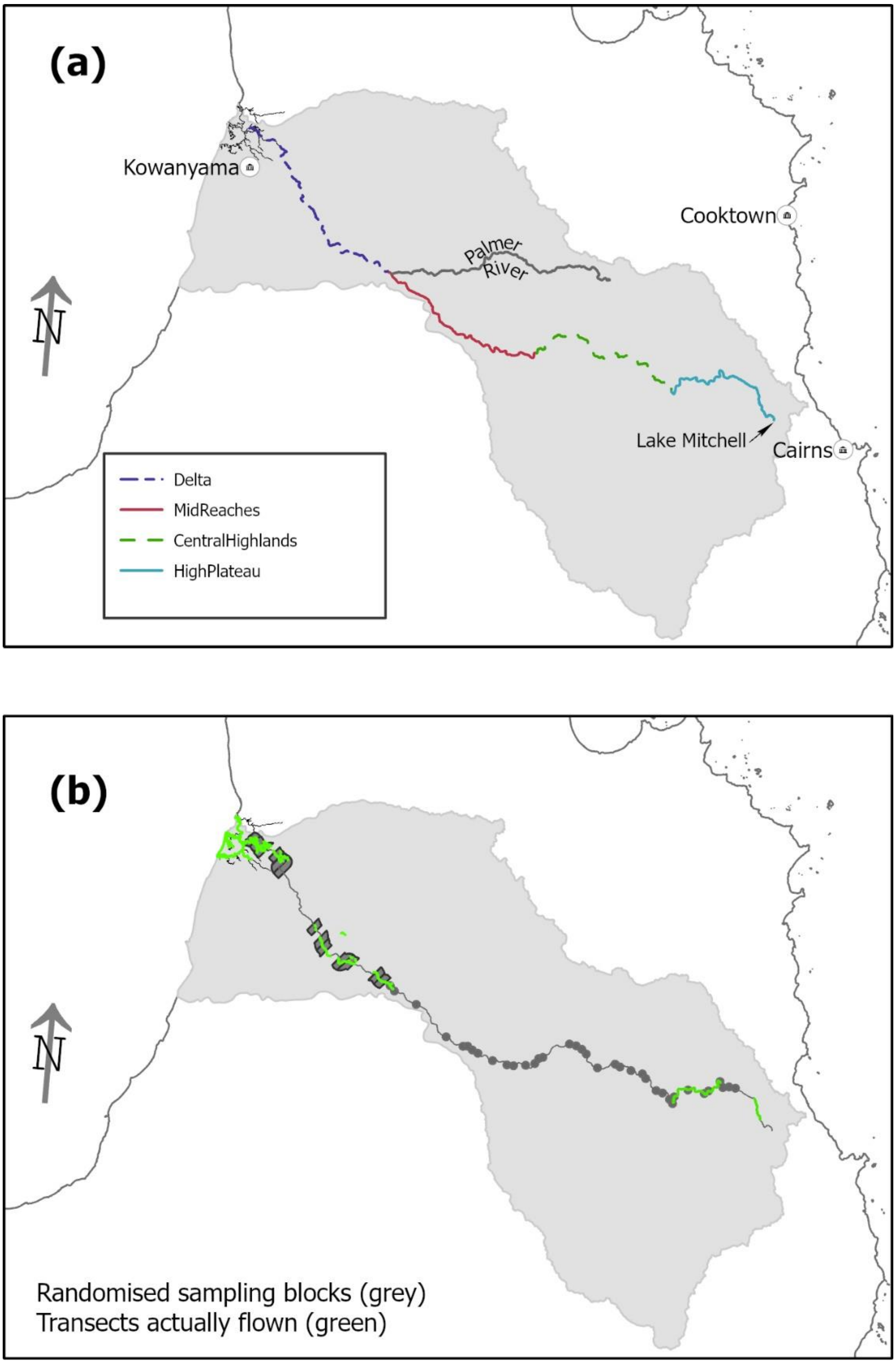
32. Some 200km of transects covering estuarine reaches of the system previously surveyed by spotlight were also defined. The Mitchell River appears to have silted up considerably since the 1980s and spotlight survey has become increasingly difficult (Britton 2008, 2009; DES unpubl. obs.). Future survey is likely to require helicopters.

33. The main survey commenced in the estuarine reaches, then proceeded upstream from the limit of navigable water in the mainstream at ~20 km. The number of estuarine crocodiles was expected to decline upstream, so the survey was terminated when sightings fell close to zero.

34. Two transects on the High Plateau near Mareeba were surveyed in August 2019 to determine whether there were significant numbers of *C. porosus* in the most upstream reaches and whether reported sightings near Mareeba were reflective of a larger crocodile management issue. The transect furthest upstream was not part of the original stratified sample but was added because of its benefit to wildlife management work (Figure 1b).

35. Surveys were conducted using one observer and one navigator/recorder in a Bell Jet Ranger helicopter from just above tree-top height (typically 30m). In the principal survey in September 2019 commencing at the Mitchell River mouth, very high densities of freshwater crocodiles (*C. johnstoni*) were recorded close to the limit of tides – so many that it became impractical to record their numbers. All sightings of individual estuarine crocodiles were logged by GPS and their size class estimated. Depending on the size, shape, and vegetation cover of waterholes, either one or both banks of waterholes were surveyed in a single fly-past. Counts from single-bank transects were doubled to adjust them to both-bank equivalents.

Figure 1: Helicopter survey transects of the Mitchell River 2019: (a) Riverine zones used for stratified sampling of upstream reaches of the Mitchell River in 2019. The estuarine reaches, shown in grey, were also surveyed as part of this exercise. (b) The stratified random sample blocks (rectilinear in the Delta zone and circular in more upstream reaches) used for survey planning and the actual transects flown. The survey upstream from the estuarine reaches was ended at the start of the MidReaches zone because estuarine crocodiles were extremely sparse at that distance inland.



Assessing crocodile density as a function of geography

36. Survey data were modelled using raw non-hatchling counts after excluding the 2-3ft size class and fitting a negative binomial generalised linear model with Latitude as a continuous predictor variable, Era, and Zone as fixed categorical effects crossed and partially crossed respectively with Latitude, and Waterway as a random effect. Latitude was standardised to reduce correlation among predictor variables.

37. The 2-3ft size class was excluded from regression analysis because, like the hatchling size class, their numbers in Queensland swing high and low from year-to-year as cohorts of hatchlings are born and eventually disperse, typically as they get into the 3-4ft and higher size classes (Messel et al., 1981b; Messel and Vorlicek, 1987). Because recruitment is volatile, especially in Queensland's extensive areas of low-quality habitat, including 2-3ft animals in regressions inflates year-on-year variance. Focusing on the larger size classes does not affect the validity of the population growth comparisons.

38. In total, 267 surveys were extracted from the dataset, covering the period 1979-2017 (Table 2). The distribution of surveys across years was, unsurprisingly, severely imbalanced because of the different focus of the survey program over time, and periods during which very few surveys were completed. There was only one survey completed in the period 1990-93 and only a handful on the populated east coast in 2011-14. These periods were excluded, as was the 1979 data covering only western and northern CYP.

39. As it commonly took several years to complete a suite of surveys across the State, an early decision was made to categorise the data into survey 'eras' of 5-6 years reflecting changes in survey focus and personnel. The data proved too sparse to compare effectively across individual years. The eras were defined to be 1984-89, 1994-99, 2000-05, 2006-10 and 2016-19. The few 2010 surveys were bundled with 2006-09 surveys because an extensive survey of PEC rivers that commenced in November 2009 was completed in early 2010.

40. The 2006-10 period saw surveys concentrated on the populated east coast and little or no focus on remote areas. This era was excluded from the Queensland-wide analysis because it provided no information about remote areas north and west of Cooktown.

41. Surveys of the Proserpine River were also excluded as it proved an extreme outlier in the general pattern of crocodile density across Queensland and along the populated east coast. It has, in fact, the highest density of non-hatchling crocodiles in Queensland, concentrated in a small waterway in otherwise climatically inhospitable area. The Proserpine River was surveyed in some detail in 2019 and its peculiarities are addressed in Appendix 6.

42. The final selection of waterways analysed shows a reasonably uniform spread of sampled rivers across waterways by Era, with some bioregional imbalances (Table 2). Importantly, we inferred survey results for a selection of Region 7 waterways that were not surveyed in the 1980s – on the basis that no crocodiles have ever been seen in surveys there and none were reported to DES from that region in the 1980s. It was a very safe assumption that, had surveys been undertaken, they would have recorded no crocodiles. This amendment to the dataset helped 'anchor' the southern latitudes of the 1980s survey era and better balance the design. The same assumption was not applied to the Fitzroy River just north of Region 7 because crocodiles have been present there in small numbers since at least the 1980s but no surveys were done.

Table 2. Summary of surveys included in generalised linear mixed model analysis of crocodile density as a function of latitude and survey era. Waterways were sorted by name within each bioregion. Counts in italics for Region 7 in the 1984-89 era represent surveys not conducted at that time but for which we can be confident, had they been conducted, zero crocodiles would have been sighted. These counts were added to help balance the distribution of surveys through time.

	Survey Era				
	1984-89	**1994-99**	**2000-05**	**2016-19**	**Total**
Bioregion 1b	**2**	**6**	**0**	**2**	**10**
Albert River	1	3		1	5
Leichhardt River	1			1	2
Nicholson River		3			3
Bioregion 1c	**5**	**5**	**0**	**1**	**11**
Bynoe River	2				2
Norman River	3	5		1	9
Bioregion 1d	**8**	**4**	**1**	**4**	**17**
Coleman River	1			1	2
Duck Creek	1				1
Gilbert River	1	1			2
Mitchell River	1			1	2
Nassau River	1			1	2
Smithburne River	1				1
South Mitchell River	1		1		2
Staaten River	1	3		1	5
Bioregion 2	**17**	**12**	**11**	**13**	**53**
Balurga Creek				1	1
Chapman River				2	2
Cowal Creek		1	1		2
Ducie River	2	1		1	4
Edward River				1	1
Embley River	2	1	5	2	10
Jackson River	1				1
Jardine River		1			1
Mission River	4	2	4	1	11
Mungkan Creek				1	1
Namaleta Creek	2			1	3
Pennefather River	1				1
Pine River	2			1	3
Port Musgrave Bay		1			1
Skardon River	1	1			2
Wenlock River	2	4	1	2	9

Bioregion 3	**5**	**3**	**8**	**4**	**20**
Claudie River			1	1	2
Escape River	1			1	2
Glennie Inlet			1		1
Harmer Creek			1		1
Hunter Inlet			1		1
Jackey Jackey Creek	1			1	2
Kangaroo River			1		1
Lockhart River	1		1	1	3
Nesbit River	1				1
Olive River	1	1	1		3
Pascoe River		1	1		2
Stewart River		1			1
Bioregion 4	**3**	**6**	**0**	**4**	**13**
Bizant River	1	2		1	4
Marrett River				1	1
Normanby River	1	2		1	4
North Kennedy River	1	2		1	4
Bioregion 5a	**2**	**0**	**0**	**0**	**2**
McIvor River	1				1
Starcke River	1				1
Bioregion 5b	**20**	**21**	**21**	**17**	**79**
Alligator Creek (Mt Elliot NP)	1			1	2
Annan River		1			1
Baratta Creek			1		1
Barramundi Creek	1		1		2
Barron River			1	1	2
Bloomfield River				1	1
Bohle River		1		1	2
Cattle Creek	1			1	2
Daintree River	1	2	2	1	6
Dallachy Creek		1			1
Endeavour River		1	1	1	3
Haughton River	1	1	2	1	5
Herbert River	3			1	4
Hull River	1	4	6	1	12
Johnstone River	1	1		1	3
Leichhardt Creek	1				1
Mackenzie Creek	1				1
Maria Creek	1	1			2
Meunga Creek		2			2
Moresby River		1		1	2
Mossman River			1		1
Mowbray River			1		1

Mud Creek			1		1
Mulgrave River		1	1		2
Murray River	3	3		1	7
Packers Creek			1		1
Plantation Creek			1		1
Ross River	1				1
Russell River		1		2	3
Saltwater Creek (Port Douglas)			1		1
Seymour River				2	2
Tully River	1				1
Victoria Creek	1				1
Wreck Creek	1				1
Bioregion 5c	**0**	**7**	**0**	**2**	**9**
Burnett River				1	1
Coorooman Creek		1			1
Proserpine River (excluded as an outlier)		4		1	5
Victor Creek		1			1
Waterhole Creek		1			1
Bioregion 6c	**0**	**6**	**24**	**4**	**34**
Fitzroy River – Eden Bann Weir		2	0	1	3
Fitzroy River - Downstream		2	7	2	11
Fitzroy River - Upstream		2	17	1	20
Bioregion 7	***(7)***	**5**	**6**	**8**	**19 *(7)***
Baffle Creek	*(1)*		1	2	3 *(1)*
Boyne River	*(1)*	1	1	2	4 *(1)*
Burnett River				1	1
Calliope River	*(1)*	2	1		3 *(1)*
Colosseum Creek	*(1)*		1		1 *(1)*
Kolan River	*(1)*		1	1	2 *(1)*
Mary River	*(1)*		1	1	2 *(1)*
South Trees Inlet				1	1 *(1)*
The Narrows		1			1
Wild Cattle Creek	*(1)*	1			1
Total	**62 *(7)***	**75**	**71**	**59**	**267 *(7)***