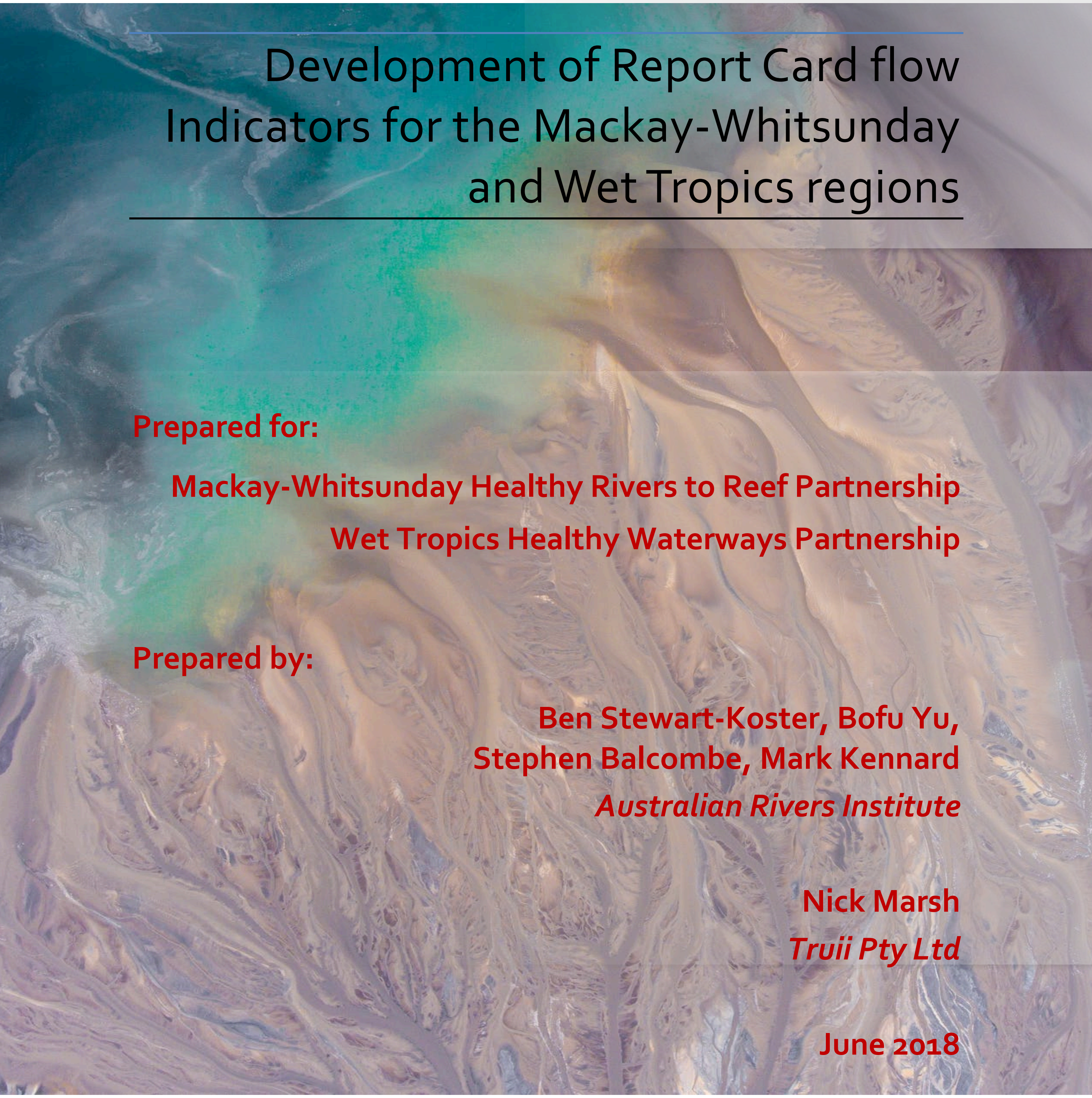

Development of Report Card flow Indicators for the Mackay-Whitsunday and Wet Tropics regions

Prepared for:

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Executive summary

The alteration of the natural flow regime is one of the primary threats to ecological condition in rivers, wetlands and estuaries. Mackay-Whitsunday Healthy Rivers to Reef Partnership and Wet Tropics Healthy Waterways Partnership see great value to including the condition of the flow regime as part of ecosystem health report cards that document the condition of aquatic ecosystems on an annual basis. This report describes the development of a flow indicator tool for the partnerships to document the condition of the flow regime in their annual aquatic ecosystem health reporting.

The approach is based around available evidence of the flow needs for ecological assets identified in the water resource plans from the regions. While these water resource plans will change, they provide an objective basis for selection of important ecological assets to guide the approach. Having identified a selection of ecological assets, the available evidence about their flow needs was synthesised to capture the key aspects of the flow regime that are known to be important for them, which would be used as indicators of flow condition (e.g. cease to flow events). The next step was to identify a series of flow metrics that described these indicators, which could be used to assess quantitatively the flow condition in a manner relevant to ecological assets.

The flow indicator follows a reference condition approach where a river with a highly modified flow regime, resulting in large deviations from an unregulated reference condition, will score poorly and a river with an unmodified flow regime, resulting in a similar flow regime to reference condition, will score well. To define reference condition, we used 100+ year time series of modelled pre-development flows from Queensland Government water resource planning activities. We calculated the statistical distribution of each of the flow metrics under pre-development (or reference) conditions to then compare with observed annual values of those flow metrics. Where an observed value for a flow metric at a stream gauge falls well outside the range of reference condition because of human alteration of flows, the river will score poorly.

The annual flow pattern in any given river will naturally vary with the prevailing climatic conditions. For example, in a free flowing river total annual discharge will naturally be lower in a drought year than a wet year. As such, it is necessary to remove the effect of climate from any assessment of the condition of river flow so that different values of the flow metrics due to the prevailing climate are not confused with a highly altered flow regime. To achieve this we use 100+ years of rainfall data to define each year as a different climatic type to derive a reference distribution for each flow metric in each of four climatic categories: drought, dry, average and wet. As such, each flow metric used in the flow indicator tool has one reference distribution for each climatic type at each stream gauge.

The process of scoring the flow condition for the prior year at a given stream gauge involves classifying the prevailing climate, given the prior year's rainfall, to determine the appropriate reference distribution of the flow metrics that should be used. Then each flow metric in the flow indicator tool is compared to its accompanying distribution to derive a score. This process is achieved through the use of the Excel based flow indicator calculation tool, applied to each available stream gauge within a catchment. Scores for each flow metric are aggregated to derive a flow indicator score for that gauge, with the scores for all gauges within a catchment aggregated to derive a catchment wide score for the flow indicator.

In addition to describing the process of the development of the flow indicator and its use, this report also documents a series of sensitivity analyses that were conducted to address key questions around the indicator development. These include the use of different numbers of climatic categories, the use of different rainfall records in defining the annual climatic category, scoring aggregation methods and the definition of the water-year.

This report is complemented by the Excel based flow indicator calculation tool which is used to derive the annual score at each stream gauge within the region. These scores can then be entered into a separate spreadsheet, the Catchment score aggregation tool, which includes several approaches to devise a final score for the flow indicator in each catchment.

Acknowledgments

We wish to thank Emma Carlos, Richard Hunt and Roger Shaw for their input and direction throughout this project. We would also like to thank members of the Independent Science Panel for their comments which have improved the document and approach. Many members of QLD’s water modelling and ecological community provided very helpful constructive feedback and other input throughout the project including, Alex Loy, Carl Mitchell, Brenden Ebner, Glynis Orr, Glenn McGregor, Chris Dench, Brett Anderson, Stephen Mackay and Bernie Cockayne.

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1) Introduction

Background

The Mackay-Whitsunday Healthy Rivers to Reef Partnership (http://healthyriverstoreef.org.au/) and the Wet Tropics Healthy Waterways Partnership (http://wettropicswaterways.org.au/) produce annual report cards which include regional assessments of waterway health for freshwater, estuarine and marine environments. The reporting follows the financial year as an approach for demarcating the year. Both partnerships have selected flow in freshwater river catchments and the receiving estuaries as indicators of aquatic ecosystem health for annual report cards. To date the methods and metrics that would best represent aquatic health have not been developed to enable their effective use for reporting. An early step in developing appropriate flow indicators involved bringing together a Flow Working Group comprised of regional experts from the Mackay-Whitsunday and Wet Tropics regions. The group's task was to undertake preliminary work to identify and recommend appropriate flow indicators for use in future report cards. As part of this working group a Pressure State Response (PSR) framework was developed in relation to hydrological function in the Mackay-Whitsunday's environment as a case study, to assist in forming a conceptual basis for development of suitable indicators. The Wet Tropics Water Resource Plan Environmental Assessment (DSITIA, 2013) was used to identify equivalent PSR information for the Wet Tropics. The working group identified the main pressures related to ecological function were:-

- Water infrastructure, namely dams and weirs affecting riverine connectivity and flows;
- Water extraction affecting cease to flow and low flows;
- Water extraction affecting low to medium flows; and
- Water extraction: event flows (high flows and floods).

Identifying these main pressures in the aquatic ecosystems of the Mackay-Whitsunday and Wet Tropics regions provide a conceptual basis to develop appropriate indicators for assessing ecosystem health. This report takes the next step from the conceptual basis and reviews potential indicators and the metrics by which they are measured as to their suitability for use in future report cards.

Given the different types of flow alteration presently (and potentially into the future) it is useful to conceptualise how a natural hydrograph will be affected by water resource development. Figure 1-1 represents a typical perennial stream in the Wet Tropics or Mackay-Whitsunday regions that has been altered by various types of human water use. It is important to conceptualise how such impacts will lead to different hydrological outcomes depending on season, especially between wet and dry. It is important to visualise how the altered hydrographs may look and be sure that the indicators we select can not only biologically represent our ecological assets but also capture the altered hydrological patterns.

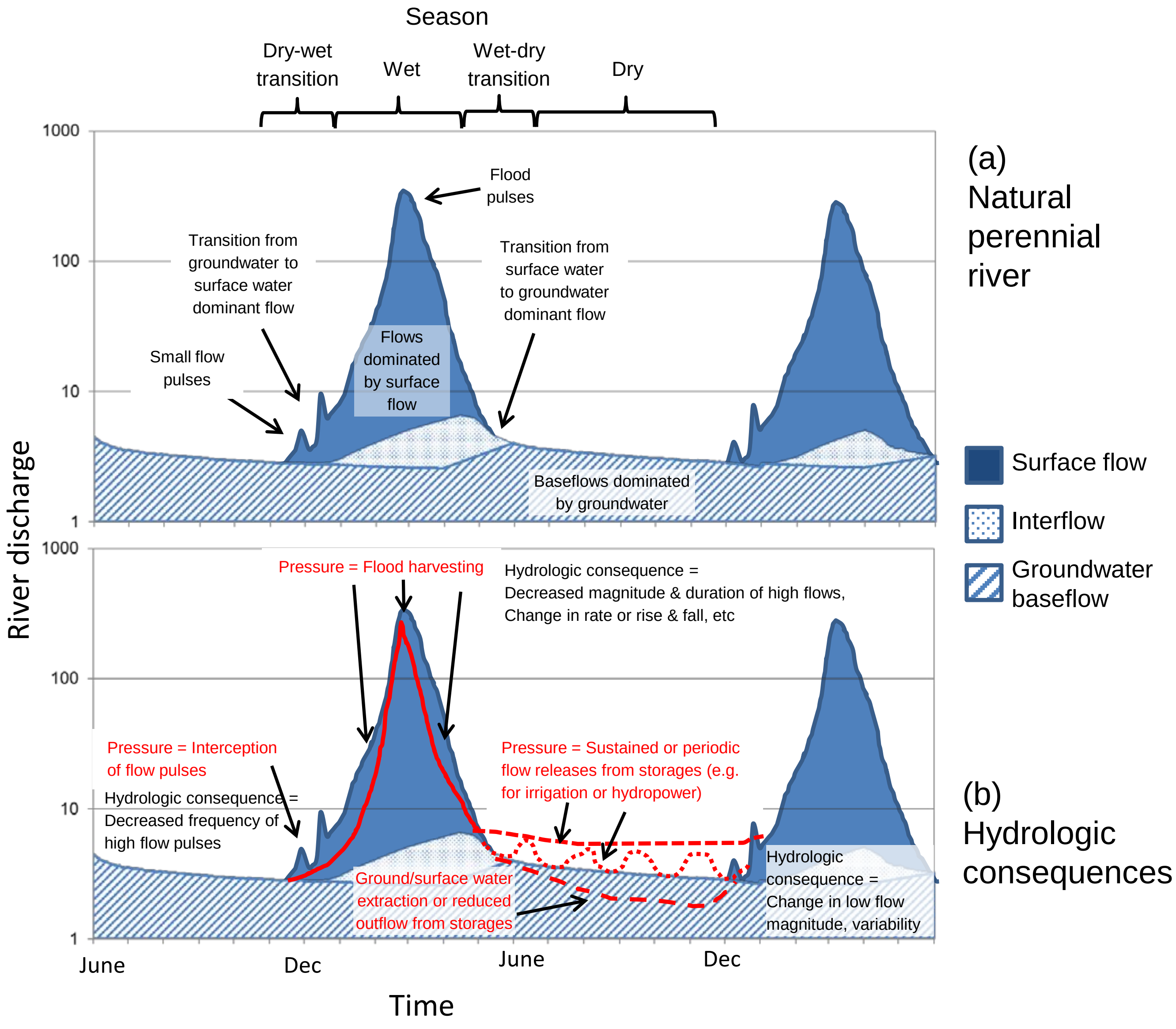

Figure 1-1. (a) Conceptualisation of (a) a typical hydrograph for a naturally perennial river in the Wet Tropics or Mackay-Whitsunday region and (b) the potential hydrologic consequences (indicated with red lines) of human pressures associated with water harvesting, interception, extraction and releases from water storages (e.g. dams, weirs and off-channel storages). Surface flow includes all overland flow and precipitation falling directly onto stream channels, interflow is the portion of the stream flow contributed by infiltrated water that moves laterally in the subsurface until it reaches a channel, and groundwater derived flow is the baseflow component contributed to the surface water flows by ground water (Ramírez, 2000). Figure modified from King et al. (2015).

Flow indicators and metrics for assessing ecosystem health

Natural flow regimes play a central role in maintaining the ecological integrity of riverine systems (Poff *et al*., 1977; Bunn & Arthington, 2002). The natural flow regime can be characterised by a range of flow events such as frequency of connecting flow events and cease to flow periods, magnitude duration, timing and rates of rise and fall of high flow events (Poff *et al.* 1977). Analysing these streamflow characteristics via hydrological indices can simplify and then explain the influence of these characteristics on stream biota (Olden & Poff, 2003). Altered flow regimes, often accompanied by other environmental stressors, drive ecological degradation and loss of biodiversity in freshwater systems (Nilsson *et al.*, 2005). For example, in a synthesis of threat's to world rivers Vörösmarty *et al.* (2010) predicted that impoundments and altered flow regimes have degraded and reduced riverine habitat with 65% of discharge and habitat under moderate to high threat thus threatening biodiversity and ecosystem services. Owing to the strong link between intact flow regimes and ecological health (Bunn & Arthington 2002), hydrological flow indicators can be used as measures of change from natural conditions brought about by human induced stress and thus represent scores of river health. The reliability of such scoring will depend on the biological relevance of these indicators, that is the biological components of the system, such as fish species abundance, are known to respond in a predictable manner to changes in these indicators (Olden & Poff, 2003). To quantify the condition of the key flow indicators, a selection of flow metrics need to be identified as representative and relevant to the indicator.

There are a multitude of flow metrics to describe the ecologically meaningful components of the hydrological regime in relation to duration and timing of flow events, frequency and magnitude and temporal variability of these measures, and these were reviewed by Olden & Poff (2003).They examined correlations among 171 flow metrics and quantified their utility to describe ecologically relevant components of hydrological regimes in 420 gauges across the continental USA. They found that 66 hydrological metrics calculated from the Indicators of Hydrologic Alteration (IHA) software package (Matthews & Richter, 2007) could adequately describe most of the major flow regimes but also recommended several additional metrics to describe the magnitude and frequency of high-flow events. Kennard *et al.* (2010a) in their classification of Australian natural flow regimes developed their own set of indices that added to the list of Olden & Poff (2003). These additional metrics were highly relevant to Australian conditions as they were focussed on the low-flow end of the hydrological spectrum and as such Kennard *et al.* (2010a) ultimately used 120 metrics for their classification analyses.

For this project our flow metrics were selected from the 120 metrics used by Kennard *et al.* (2010a) but were also somewhat focussed in part on the indicators already suggested by the working group. The proposed indicators (baseflow variability, change in cease to flow/low flows, change in low flows-medium flows, change in event flows) were reviewed for their suitability for reporting in accordance with the following criteria:-

- Include flow metrics that have demonstrated links to ecosystem flow requirements;
- Include the range of flow requirements provided by the natural flow regime;
- Assess ecological responses that are linked to measurable flow characteristics such as magnitude, duration, timing, frequency, and rate of change of flows;
- Be appropriate for reporting in both the Mackay-Whitsunday and Wet Tropics region;
- Be appropriate for reporting in freshwater catchments and estuaries (may require different indicator sets);
- Be suitable for annual reporting.

Ecological Assets and key flow requirements

The water resource plan (WRP) for the Wet Tropics was developed to guide water management for later environmental assessment of the key flow-related surface water and groundwater dependent ecosystems for the region. A key aim was to identify environmental risks associated with a range of potential water allocation and management scenarios. The environmental assessment of the WRP identifies ecological assets linked to both the plan area and its surface/groundwater resources that are sensitive to changed water allocation and management conditions. The WRP identifies the critical water requirements of these assets (magnitude duration, timing, rate of change, quality of flow/groundwater exposure) which provide opportunities for key ecological responses and/or geomorphic processes that support the viability of the assets. Further, analyses of modelled flow using the Integrated water Quantity and Quality simulation Model framework (IQQM) at each of the nodes revealed risks to assets using thresholds of concern (ToC). For example, for low-flow spawning species a ToC may may be triggered if a species gets <2 spawning opportunities in a given year. In this report we focus on the assets already chosen by DSITIA (2013b) to investigate the potential indicators (and more specifically the metrics behind them) that will be appropriate to be used in the annual report card to best represent ecological condition. We have used the same ecological assets as per the Wet Tropics WRP (DSITIA 2013b) and searched the literature for any additional species and ecosystem services that could be relevant for the Mackay-Whitsunday region. The assets fall under broad categories, fish, amphibians, ecosystem services, ecosystem processes and protection of waterholes:

- Fish
    - *Mogurnda* spp. (purple spotted gudgeons)
    - *Melanotaenia splendida splendida* (Eastern rainbowfish)
    - *Ambassis agassizii* (Olive perchlet)
    - *Cairnsichthys rhombosomoides* (Cairns rainbowfish)
    - *Tandanus tandanus* (Eel-tailed catfish)
    - *Pseudomugil signifer* (Pacific blue-eye)
- Amphibians
    - *Littoria jungguy* (Northern stony creek frog)
    - *Littoria wilcoxii* (Eastern stony creek frog)
- Ecosystem services – fisheries production
    - *Lates calcarifer* (Baramundi)
    - *Fenneropenaeus merguisensis* (Banana prawn)
- Ecosystem processes
    - Provision of riffle habitat
- Protection of waterholes

The ecological and hydrological needs of these assets are described fully in Appendix 1 their occurrence in the catchments within the Wet Tropics and Mackay-Whitsunday regions and the types of flows that will support them are listed in Table 1-1.

We have focussed on the use of asset species as per the approach to WRPs with an expectation these assets represent the ecological needs of a broader range of species, including those closely related due to having similar ecological traits. There will be always be specialist species that may warrant particular focus even though they may not occur over broad areas within a catchment. For example, while cling gobies *Stiphodon* spp. live in specialised habitats (i.e. high velocity upland streams) (Donaldson et al. 2013) they are nonetheless an ideal candidate species for water planning in the Wet Tropics where flow velocity has been impacted by flow alteration, as they will be highly sensitive to such changes. This would also then need to focus not only changes to hydrology but also hydraulics. Further, as our knowledge in molecular ecology is increasing new species are being identified and understanding their ecological requirements can be challenging. In this initial development of a flow indicator, a general approach was needed, hence the focus on widespread and broadly understood species. There is always an opportunity to examine special cases of unique or newly discovered species in the future, should a need and will arise to address the preservation of such biodiversity.

Since the completion of this phase of the project, water resource plans have been updated to water plans (e.g. Water Plan (Wet Tropics) 2013), however, we refer to the WRPs as they provided the basis for the selection of ecological assets.

Table 1-1 Summary of Ecological Assets and key flow events to meet ecohydrological requirements. Note: codes: Mog (Mogurnda sp.), Mel (Melanotaenia splendida splendida), Amb (Ambassis agassizii), Cai (Cairnsichthys rhombosomoides), Tan (Tandanus tandanus), Pse (Pseudomugil signifer), Ljung (Littoria jungguy), Lwil (Littoria wilcoxii). Bara (Barramundi fishery), praw (banana prawn fishery, riff (riffle habitat) wat (waterholes). Catchments: Wet Tropics (WT): – dain (Daintree), mos (Mossman), bar (Barron), mul (Mulgrave Russell), Joh (Johnstone), tul (Tully), her (Herbert), mur (Murray); Mackay-Whitsunday (MW):- pro (Proserpine), oco (O'Connell), pio (Pioneer), pla (Plane), don (Don).

ASSET	Mog	Mel	Amb	Cai	Tan	Pse	Ljung	Lwil	Bara	Praw	Riff	**Wat**
Locations present	WT (all) MW (all)	WT (all) MW (oco, pio, pla)	WT (mos, bar, mul, joh, tul, her, mur) MW (pio, pla, don)	WT (mul, joh, tul)	WT (dai, mos, bar, mul, joh, tul, mur) MW (pio, pla, don)	WT (all) MW (pro, oco, pio, don)	WT (joh, tul, mur, her)	WT (joh) MW (all)	estuaries	estuaries	WT (all) MW (all)	WT (all) MW (all)
Low stable flows and timing of these	Aug- Nov	Aug- Nov	Aug-Nov	Sep - Oct	Oct - Jan	July - Oct						
Continuous baseflow to provide refugial waterholes > 2m deep												All year
Stable low and medium flows							Nov - Mar	Nov-Mar			All year	
High flows at end of system									Dec-Feb	Dec-Feb		

Simplifying assets and key links to hydrology to simplify the indicator selection

In providing the background to key ecological assets and their flow requirements we can now distil these down into some simplified groupings based on similar flow requirements and flow periods (i.e. timing or seasonality) within annual hydrographs. There are clearly four key flow types that are relevant to the assets previously discussed: cease to flow (amphibians, riffles and waterholes); low flows (all low flow spawning fish species, reptiles, amphibians, riffles and waterholes), medium flows (riffles only); and high flows (fisheries production in estuaries). Similarly, assets themselves can also be grouped together. While we acknowledge there is variability in peak spawning and recruitment times for the low-flow recruiting fish species these periods do have significant overlap, and while the ecohydrological rules provided in the environmental assessment of the Wet Tropics WRP did derive minimum periods needed for successful spawning, egg development and larval growth, for some there will still be errors in these times due to incomplete ecological knowledge about these species and variability in their breeding biology across and within catchments. Hence in Table 1-1 we identify groups and key periods to simplify our indicator selection.

An overview of the ecological assets with their eco-hydrological dependencies is provided in Appendix 1 and a complete list of potential hydrological metrics, from which the final set were chosen, is listed in Table 5-1, along with an explanation of the ecological basis for them.

Flow metrics used for the flow indicator

Having identified a broad list of ecological assets and their eco-hydrological needs, a set of hydrological indicators and flow metrics that would represent them were compiled in Table 1-2. The challenge for this project was to develop an annual scoring system based on metrics that are typically used to report on a multi-year flow record.

We tested ten key flow metrics for reporting that encompass the timing, frequency and duration of low, medium and high flow spells, respectively (Table 1-3). Four of the ten metrics had three alternative thresholds (low and high flow spells) to be tested making a total of 18 metrics to be considered.

Table 1-2. Relevant indicators for assessing hydrological measures relevant to ecological assets (and key ecosystem components and processes) in the Wet Tropics and Mackay-Whitsunday regions

Flow category	Key Asset	Additional assets	Types of indicators	Timing of flow event (season)	Duration of flow
Low flows	Low flow spawning fish	Maintain critical aquatic habitat (e.g aquatic macrophytes) and water quality for aquatic biota. Maintain river longitudinal connectivity	Duration of low flow events Frequency of low flow events Timing of low flow event Magnitude of flow events Variability of baseflow	July – Jan (Mostly dry)	Maximum change in depth of 5cm over whole stable period (min of 25 d to meet needs of all species)
Cease to flow	Amphibians	Macro-invertebrates Maintenance of refugial waterholes and provision of critical habitat for dependant taxa	Duration of low flow events Timing of low flow event	Aug – Dec (dry)	Short duration of zero flow
Low to Medium flows	Creation or maintenance of riffle habitat and associated biota	Maintain macrophyte habitat	Duration of low to medium event Frequency of low-medium medium flows	Year round (all)	Long duration of low to medium events High frequency of these events
High flows	High production of prawns and barramundi fisheries Downstream sediment delivery	Scouring of riparian zones ensures no vegetation encroachment	Magnitude of high flow events Duration of high flow events	Dec- Mar (wet)	High magnitude and duration of high flow events

Table 1-3: Final list of flow metrics used for the flow indicator. For the metrics based on thresholds of flow, low or high flow durations, three different thresholds to define low or high flow were tested.

flow metric	Season	Flow threshold	Hydrologic Metric definition
Low flow Duration	July-Jan	Test three thresholds: 25th, 10th, 5th percentiles*	Total duration of flows which remain equal to or below a lower threshold for the reporting period (annual).
Low flow Frequency	July-Jan	Test three thresholds: 25th, 10th, 5th percentiles*	Count of the number of occurrences during which the magnitude of flow falls to or below the threshold during the reporting period (annual).
Low flow variability	July-Dec		Coefficient of variation (stdev/mean) of daily flow for dry season.
Driest six Months	July-Dec		Proportion of annual discharge contributed during the months July-December.
Cease to flow Duration	All year	0	Total duration of where flow ceases during the reporting period (annual).
Cease to flow Frequency	All year	0	Count of the number of occurrences during which flow ceases during the reporting period (annual).
Medium flow Duration	All year	Median (50th percentile)	Total duration of flows which remain equal to or above a threshold for the reporting period (annual)
Medium flow Frequency	All year	Median (50th percentile)	Count of the number of occurrences during which the magnitude of flow passes from below to equal or above the threshold during the reporting period (annual).
High flow duration	All year	Test three thresholds: 75th, 90th, 95th percentiles*	Total duration of flows which remain equal to or above a threshold for the reporting period (annual)
High flow Frequency	All year	Test three thresholds: 75th, 90th, 95th percentiles*	Total count of flows which remain equal to or above a threshold for the reporting period (annual)

*percentile – the percentage of the flow record below this value (low percentile = low flow). This is often confused with the often used hydrological nomenclature of Q10, Q90 – where Q10 is the flow that is exceeded 10% of the time.

After reviewing the 18 flow metrics, we reduced the total number of metrics to ten by adopting the low flow threshold of 10%ile (and discarding 5% and 25%) and the high flow threshold of 90%ile (discarding the 75% and 95%). The rationale for this decision was that the greater and lesser percentiles (5% and 95%) had few events and allowed limited discrimination between climatic conditions and across the scoring levels. The 10% was similar to the 25%ile and the 90%ile and 75%ile were also similar in the general distribution. Additionally, the 10%ile is in common use as a simple rule of thumb for baseflow and the 90%ile is in common use to represent a high flow threshold.

2) Development and Application of flow indicator tool

Having established the ecological assets around which to select flow indicators and subsequently, flow metrics, the next stage of work was to develop and test a hydrological reporting system. This stage:

1. Develops a scoring system based on the distribution of the flow metrics under pre-development conditions (benchmark).
2. Applies the scoring system to a number of sites in the Mackay-Whitsunday and Wet Tropics regions.
3. Tests and applies alternative metric aggregation methods to produce an ‘at-site’ annual hydrological condition score.

We developed, evaluated and applied an approach to report on annual hydrologic condition using the timing of the current report cards, being the financial year. To that end, the approach uses a water year as being the 12 months from July-June. The method develops a benchmark distribution for each of a series of ten flow metrics. The benchmark distribution of flow metrics is based on calculating the metrics for a long-term (1890-2008) modelled pre-development (natural) flow sequence. The hydrologic condition score is then determined based on where the flow metric for the observed flow for a given year falls with respect to the distribution of the flow metric across the modelled pre-development years (Figure 2-1).

To support the ongoing application of the approach, we have developed and excel based calculation tool. The tool allows the user to apply the method to a new site. The tool also allows the user to test the sensitivity of the flow metric settings or to develop locally specific variations of the flow metrics (See Appendix 3).

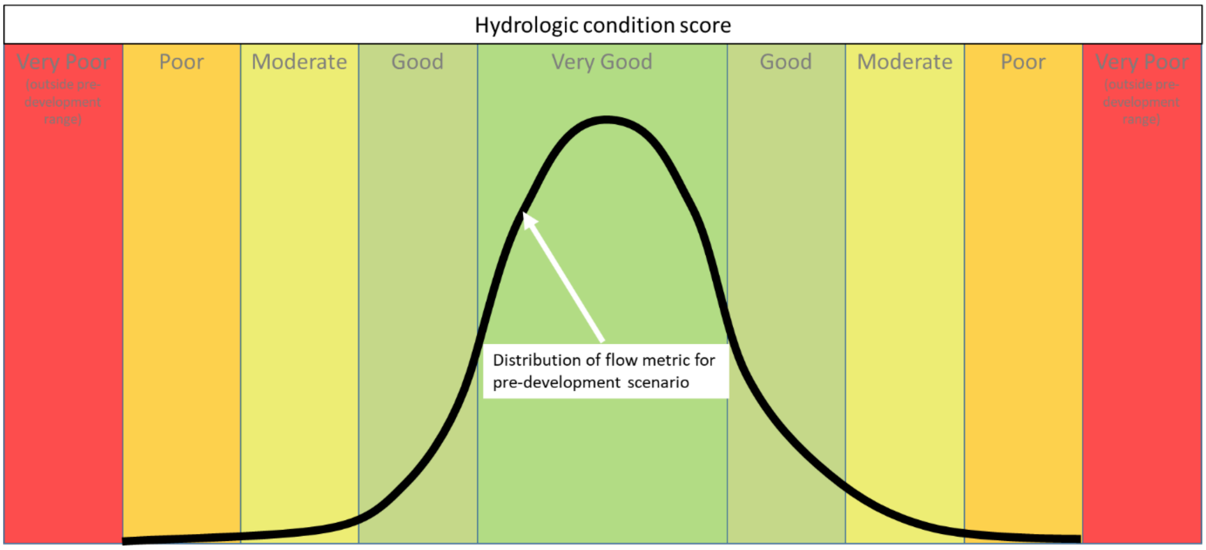

Figure 2-1. Hydrologic condition score based on the flow metric for the observed flow compared to the distribution of the flow metric for the pre-development scenario.

Methodology: Determining a flow indicator score

The process for determining the hydrologic condition score required firstly the determination of a benchmark distribution of each flow metric (steps 1-3 in Figure 2-2). The benchmark distribution was based on the analysis of a modelled long term pre-development scenario. To allow a tighter range in the benchmark distribution, the results of the pre-development analysis were divided according to the prevailing climatic conditions. This produced a distribution of each flow metric for each prevailing climatic condition (drought, dry, average, wet).

After the benchmark distributions for flow metrics were determined for a site, the annual reporting process is to calculate the flow metric for the reporting year and compare it to the benchmark distribution for the prevailing climatic conditions. The flow metric scores are then combined to provide a single site based score (steps 4-5 in Figure 2-2).

The basic procedure to derive a flow indicator score is as follows:

1. Identify flow data for the benchmark period (1890-2008)
2. Define the prevailing climate for each year of the benchmark period
3. Define benchmark flow conditions for each climate type
4. Calculate the score for each flow metric relative to the benchmarks of the prevailing climate
5. Report the score for each flow metric and aggregate to an overall flow indicator score

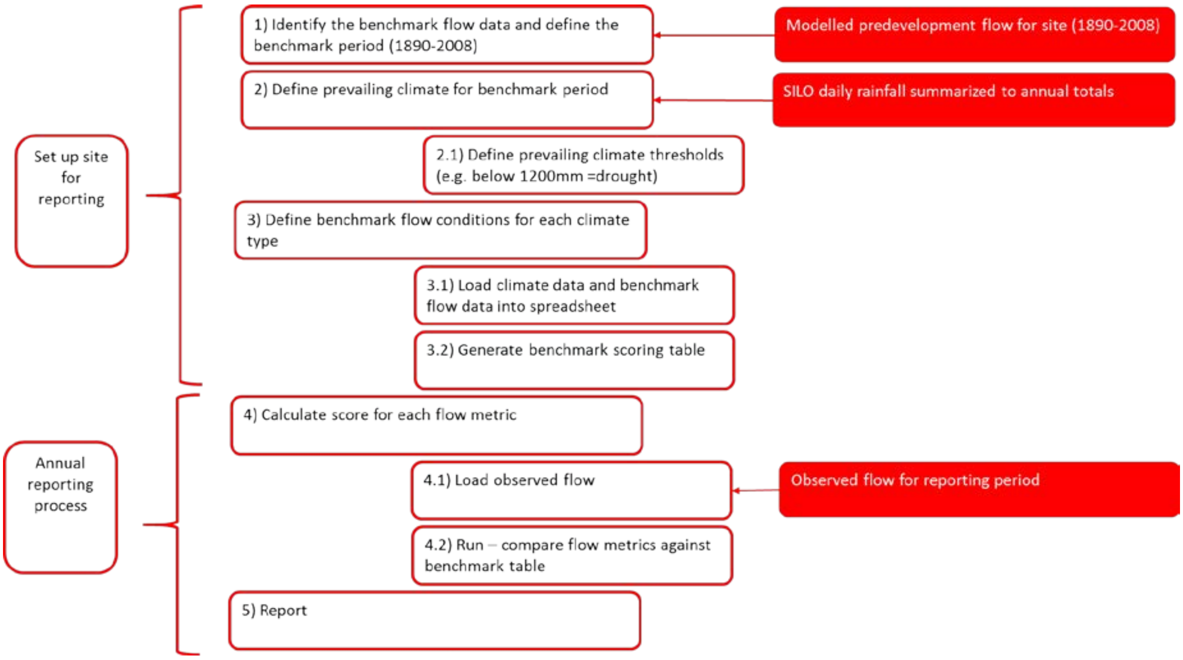

Figure 2-2. Summary of the process for determining the hydrological condition score

The following sections step through the methodology of developing and applying the flow metrics.

1. Identify flow data for the benchmark period

In order to determine a benchmark distribution of each flow metric to report against we have used the IQQM modelled pre-development scenario, for years 1890-2008, developed by the Queensland Government for water resource planning activities.

2. Defining the prevailing climatic conditions

The flow-indicator requires reporting on an annual basis. However, interannual variation in rainfall and hence streamflow is often substantial, leading to comparatively drier or wetter years compared to the long term average. This interannual rainfall variation requires establishing appropriate benchmarks to avoid a scoring system which is dominated by reporting the effect of rainfall variability.

In order to define a more constrained baseline hydrological condition against which to report we have considered the prevailing climatic conditions. In this way we use a subset of years from the hydrological record to define the baseline conditions against which the current condition is assessed.

We have used a representative rainfall record from the Queensland Government SILO program for each catchment. The rainfall record covers the entire hydrological modelling period (1890 – 2008) and continues to the present day. In order to define the prevailing climate we calculated the total annual rainfall for each reporting year (July-June) and separated those years into quartiles. We have defined the prevailing climate as:

- Drought: Annual rainfall<=25th percentile year
- Dry: 25th percentile year<Annual rainfall>= 50th percentile year
- Average: 50th percentile year<Annual rainfall>= 75th percentile year
- Wet: Annual rainfall>75th percentile year.

For a catchment, each year of the hydrological record is then ascribed a 'prevailing climate'. Of the 118 years of hydrological model record there are 29 or 30 years from each prevailing climate category. This is an adequate sample size from which to characterize long term hydrologic regimes using flow metrics (Kennard et al. 2010b).

3. Defining the benchmark flow conditions

To determine the benchmark flow conditions for each climatic classification, we used the pre-development scenario that represents the rainfall-runoff processes but removes any anthropogenic water extraction or storage activities. It represents a case where the current (actually the period of calibration) land-use is in place but there is no water resource development. We have used the modelled pre-development scenario to define the benchmark distribution for each flow metric.

A second IQQM model scenario has also been applied – full development – this scenario applies the full use of current level of water resource entitlement. While this may occur in some locations, in practice, water resource entitlements are rarely used in full, hence this scenario should represent an extreme case. The full development scenario is a good test case to assess if the flow metrics are sufficiently sensitive to discriminate between the flow scenarios. If the flow metrics showed little difference between the pre-development and the full development scenarios then there is a good case to discard the metric. The metric may still be ecologically relevant, however if the component of the hydrograph described by the metric is unaffected by likely water resource development then it adds no value to the reporting process.

Load climate data and benchmark flow data

In developing the approach, we applied the approach using modelled flow data from a set of nine IQQM model nodes supplied by the Queensland government. The procedures described below are generalised and can be applied to all remaining reporting locations by Terrain and Reef Catchments, when the modelling data has been provided.

Determining the benchmark reporting cutoffs

The reef report card reporting process requires five categories from very poor to very good. The default settings of the adopted approach for the flow indicator is that if the reported flow metric for the test year fall within one standard deviation of the mean for the modelled pre-development (benchmark) case then it receives a score of very good. The scores would then decrease with each successive standard deviation they deviate from the mean (Figure 2-1). This default scoring system assumes that low values are equally as bad as high values. The excel tool developed to support the calculation of metrics allows the adjustment of the scoring thresholds for every flow metric for every site.

The method using standard deviations away from the mean is based on the principles of a normal distribution and parametric statistics. We reviewed several metrics across several gauge sites and metrics quantifying the duration and frequency of flow events did closely approach a normal distribution. However, to avoid potential statistical problems by assuming a normal distribution, our approach is to set the scoring thresholds based on percentiles (non-parametric approach), where those percentiles approximately correspond to the number of standard deviations for a normal distribution (Table 2-1). For example, the percentile of the point one standard deviation below the mean of a standard normal distribution is approximately the 15.87th percentile and one standard deviation above the mean is the 84.13th percentile.

Table 2-1: The benchmark measures for all the flow metrics expressed as standard deviations from the mean and approximate percentiles

Score	Target standard deviations from mean	Rationale	Percentile range
Very good (5)	1	within 68.27% observed range	15.87-84.13
Good (4)	2	within 95.45% observed range	2.28-15.87, 84.13-97.72
Moderate (3)	3	within 99.73% observed range	0.13-2.28, 97.72-99.87
Poor (2)	4	within 99.99% observed range	0-0.13, 99.87-100
Very poor (1)	5	outside the observed range	<0, >100

Benchmark cutoffs – worked example

To demonstrate the calculation and refinement of benchmarks for a metric the following section is focused on the Murray (Murray@UpperMurray – gauge 114001A). As an example, if the duration of flows above the median flow was six days in an average year, then the score for that metric for that year would be *moderate* (highlighted in orange in Table 2-2 where six days is above the moderate threshold of 4, and below the good threshold of 12). A score of *moderate*, would yield a numeric score of 3 for that metric (Table 2-1), which would then contribute to the overall aggregation. Where there are ties in the thresholds, such as between moderate and poor for dry and average years, the current implementation of the Excel Tool is to use the higher score of the two.

The procedure for determining the benchmark metrics was to create the equivalent of Table 2-2 for each of the ten flow metrics for all gauge locations where pre-development flow was provided.

Table 2-2: Benchmark thresholds for flow metric ‘duration above median flow’ at Murray@UpperMurray

Climate	Benchmark thresholds (number of days)							
	Poor	Moderate	Good	Very good	Very good	Good	Moderate	Poor
	0%ile	0.13%ile	2.28%ile	15.87%ile	84.13%ile	97.72%ile	99.87%ile	100%ile
drought	4	4	5	11	67	91	109	110
dry	0	0	1	16	82	107	114	114
average	4	4	12	24	115	138	145	145
wet	8	9	17	39	130	171	207	209

4. Calculate the score for each flow metric

Having created the benchmark table for each flow metric (equivalent to Table 2-2), the score for the metrics can be calculated by comparing the value of the metric for the given year with the appropriate benchmark in the table, depending on the climate classification. This creates ten scores, one for each flow metric, for a given location in a given year.

5. Annual score aggregation

The individual metric scores should be reported to ensure that the potential ecological impacts of low scores for different indicators are able to be considered by stakeholders, however, a single summary is required for the higher levels of reporting. There are many potential ways to integrate metrics into a single score and the choice of integration method can have a large effect on final scores (see Robinson & Kennard 2010). We considered four alternative approaches, each of which has advantages and disadvantages:

1. Average: Assumes metrics are correlated and can yield results towards the centre of the distributions (especially with more metrics as averaging large numbers of scores results in a narrow distribution of integrated scores), hence less variability and potentially more difficulty in identifying extreme cases.
2. Mode: Taking the most common value across the metrics can often overestimate the score, particularly if there is a low value for a metric that has a catastrophic effect on the ecological asset of interest.
3. Minimum: This approach is overly punitive for a single low-scoring metric.
4. Bottom 30%ile (referred to as the bottom third): This percentile based approach simply takes the third worst metric (30th%ile of ten metrics). It is similarly conservative (as the minimum approach) but does not score a site as extremely poor if there is single low metric result.

We recommend the bottom third approach as a compromise among these options.

3) Results: Illustrative examples for available data

The process of developing benchmarks and running the pre-development, full development and observed flows described above was conducted for nine gauge locations where pre-development flows where available at the time of flow indicator development.

To illustrate the differences among the different aggregation approaches, we present the pre-development scores for all ten flow metrics at the Upper Murray gauge for years 1995-2-17 (Table 3-1). Each year is classified according to the prevailing climate which defines which of the benchmarks to use for the flow metrics. The score for each metric is then determined as either very good to very poor, scores of 5 to 1 respectively.

By way of example, in 2017, which was a dry year, the upper Murray River (Murray@UpperMurray – gauge 114001A) was scored as very good for both of the cease to flow metrics (CTF duration and frequency), indicated by the green cells and score of 5 for the first two metrics in the final row of Table 3-1. In contrast, it was scored as very poor for the duration of flow above the 50th percentile of flows, indicated by the red cell with a score of 1, in the final row of Table 3-1. The results of the alternative aggregation approaches can be seen in the last four columns of Table 3-1.

Table 3-1: Upper Murray pre-development scores – the scores for observed flows (Scores- 1= very poor, 2=poor, 3=moderate, 4= good, 5= very good) with annual aggregation calculated with the four different potential approaches.

		Hydrologic metrics										Aggregation options			
Report year	Climate*	CTF Duration	CTF Frequency	Below 10%ile Duration	Below 10%ile Frequency	Ratio dry/total	CV dry season	Above 50%ile Duration	Above 50%ile Frequency	Above 90%ile Duration	Above 90%ile Frequency	Average	Mode	Min	bottom 1/3
1995	Drought	5	5	5	5	5	3	3	5	5	5	4.6	5	3	5
1996	Avg	5	5	5	5	4	1	4	4	5	5	4.3	5	1	4
1997	Avg	5	5	5	4	5	5	5	5	5	5	4.9	5	4	5
1998	Avg	5	5	5	5	5	4	5	5	4	4	4.7	5	4	4.7
1999	Wet	5	5	5	5	5	5	1	5	5	5	4.6	5	1	5
2000	Wet	5	5	5	5	5	4	5	5	5	4	4.8	5	4	5
2001	Avg	5	5	5	5	3	5	1	4	5	4	4.2	5	1	4
2002	Drought	5	5	4	4	5	4	5	1	5	4	4.2	5	1	4
2003	Drought	5	5	4	5	5	5	1	5	5	5	4.5	5	1	5
2004	Avg	5	5	5	5	5	4	5	5	5	5	4.9	5	4	5
2005	Drought	5	5	4	4	5	5	5	5	4	4	4.6	5	4	4
2006	Avg	5	5	5	5	4	5	5	5	5	4	4.8	5	4	5
2007	Avg	5	5	5	5	5	5	4	5	5	5	4.9	5	4	5
2008	Avg	5	5	5	5	5	1	5	4	5	5	4.5	5	1	5
2009	Wet	5	5	5	5	5	5	5	5	5	5	5	5	5	5
2010	Dry	5	5	5	5	5	5	5	5	5	4	4.9	5	4	5
2011	Wet	5	5	5	5	4	4	3	5	1	1	3.8	5	1	3.7
2012	Wet	5	5	5	5	4	4	4	5	5	1	4.3	5	1	4
2013	Dry	5	5	5	5	5	5	4	5	5	4	4.8	5	4	5
2014	Wet	5	5	5	5	5	3	5	5	5	4	4.7	5	3	5
2015	Drought	5	5	4	2	4	5	5	4	5	5	4.4	5	2	4
2016	Dry	5	5	5	5	5	5	5	5	5	5	5	5	5	5
2017	Dry	5	5	5	5	4	4	1	5	4	4	4.2	5	1	4

Annual aggregated flow scores for nine sites throughout the Wet Tropics and Mackay-Whitsunday regions are shown for the period from 1961, using the bottom third approach to aggregation (Table 3-2). The detailed results for every metric for every year of the observed flow are available in the underlying site based spreadsheets provided separately.

Table 3-2: Results of the flow indicator score (1= very poor, 2=poor, 3=moderate, 4= good, 5= very good) for nine sites where there was available flow data at each stream gauge. In this table the annual aggregated score has been calculated via the bottom third approach to aggregation.

Year	Murray@ UpperMurray 114001A	Barron@ Myola 110001D	Mossman@ Mossman 109001A	Tully@ Euramo 113006A	Herbert@ Ingham 116001F	Pioneer@ Sarichs 125002C	Pioneer@ MiraniWeir 125007A	CattleCk@ Gargett 125004B	BlacksCk@ Whitefords 125005A
1961		4.7			5	1			
1962		4			4	1.7			
1963		4.7			4.7	1			
1964		5			5	3.7			
1965		4			5	2.7			
1966		4.7			5	1.7			
1967		4.7			4.7	4			
1968		5			5	3.1			
1969		4			5	4			
1970		4			5	4			
1971	4	4.7			4.7	4			
1972	5	1			4	3.7			
1973	5	5		5	3.7	3.7			
1974	4	4		4	5	2			
1975	5	4		4.7	4	1.7			4
1976	4.7	4		4	4	2			5
1977	4.7	4.7		5	5	1			4.7
1978	5	5		5	5	2.7			4.7
1979	5	4.7		4	4.7	2	4		5
1980	5	4.7		4	5	2	4		4.7
1981	4	4		5	5	1	4.7		5
1982	5	5		4.7	5	4	4		4
1983	5	5		4	5	3.8	4		5
1984	5	4.7		5	5	4	4		5
1985	4.7	4.7		5	4.7	4	4.7		4

1986	4	4.7		5	5	3.4	4		4
1987	5	5		5	5	4	3.1		5
1988	5	4.4		4	5	4.7	4	4	5
1989	5	5		4.7	5	1.7	4	4.7	5
1990	5	4.7	5	4.7	5	4.7	4.7	4	4.7
1991	4.7	4	5	4.7	4	2	4	4	4.7
1992	4	5	5	4	5	1	4.7	5	3
1993	5	4	4	5	5	4.7	3.7	3.7	4
1994	5	4.7	4	5	5	5	4	4	5
1995	5		4.7	4	5	3.7	4.7	4	3
1996	4		5	4.7	5	4	3.7	4.7	5
1997	5		4.7	5	5	4	4	4	3.7
1998	4.7		1	4.7	5	4.7	4	4.7	4
1999	5		5	4.7	4.7	3.4	4	2.4	4.7
2000	5		4.7	5	4	2	4	4.7	5
2001	4		4.7	5	4.7	1	4	4	4.7
2002	4		5	3.4	5	4	4	5	3.1
2003	5		4	4.7	5	2	5	4.7	4
2004	5		5	5	5	2	4	4.7	4
2005	4		5	3.1	5	4.7	4	4	5
2006	5		5	5	5	3.7	5	5	4.7
2007	5		4.7	4.7	4.7	3.1	4	5	5
2008	5		5	5	5	4	4	5	5
2009	5		4	1.7	4.7	3.1	4	4.7	5
2010	5		5	4	5	4	4	4	5
2011	3.7		4	1.7	1	2	4	2.4	2.7
2012	4		5	1.7	4.7	2	4	4	4
2013	5		4	1.7	4.7	3.7	4	4	4.7
2014	5		5	2.7	5	1	4	4	5
2015	4		4	2	5	1.7	4	2	2.7

2016	5		5	2	5	3.4	4	4	5
2017	4		4.7	3.7	4		4.7	4	4.7
Average (from 1961)	4.7	4.5	4.5	4.1	4.7	3.0	4.1	4.1	4.4

Flow indicator tool: concluding remarks

Rolling out the approach across the regions

There are 71 stream gauges across the Mackay-Whitsundays and Wet Tropics region. Of these approximately 56 are within the IQQM modelled water resource regions and have suitable data availability. Modelled pre-development and modelled full development flow time series should be requested to apply the flow indicator tool. These data should be provided under the existing IQQM model licenses entered into through this project.

Deriving a basin score from multiple gauges within a catchment

The final flow score for a catchment, which combines multiple locations within a catchment will need to be aggregated to derive a final catchment score for the flow indicator. The same aggregation approaches are possible for deriving a final catchment score as for aggregating across flow metrics as well as other options based on averages.

When aggregating scores from multiple locations within a catchment, it is feasible to use averages because the different scores operate on the same scale, as opposed to the different scales of the flow metrics comprising the flow indicator score. The arithmetic mean, being the raw unweighted average is an approach that treats all locations equally regardless of catchment area. An alternative is to use an area weighted mean, where the relative contribution of the flow indicator score in a sub-catchment, depends on the relative area of that sub-catchment in the whole catchment. For example, a sub-catchment that makes up 50% of the area of a catchment will contribute 50% of the information towards the area weighted mean and a sub-catchment with 20% of the area will contribute 20% of the information towards the area weighted mean. This approach has the advantage that the stream gauge representing the largest area of the catchment has the largest impact on the overall score. Another alternative would be to use the lowest score for any gauge in the catchment, on the basis that the condition of a catchment can only be considered as good as its worst location, however, this is a heavily punitive approach. Each approach has its own advantages and disadvantages and the decision is necessarily a somewhat subjective one.

As we were unable to test any of the options while undertaking the project, due to a lack of available data at the time, we recommend that the Report Card developers test the approaches when the data becomes available. We have provided a separate spreadsheet with the different options coded in, “MWWT Catchment Score aggregation tool.xlxs” so different approaches can be explored with the first year of reporting.

Scoring at locations without flow data

A primary issue for report cards is deriving scores in locations where there is not available data upon which to do it. In this case, water resource planning models (IQQM models) are not available for all catchments in the region. A comparable high quality modelling process has been conducted for the Office of the Great Barrier Reef. This may be a source of pre-development scenarios for the gauge nodes in order to develop benchmarks for all sites, however, a shorter time series means the classification of prevailing climates will not be possible. In addition, the different definition that the OGBR use for pre-development (based around land management), compared to the IQQM models (which is based on water resource development) means that any use of these models would not be directly comparable with the metrics devised here using the IQQM models.

It is understood that there is a need to develop scores for locations outside the gauging and IQQM model network. One approach may be to apply the score from the nearest gauged stream with the confidence on the score declining with increasing distance from the gauge. *However, we advise against this approach due to the unknown degree of error that the approach would introduce.* There are multiple sources of uncertainty in streamflow modelling including; measurement uncertainty, modelling uncertainty, spatial extrapolation uncertainty (Kennard et al. 2010b).

Measurement uncertainty in river flow assessment comes from multiple sources including errors in stage measurement and temporal variation in accuracy due to physical processes such as geomorphic change from sediment delivery in gauged reaches (Kennard et al. 2010b). There is also uncertainty in deriving the stage-discharge relationship and subsequent predictive uncertainty from rating curves. Once the data are collected, the development of models themselves (such as IQQM models) introduces additional uncertainty, which may include parameter or structural uncertainty (Jakeman et al. 2006). Consequently, even with the most accurately measured flow as input data, errors in model outputs will invariably exist. Finally, the most relevant aspect for this problem is that of spatial extrapolation uncertainty, that arises when using data from an existing streamflow model (or stream gauge) for nearby ungauged streams. Spatial variation in streamflow regimes can be so great, even within very close proximity, that in their work to classify the flow regimes of ungauged streams in Australia Kennard et al. (2010a, p 187), noted that:

“stream gauges from certain flow-regime classes often being non-contiguously distributed across the continent. … As a consequence, caution should be used if extrapolating flow-regime characteristics from individual gauges to ungauged areas, even those within relatively close proximity”

The effect of spatial extrapolation uncertainty is not only significant between catchments, but also within (Bond and Kennard 2017), consequently, we are unable to recommend an approach to developing a hydrological indicator score at stream sites for which data are not available.

Because of the certain introduction of error in extrapolating to unknown locations without appropriate rainfall-runoff models, we recommend excluding the flow indicator from the overall ecosystem health score in streams without stream gauges.

A flow indicator score for estuaries

There is a need to develop a flow indicator tool for estuaries in addition to the freshwater reaches, which is difficult due to the lack of flow gauges in these parts of catchments. The ecological condition of estuaries is very closely tied to the natural flow regime. This has been shown to be the case for several species of estuarine ecology including water quality conditions, fish ecology and fisheries production (Kimmerer, 2002). While causal relationships are not necessarily yet understood, patterns between estuarine ecology and river flow have been found to be particularly strong in estuaries of northern Queensland (e.g. Robins et al. 2005). For example, in fisheries production, years with higher river flows have been correlated with stronger year-class strength in estuarine fisheries (Staunton-Smith et al. 2004; Halliday et al. 2008). As a result, estuarine systems are very much a part of environmental flow assessments and the natural flow regime is an important conceptual framework (Poff et al. 2010).

The lack of reliable flow gauges in estuaries in the region creates a similar issue to the difficulty of scoring in ungauged reaches. However, the known ecological relationships between freshwater flows and estuarine ecology provide a basis for selecting the nearest gauge on the same branch of river as an indicator. As such, we recommend the use of the flow indicator score from the most downstream gauge on the main branch of each catchment as an indicator of estuary conditions.

Flow indicator calculation tool

As an output from this project we have a developed a series of hydrological reporting tools (excel spreadsheets) for the further development and application of the methods described.

The Excel based tool requires the pasting of climate data, modelled pre-development flow and observed flow data. The tool calculates the benchmark distribution based on the modelled pre-development flow. The tool then calculates the resulting hydrologic condition score by comparing the flow metrics derived from the observed flow series with pre-development distribution of flow metrics. There are several parameters which the user can adjust with the tool to conduct sensitivity analysis or create a custom report for a specific site:

- Annual reporting year start;
- Flow metric thresholds;
- Months of application of the flow metrics;
- Percentile basis for defining condition thresholds.

See Appendix 3 for screenshots and instructions.

4) Climate variability and sensitivity analysis

Introduction

As described in previous sections, ten separate flow metrics were first evaluated using observed daily streamflow data for each year. These ten metrics were then combined to generate four aggregate annual flow indicator values. For annual flow indicators, it is important to consider the flow metrics of ecological relevance given the prevailing climatic conditions for the year. In other words, we compare and evaluate the flow metrics for a year in the context of the frequency distribution of these metrics for similar years in terms of the annual rainfall. For coastal catchments in the Wet Tropics and Mackay-Whitsunday regions, annual rainfall varies considerably across space and over time. The rainfall variability and how to represent this variability for catchments of varying sizes require operators of the annual flow indicators to make a number of choices in defining the prevailing weather condition for the year under consideration. This section reports on a sensitivity analysis of the aggregate flow indicators in relation to the interannual variability of rainfall over the catchment for which streamflow data were collected to determine these flow indicators. Two stream gauging stations were selected for this sensitivity analysis: the Herbert River at Ingham in the Wet Tropics and the Cattle Creek at Gargett in the Pioneer River catchment in the Mackay-Whitsunday to cover the range of catchment area in these two regions.

The objectives of this sensitivity analysis were:

- To identify which of the four aggregate scoring approaches generate the most inter-annual variability;
- To evaluate the effect of the number of annual rainfall classes on the aggregate flow indicators;
- To evaluate the effect of representing catchment rainfall for classification purposes on the aggregate flow;
- To evaluate the effect of using different definition of a water year for reporting purposes;
- To make recommendations to operators to produce aggregate flow indicators on an annual basis.

Data and method of analysis

For each water year (July-June, as currently defined by the report card), rainfall for the year would be compared with the probability distribution of annual rainfall to determine the type of ‘climate’ to which this year belongs. If we classify annual rainfall into four classes of equal probability of occurrence for example, a year is said to be a ‘drought’ year when the annual rainfall for the year is less than the 25th percentile of annual rainfall. We could similarly classify annual rainfall into two classes: below average (≤ 50th percentile) and above average (> 50th percentile). In both cases, flow indicators for the year would then be compared with the distribution of the indicator values for all the years of the same class to generate flow metrics of ecological significance for the year. In addition to different ways in which annual rainfall is classified, it is also important to determine what annual rainfall to use for classification purposes for each site for which annual flow indicator metrics are required.

A simple method to extract annual rainfall totals for a site is to use what is known as Data Drill as one of the SILO products updated daily by the Queensland government (https://www.longpaddock.qld.gov.au/silo/). Daily rainfall data can be downloaded for a site close to the stream gauging station to 0.05 degree accuracy. The method is straightforward to apply, and easily reproducible for any site of interest in the Wet Tropics and the Mackay-Whitsunday regions. Daily rainfall data so extracted are complete and 'clean' to generate annual totals and their probability distribution to define 'climate' types, or rainfall classes.

There is, however, considerable rainfall variability in space and time. Rainfall extracted using Data Drill to represent a single location, such as a BOM rain gauge, may not represent the total rainfall over the entire catchment, especially for large river catchments such as the Pioneer and the Herbert where rainfall decreases markedly away from the coast. To assess the rainfall variability and the likelihood of misclassification, we compared the impact of using a gauge rainfall and catchment rainfall to classify the climate. We define gauge rainfall as the rainfall record from the SILO Data Drill for a grid point that is the closest to the stream gauging. We define catchment rainfall as the spatially averaged rainfall over the entire catchment upstream from the gauging station. To estimate catchment rainfall we use up to 12 locations in a catchment which we refer to as the areal rainfall. Areal rainfall is used to describe the spatial representation of the rainfall that fell on the catchment, rather than the actual total rainfall that fell in the catchment.

We compared the effect of using these two approaches in the largest catchment in the Wet Tropics and the Mackay-Whitsunday, namely the Herbert and also Cattle Creek at Gargett, a tributary of the Pioneer which has a relative small catchment area (326 km^2). Together sensitivity analysis for the two sites would provide insight into the effect of various choices in representing the spatial and temporal rainfall variability on the aggregate annual flow indicators for these two regions.

The Herbert River at Ingham (116001F) has a catchment area of 8581 km^2. Twelve sites upstream from the gauging station were selected to estimate the areal rainfall for the catchment (Figure 4-1). Annual areal rainfall was compared with the annual rainfall at Ingham (-18.65S, 146.15E) that is closest to the gauging station (18°37'57.9"S, 146°08'33.6"E) to 0.05 degree accuracy. Six of the 12 sites are Bureau of Meteorology stations (Table 3-1). For these sites, patched daily data from SILO were available and extracted. For patched data, observations were used when available, and interpolated data were used for days without observations. For the remaining six sites, Data Drill was used to extract continuous daily data (Table 3-1). Data from Data Drill were exclusively interpolated from observations of various sources in SILO at 0.05 degree resolution (Jeffrey *et al.* 2001). Data for a period of 118 years from 1 July 1890 to 30 June 2008 were used to derive the probability distributions, to be consistent with IQQM modelling period for flow assessment. The arithmetic average of the annual rainfall totals for the 12 sites was used to represent the catchment rainfall for the Herbert River at Ingham as these sites were carefully selected and fairly uniformly distributed in space (Figure 4-1).

Figure 4-1: Location map for the Herbert River at Ingham. Ingham on the map is the grid point closest to the gauging station with 0.05 degree accuracy for which Data Drill data were available from SILO.

Table 4-1: Site location and the mean annual rainfall for 12 sites upstream from Ingham and those at Ingham in the Herbert River catchment.

No.	Location	Latitude	Longitude	Elevation (m)	Mean Annual Rainfall (mm)	BoM Station No.	Drilled or Patched
1	Peacock Siding	18.65°S	146.00°E	30	1760	-	Drilled
2	Elphinstone Pocket	18.50°S	146.00°E	41	1821	032091	Patched
3	Herbert Gorge	18.35°S	145.75°E	81	1536	-	Drilled
4	Kirrama	18.15°S	145.60°E	594	1124	-	Drilled
5	Gleneagle	18.17°S	145.34°E	557	794	032018	Patched
6	Meadowbank	18.24°S	144.99°E	366	748	031175	Patched
7	Koombooloomba Dam	17.84°S	145.60°E	760	2191	031083	Patched
8	Glen Ruth	17.90°S	145.45°E	650	1191	-	Drilled
9	Gunnawarra Airport	17.95°S	145.15°E	615	738	-	Drilled
10	Rudd Creek	17.95°S	144.95°E	658	713	-	Drilled
11	Evelyn State Forest	17.54°S	145.48°E	1006	1469	031024	Patched
12	Mt Garnet Post Office	17.68°S	145.12°E	658	807	031046	Patched
	Ingham	18.65°S	146.15°E	18	2053	-	Drilled

For the Herbert River, pre-development flows for the 1 July 1890 – 30 June 2008 period were used to calculate the frequency distribution of various rainfall classes. Combined observed daily flows for 116001A, 116001B, 116001C, 116001D, 116001E, 116001F for the period from 2 August 1915 to 6 November 2017 were used to assess the effect of using catchment versus gauge rainfall as well as using different classification schemes. The following classification schemes were considered:

1. class: effect of annual rainfall on flow indicator was not considered
2. class: ≤ 50th percentile; > 50th percentile
3. class: ≤ 33.3rd percentile; > 33.3rd percentile and ≤ 66.7th percentile; > 66.7th percentile
4. class: ≤ 25th percentile; > 25th percentile and ≤ 50th percentile; > 50th percentile and ≤ 75th percentile > 75th percentile

In all cases, annual rainfall totals were sorted in an ascending order, and various percentiles were determined. Each water year was assigned a rainfall class depending on the rainfall for the year and these threshold percentiles. Note that the 4th option from this list was used in Chapter 2 for the development of the flow indicator.

The ten flow metrics and four aggregate flow indicator scores were calculated for each year when observed daily flow data were available. These were repeated for each classification scheme and for two distinct rainfall data sets. The average and standard deviation of each of the four aggregate flow indicators were compiled, so was annual discrepancy in the aggregate flow indicators using different rainfall data sets.

This process was repeated at Cattle Creek at Gargett (125004B), which is a much smaller catchment (326 km^2) than the Herbert. Three sites upstream from the gauging station were selected to estimate the areal rainfall for the catchment (Figure 4-2). Annual areal rainfall was compared with the annual rainfall at Gargett (-21.20S, 148.75E) that is closest to the gauging station (21°10'41.8"S, 148°44'36.8"E) to 0.05 degree accuracy (Figure 4-2). Data Drill was used to extract continuous daily data for the three sites inside the catchment and for Gargett just outside the catchment (Table 4-2). As for the Herbert River, the arithmetic average of the annual rainfall totals for the three sites was used to represent the catchment rainfall for the Cattle Creek at Gargett as these sites were carefully selected and fairly uniformly distributed in space (Figure 4-2).

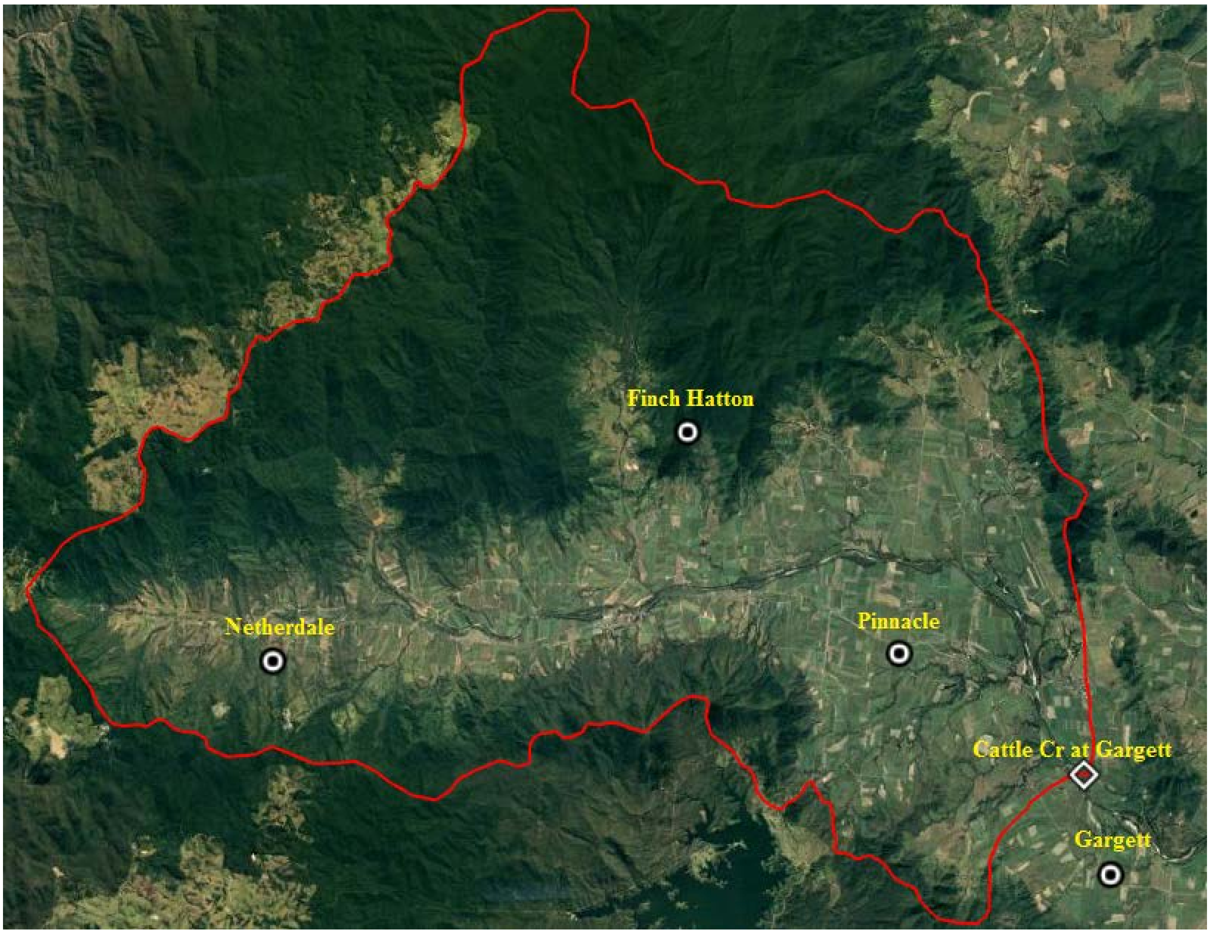

Figure 4-2: Location map for the Cattle Creek in the Pioneer River catchment. Gargett just south of the stream gauging station is the grid point closest to the gauging station for which Data Drill data were available from SILO.

Table 4-2: Site location and the mean annual rainfall for three sites upstream from Gargett and those at Gargett in the Cattle Creek catchment in the Pioneer River catchment.

No.		**Latitude**	**Longitude**	**Elevation (m)**	**Mean Annual Rainfall (mm)**	**BoM Station No.**	**Drilled or Patched**
1	Finch Hatton Gorge	21.10°S	148.65°E	300	1469	-	Drilled
2	Netherdale	21.15°S	148.55°E	212	1706	-	Drilled
3	Pinnacle	21.15°S	148.70°E	81	1526	-	Drilled
	Gargett	21.20°S	148.75°E	117	1391	-	Drilled

For the Cattle Creek catchment, the pre-development period was 1 July 1900 to 30 June 1996, while the observed daily flows were available for a period of 30 years from 4 April 1986 to 13 July 2017. Sensitivity analysis was repeated for the Cattle Creek in the same fashion as outlined for the Herbert River.

Results

Effect of different classification schemes

Table 4-3 shows the average aggregate flow indicators using the catchment rainfall for the Herbert River at Ingham and Cattle Creek at Gargett. For both sites, it is fairly clear that as the number of rainfall classes increases, the average flow indicator would decrease for all four aggregate scoring approaches. The decrease is greater for the minimum of the ten flow metrics than other aggregation approaches, and the decrease would be smaller if we use the mean or the mode as the aggregate flow indicator.

To be conservative, i.e. erring on the side of a lower score, classification of annual rainfall to capture the interannaul rainfall variability is highly recommended. The number of classes could be determined so that we have about 30 years of pre-development flows to construct the frequency distribution for each of the classes. Accordingly, for the Herbert River at Ingham, four classes would be justified (29.5 years on average for each class), while for the Cattle Creek, three classes may be more appropriate (32 years on average for each class). For both sites the difference between using three and four classes is no more than 0.2 for all the four aggregate scores. Thus, for sections that follow, the results using four classes for the Herbert and three for the Cattle Creek are focused in the report.

Table 4-3: Effect of rainfall classification on aggregated scores, using the catchment rainfall for the Herbert River at Ingham and the Cattle Creek at Gargett.

Site	**No. of rain classes**	**Mean**	**Mode**	**Min.**	**30%tile**
Herbert River	4	4.7	5.0	3.6	4.7
	3	4.7	5.0	3.8	4.7
	2	4.7	5.0	3.7	4.7
	1	4.8	5.0	4.0	4.9
	Difference between 1 and 4 classes	2%	0%	10%	3%
Cattle Creek	4	4.4	4.9	3.0	4.1
	3	4.5	4.9	3.1	4.3
	2	4.4	4.8	3.0	4.3
	1	4.6	5.0	3.3	4.6
	Difference between 1 and 4 classes	5%	2%	12%	12%

Interannual variability of aggregate scores

In the description of the methodology, we recommended the use of the bottom third approach to aggregating scores across the flow metrics on a conceptual basis. Here we present a quantitative analysis to demonstrate the variability in scores using the four different approaches to aggregating cscores, over 100 years of reporting. Table 4-4 shows the average and the coefficient of variation for each of the four aggregating approaches. The coefficient of variation (CV) is the standard deviation of the annual scores divided by the average, and is commonly used to quantify variability, here indicating the inter-annual variability of each aggregation approach. It is clear from Table 4-4 that the mean and the mode of the ten annual flow metrics do not vary much over time with CV< 0.1 in all cases, which suggests that they are likely to be less effective in highlighting changes in flow conditions from year to year. This is due to the impact of a single flow metric being comparatively low. The method we have recommended, the bottom third approach which uses the 30th percentile of the ten flow metrics, demonstrates a reasonable degree of variation, which suggests it will capture inter-annual variation in flow conditions based on the ten flow metrics.

Table 4-4: The average and interannual variability (CV) of the four aggregate flow indicators for the Herbert River (4-class) and Cattle Creek (3-class), using the rainfall over the catchment.

Site	Area (km^2)	Period		Mean	Mode	Min.	30%tile
Herbert River at Ingham (116001F)	8581	1917-2017	Average	4.7	5.0	3.6	4.7
			CV	0.06	0.02	0.34	0.11
Cattle Creek at Gargett (125004B)	326	1988-2017	Average	4.5	4.9	3.1	4.3
			CV	0.09	0.08	0.43	0.16

Effect of using gauge and catchment rainfall to characterise climate variability

Once again, gauge rainfall is defined as Data Drill rainfall data from SILO for a grid point that is the closest to the stream gauging station with a 0.05 degree accuracy. Gauge rainfall locations are shown in Figure 4-1 and Figure 4-2 for these two sites. The advantage in using gauge rainfall is that the Data Drill site is uniquely defined, and the daily rainfall data extracted from SILO are readily reproducible, and easy to prepare for future years. The disadvantage in using gauge rainfall is that the rainfall for the grid may not represent the temporal variations in rainfall for the catchment as a whole. For these two sites, the grid point for which gauge rainfall is extracted is not actually located within the catchment (Figure 4-1 and Figure 4-2).

As stated above, catchment rainfall is defined as the spatially averaged rainfall over the catchment upstream from the gauging station. The advantage in using catchment rainfall to take into account the climate variability is that this approach is justifiable hydrologically, for it is the rainfall over the catchment that is collectively responsible for the flow recorded at stream gauging stations. However, preparing catchment rainfall is more involved, often subjective, and it is therefore more difficult to ensure that catchment rainfall is prepared in a consistent manner on an annual basis for future years.

Annual rainfall at Ingham and the catchment rainfall were compared, so were the rainfall percentiles to define the climate. These comparisons were undertaken to address the following specific questions:

1. How different are the annual rainfall at the gauging station from the spatially averaged rainfall from the contributing area, in terms of the mean and inter-annual variability? Are the two highly correlated?
2. Would the annual gauge rainfall near the gauging station and areal rainfall over the catchment lead to the same ‘climate’ type for flow indicator calculations?

The mean annual rainfall at Ingham was 2053mm for the 118 years. The mean annual rainfall ranged from 713 to 2191mm among the 12 sites in the Herbert River catchment. The catchment mean annual rainfall was 1241mm, or about 60% of the mean annual rainfall at Ingham. The coefficient of variation (CV) was 0.32 for the annual rainfall at Ingham, and CV was 0.29 for the catchment annual rainfall for the Herbert River catchment. Annual rainfall at Ingham and the catchment rainfall are reasonably well corrected ($r^2 = 0.64$), and the relationship between the two can be well represented by a straight line through the origin (Figure 4-3).

Figure 4-4 shows, for each year, the rainfall percentile for Ingham and the corresponding percentile for the areal rainfall over the catchment. The grid lines in Figure 4-4 show the thresholds used for climate classifications. It is fairly evident that the ‘climate’ type using areal rainfall would be misclassified if we use the annual rainfall at Ingham for a large number of years. Table 4-5 shows that the number of years for each ‘climate’ type if we use annual rainfall at Ingham, and the number of years that would have been similarly classified using the areal rainfall for the catchment for these years. For ‘drought’ and ‘wet’ years, about 2/3 of years would have been classified similarly using rainfall data at the gauging station and for the ‘dry’ and ‘average’ years, about half of the years would have been classified similarly. This is likely due to the fact that it tends to be wet or dry everywhere in the catchment for extremely wet and dry years. For average years, rainfall may be high or low at a particular site, and rainfall at a site is less likely to be strongly corrected with areal rainfall for these average years (Figure 4-3 and Figure 4-4).

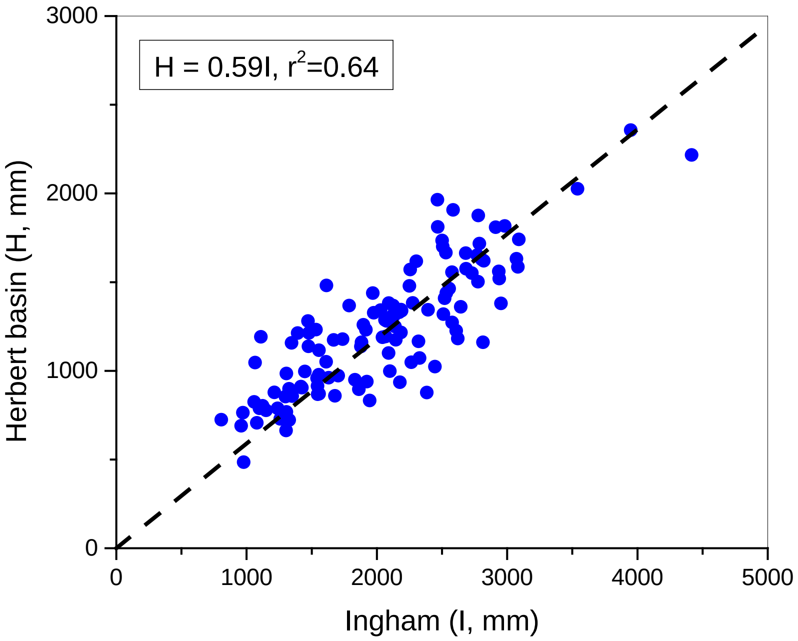

Figure 4-3: Annual rainfall at Ingham (data drill) near the gauging station and the corresponding annual areal rainfall based on 12 sites upstream in the Herbert catchment.

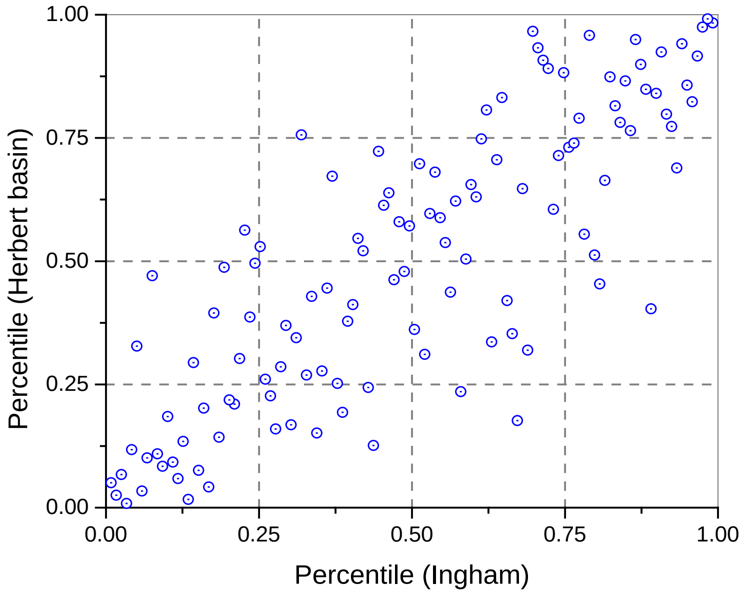

Figure 4-4: Annual rainfall percentile for Ingham (data drill) and the corresponding annual areal rainfall percentile based on 12 sites upstream in the Herbert catchment. Dashed lines represent the thresholds for classifying ‘climate’ types.

Table 4-5: Classification outcome using annual rainfall near the gauging station and the areal rainfall over the catchment.

‘Climate’ type	Criteria	No. of years using annual rainfall near the gauging station	No. of years using the areal rainfall given gauge-based classification
Drought	<25%	29	20 out of 29
Dry	≥25% & <50%	30	13 out of 30
Average	≥50% & <75%	30	14 out of 30
Wet	≥75%	29	21 out of 29

The mean annual gauge rainfall at Gargett was 1391 mm for the 118 years. The mean annual rainfall ranged from 1469 to 1706mm among the three sites in the Cattle Creek catchment. The catchment mean annual rainfall was 1567mm, or about 13% higher than the gauge rainfall at Gargett. The coefficient of variation (CV) was 0.40 for both the gauge and catchment rainfall for the Cattle Creek catchment. Annual rainfall at Gargett and the catchment rainfall are highly correlated ($r^2 = 0.95$), and the relationship between the two can be well represented by a straight line through the origin (Figure 4-5).

Figure 4-6 shows, for each year, the rainfall percentile for Gargett and the corresponding percentile for the areal rainfall over the catchment. The grid lines in Figure 4-6 show the thresholds used for climate classifications for the catchment (4 classes). It is fairly evident that the ‘climate’ type using catchment rainfall could still be misclassified if we use the annual rainfall at Gargett for a large number of years. Table 4-6 shows that the number of years for each ‘climate’ type if we use annual rainfall at Gargett, and the number of years that would have been similarly classified using the areal rainfall for the catchment for these years. For ‘drought’ and ‘wet’ years, almost all years would have been similarly classified using rainfall data at the gauging station and for the ‘dry’ and ‘average’ years, about two thirds of the years would have been similarly classified.

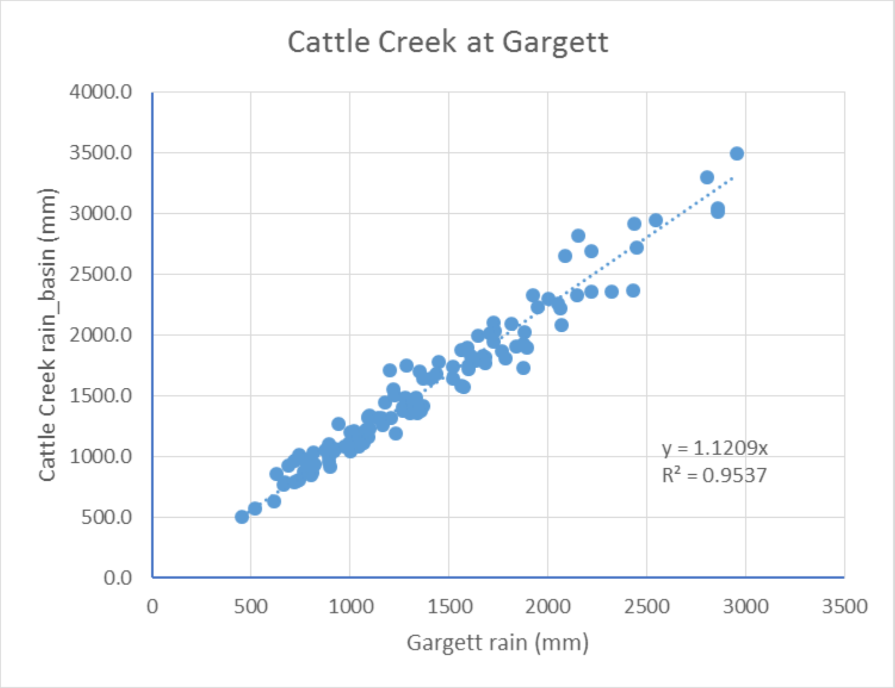

Figure 4-5: Annual rainfall at Ingham (data drill) near the gauging station and the corresponding annual areal rainfall based on three sites upstream in the Cattle Creek catchment.

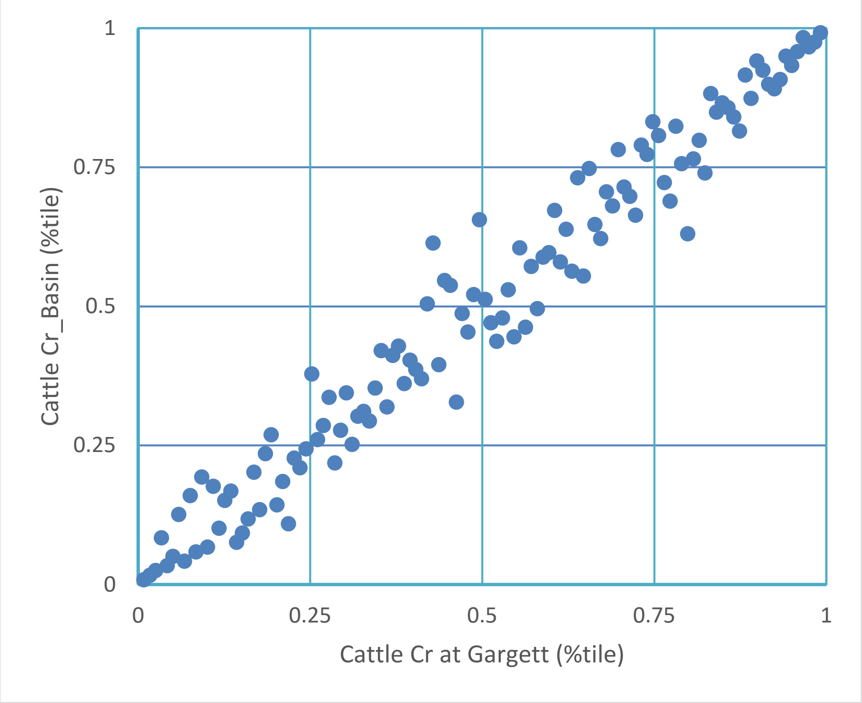

Figure 4-6: Annual rainfall percentile for Gargett (Data Drill) and the corresponding annual areal rainfall percentile based on three sites upstream in the Cattle Creek catchment. Dashed lines represent the thresholds for classifying 'climate' types.

Table 4-6: Classification outcome using annual rainfall near the gauging station and the areal rainfall over the Cattle Creek Catchment in the Pioneer River catchment

'Climate' type	Criteria	No. of years using annual rainfall near the gauging station	No. of years using the areal rainfall given gauge-based classification
Drought	<25%	29	28 out of 29
Dry	≥25% & <50%	30	23 out of 30
Average	≥50% & <75%	30	20 out of 30
Wet	≥75%	29	25 out of 29

Figure 4-7 shows the annual aggregate score using the 30th percentile for the Herbert River at Ingham. For most years (55%), there is no change whether we use the gauge or catchment rainfall. However, for about a quarter of the years (23%), the discrepancy would be large enough to result in a different score, i.e. absolute difference > 0.5. There also can be outliers evident in the results such as in 2010, when the annual score was 3 using the gauge rainfall, and the score was 1 if the catchment rainfall (Figure 4-7). In 2010, there were four flow metrics having a value of 1 based on catchment rainfall, and there were only three 1s when gauge rainfall was used.

Being much smaller in size, the discrepancy in the aggregate score for the Cattle Creek catchment is reduced whether we use catchment or gauge rainfall. Two third of the years, there would be no change in the aggregate scores for the Cattle Creek, although there are still years with a different annual score, especially when the annual rainfall was separated into four classes (Figure 4-8, Table 4-7).

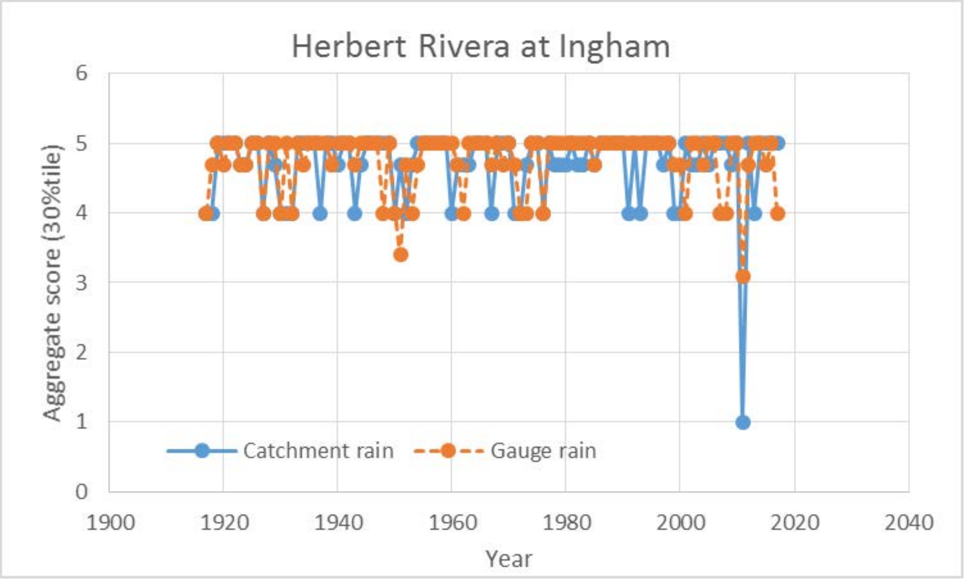

Figure 4-7: A comparison of the annual aggregate scores based on the 30th percentile of the ten flow metrics for the Herbert River at Ingham using catchment and gage rainfall. Four rainfall classes were used.

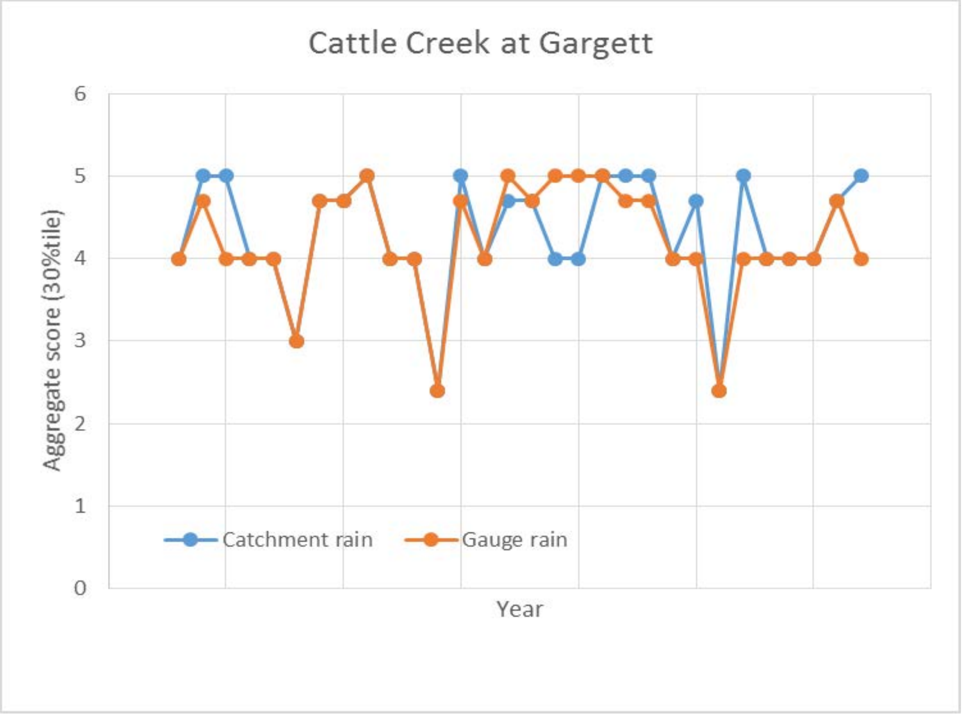

Figure 4-8: A comparison of the annual aggregate scores based on the 30th percentile of the ten flow metrics for the Cattle Creek catchment using catchment and gage rainfall. Three rainfall classes were used.

Table 4-7: The number of year with different absolute discrepancy in the annual aggregate score (30th percentile of the ten flow metrics) for the two selected gauge stations using different rainfall data and classification schemes.

	Herbert River (Area = 8581km^2, four rainfall classes)		**Cattle Creek (Area = 326km^2, three rainfall classes**		**Cattle Creek (four rainfall classes)**	
	Min.	30%tile	Min.	30%tile	Min.	30%tile
Total no. of years	101	101	30	30	30	30
No change	69 (68%)	56 (55%)	27 (90%)	19 (63%)	25 (83%)	20 (67%)
0 – 0.5	-	22 (22%)	-	5 (17%)	-	1 (3%)
0.5 – 1.5	18 (18%)	22 (22%)	1 (3%)	6 (20%)	1 (3%)	9 (30%)
>1.5	14 (14%)	1(1%)	2 (7%)	0 (0%)	4 (13%)	0(0%)

While it is highly desirable to use rainfall at or near a gauging station to classify ‘climate’ types for each water year because the method is inexpensive and reproducible, it is quite important, as demonstrated here, to be aware of the considerable spatial variation in annual rainfall. Annual rainfall at the gauging station may not represent the areal rainfall upstream from the gauging station over the catchment, particularly for large catchments and during average years.

Spatial variation in rainfall is large and how to represent and estimate catchment rainfall is very much an area of active research, especially for urban catchments with rapid hydrologic response (Segond et al., 2007; Ochoa-Rodriguez et al., 2015). As rainfall over the catchment brings about streamflow recorded at the gauging stations, it may be important to use catchment rainfall to define and characterise the inter-annual rainfall variability for each of the gauging stations for which flow assessment is required. Generally speaking, rain gauge density should be proportional to the square of CV of rainfall based on the sampling theory from statistics:

$$N = \left(\frac{\mathrm{CV}}{\varepsilon}\right)^2 \qquad (1)$$

where N is the number of rain gauges, CV coefficient of variation and ε desired error of estimated areal rainfall, both as percent. For the Herbert River as an example, the CV of annual rainfall among the 12 sites varied from 0.25 to 0.71 among the 128 years (1890-2017). If we allow 20% error in the estimated areal rainfall, this would amount to 2-13 sites to estimate the catchment rainfall according to equation (1) above. In general, the higher the spatial variability of rainfall, the more sites would be required to estimate the catchment rainfall for a given acceptable standard error. As a guide, one rainfall site per 600 to 900 km^2 of the catchment would be adequate to capture the spatial variation in rainfall (WMO, 1969). For the mean precipitation, two properly located rain gauges would be adequate for its estimation (Eagleson, 1967). To put this in context, there are currently 1194 operational rain gauges in Queensland with at some daily recordings in 2017. This represents a density of 1551 km^2 per gauge in Queensland with a much lower density in rural areas. It is important to note that observations at these gauges underpinned the grid-based SILO product for Queensland (Jeffrey et al., 2001).

Effect of using different definition of a water year

There have been some concerns about how ‘a year’ is defined for reporting purposes. Users of the Excel spreadsheet can specify any 12-month period to calculate annual flow indicators. By setting the cell C13 to 7 in the ‘notes’ worksheet, the users would consider Jul-Jun as effectively the water year. Similarly, the users can use 10 for C13 to define a water year from October to September, commonly used in Queensland. A simple sensitivity analysis was performed to assess the effect of using different definitions of a water year on the final annual flow indicator for these two selected sites. Catchment rainfall was used for this analysis. For the Herbert River, four rainfall classes were used; for the Cattle Creek, three classes were used to be consistent with analysis reported above. There was no difference in all four aggregate scores for each of the 101 years where observed flow data were available. Likewise, all four aggregate scores were identical whether or not we use Jul-Jun or Oct-Sep to define water years for reporting purposes for the Cattle Creek catchment.

Recommendations:

Based on this sensitivity analysis, we make the following recommendations in order of increasing complexity:

- Choose either Jul-Jun or Oct-Sep to define a water year, as there is no material difference to aggregate scores on an annual basis;

- The minimum or the 30th percentile of the ten flow metric be used as an aggregate score, as these are highly variable annually by comparison and presumably most indicative of the variations of ecological relevance on an annual time scale;
- The underlying temporal variation in rainfall be considered in flow assessment; three or four classes be used depending on the record length for pre-development flows;
- Use at least two sites within each catchment to determine the catchment rainfall. For large catchments, the number of sites selected should have a density around 500-1000 km^2 per site. It is critical to consider the spatial distribution of rainfall when selecting the sites. Sites should be as uniformly distributed in space as possible so that a simple arithmetic mean of the annual rainfall can be used to estimate the catchment rainfall. Once the sites are selected and finalised, these should not be changed when calculating annual flow indicators for future years for the catchment.

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5) Appendix 1: Ecological assets used to guide the development of the flow indicator

The ecological indicators used in the development of the flow indicator have distinct ecological and hydrological needs, which are described in detail. A synthesis of the ecological relationships described below was conducted (Table 1-1) which was used to determine appropriate flow indicators (Table 1-2) and subsequently, suitable hydrological metrics to represent them (Table 1-3). These fall under broad categories, fish, amphibians, ecosystem services, ecosystem processes and protection of waterholes.

Fish

Mogurnda spp. (purple spotted gudgeons)

This group includes two described and potentially other undescribed species of purple spotted gudgeons. The two described species are the purple spotted gudgeon (*Mogurnda adspersa*) and the northern purple spotted gudgeon (*Mogurnda adspersa*). Both species are present in the Wet Tropics (WT) and Mackay-Whitsunday (MW) catchments (Pusey *et al.* 2004), although the southern limits of *M. mogurnda* is less certain. In the absence of alternative information, it is assumed that both species (and any undescribed species) have similar biology and thus are treated as one ecological asset (DISITIA 2013b). While common across large parts of eastern Australian *M. adspersa* distribution has contracted largely throughout its southern range due to flow regulation, in-stream barriers and habitat degradation (Lintermans, 2007). *Mogurnda* are considered asset species as they represent diverse and viable communities of freshwater and inshore species and their associated habitats (Ecological value 11 – DSITIA 2013a). The peak breeding season for *Mogurnda* occurs between August and November when water temperatures exceed ≥ 20°C. Successful breeding is likely to occur during low flows (daily discharge ≤ median flow), with periods of flow stability where water level fluctuations remain ≤ 5 cm in depth for a minimum of nine days (DSITIA 2013b). The ToC for *Mogurnda* is one annual recruitment opportunity, with the Node Failure threshold being three consecutive years with < opportunities than ToC (i.e. three years with no recruitment opportunities).

Melanotaenia splendida splendida (Eastern rainbowfish)

This species is widespread through coastal drainages of eastern Queensland between Central Cape York Peninsula and Gladstone and thus are widespread throughout the WT and MW (except Proserpine) regions (Pusey et al. 2004). They are an important ecological asset as a widespread and abundant species that play an important role in aquatic food webs as food sources for waterbirds and commercially important fish species such as barramundi. The breeding season for *M. splendida splendida* is spread from August to November when water temperatures exceed ≥ 20°C and during stable flow conditions before the wet season (Pusey *et al.,* 2004). Thus, successful breeding and recruitment is likely to occur during low flows (daily discharge ≤ median flow), with periods of flow stability where water level fluctuations remain ≤ 5 cm for a minimum of 12 days (DISITIA 2013b). The ToC for *M. splendida splendida* is two annual recruitment opportunities, with the Node Failure threshold being two consecutive years with < opportunities than the ToC.

Ambassis agassizii (Olive perchlet)

This is a widespread species found in the Murray Darling Basin and coastal catchments of eastern Australia. They are likely widespread through the WT (except the Daintree) and the Pioneer and Plane catchments in the MW (Pusey et al. 2004). *A. agassizii* are a schooling species often associated with aquatic macrophytes (Pusey *et al.*, 2004). The species is an ecological asset as part of an important aquatic community and additionally as a conservation priority species (Ecological Value 7 – DSITIA 2013a). There is likely to be other *Ambassis* species, across the reporting area, however, the most reliable published ecological information exists for *A. agasizzii* and thus we assume closely related species will have similar traits. The breeding season for *A. agassizii* occurs between August to November when water temperatures exceed ≥ 22°C and during stable flow conditions before the wet season (Pusey *et al.* 2004). Thus, successful breeding and recruitment is likely to occur during low flows (daily discharge ≤ median flow), with periods of flow stability where water level fluctuations remain ± 5 cm from the starting depth for a minimum of seven days for egg development and additionally a further 20 days ≤ 5cm /day for larval development. The ToC for *A. agassizii* is one annual recruitment opportunity, with the Node Failure threshold being three consecutive years with < opportunities than the ToC.

Cairnsichthys rhombosomoides (Cairns rainbowfish)

This is a moderately sized rainbowfish restricted to the WT region with limited distribution within this region (Mulgrave-Russell, Johnstone and Tully catchments) (Pusey et al. 2004). It is listed similarly to *A. agassizii* (Ecological Values 7, 11 –DSITIA 2013a). *C. rhombosomoides* is often found in reaches with a relatively intact riparian canopy. The key breeding period for this fish is between September and October. Likely successful spawning and recruitment will occur during this period when water temperatures are ≥ 22°C during stable water conditions (daily discharge ≤ median flow and stable flow with water levels fluctuating ≤ 5cm for at least seven days. The ToC for *C. rhombosomoides* is two annual recruitment opportunities, with the Node Failure threshold being two consecutive years with < opportunities than the ToC.

Tandanus tandanus (Eel-tailed catfish)

This large-bodied iconic fish is a widespread species in costal catchments of NSW and Qld and within the Murray-Darling Basin (Pusey *et al.* 2004). While the species is listed as an asset (Ecological Value 11 –DSITIA 2013a), it is not listed as a species with a conservation priority. However, its' distribution and abundance has been severely reduced due to human impacts including water resource development in the Murray Darling Basin (Lintermans, 2009). It is likely that *T. tandanas* have been introduced to some of the catchments, particularly the WT where the closely related species *T. tropicanus* (Welsh et al. 2017) is native. However, given the amount of information on the ecology of *T. tandanus* we accept that this species will likely represent ecological requirements of both species until new peer-reviewed information comes to light. *Tandanus tandanus* are valued by many communities as a significant recreational riverine fish species. They are found in both the MW (Pioneer and Plane) and WT (but not the Herbert Catchment) (Pusey et al. 2004). Spawning peaks are between October and January when water temperatures are ≥ 23.4°C with specific flow velocities required during stable low flows (≤ 0.33 m/s and stable for seven days for egg and larval development. Further, water depths in slow flowing habitats need to be between 0.45 and 0.95 m. for period of egg and larval development. The ToC for *T. tandanus* is one annual recruitment opportunity, with the Node Failure threshold being five consecutive years with < opportunities than the ToC.

Pseudomugil signifer (Pacific blue-eye)

P. signifer are a small-bodied widespread species found in coastal catchments from the eastern Cape York Peninsula down to Narooma in southeastern NSW. They are common throughout the MW (but not the Plane) and WT catchments found in a variety of habitats including riffles, but mostly in shallow (< 50 cm deep) habitats (Pusey et al. 2004). This species is represented by Ecological Value 11 (DSITIA 2013a) as a widespread and ecologically important species. Although *P. signifer* have an extended spawning season they largely spawn between July and October in low flow periods. To ensure successful spawning and recruitment during low flows (daily discharge ≤ median flow), stable flow water level remains ≤ 5cm for 19 days, when water temperatures ≥ 22°C. The ToC for *P. signifer* is two annual recruitment opportunity, with the Node Failure threshold being two consecutive years with < opportunities than the ToC.

Amphibians

Littoria jungguy (Northern stony creek frog)

L. jungguy are found in rainforest habitat close to streams from North east Qld to the Barron river drainage. They are found in WT drainages (Johnstone, Tully, Murray and Herbert catchments) (DISITI 2013b). This species is listed on the IUCN Red List as near threatened and is included in the Queensland recovery plan for conservation of stream dwelling frogs in the WT bioregion (DERM 2001). It supports Ecological Values 7 and 11 (DSITIA 2013b). The breeding season for this frog occurs in the wet season approximately between November and March. Ecohydrological requirements for this species are the persistence of low order streams during the breeding season (maintenance of base flows). There was insufficient ecological knowledge to set a ToC for this species.

Littoria wilcoxii (Eastern stony creek frog)

L. wilcoxii are widely distributed from the Hawkesbury Nepean River in NSW to the Paluma Range (DSITIA 2013b). It is found in both the MW (all catchments) and WT (Johnstone catchment only) regions and is included in the Queensland recovery plan for conservation of stream dwelling frogs in the WT bioregion (DERM 2001). It supports Ecological Values 7 and 11 (DSITIA 2013b). The breeding season for this frog occurs in the wet season between November and March. Ecohydrological requirements for *L. wilcoxxii* are the persistence of low order streams during the breeding season (maintenance of base flows). There was insufficient ecological knowledge to set a ToC for this species.

Ecosystem Services – Fisheries production

Lates calcarifer (Barramundi)

L. calcarifer is one of the main target species of both commercial and recreational fishers in northern Australia and important to indigenous communities (Pusey *et al.* 2004; Robbins & Ye 2007). The species is not threatened but there is a high potential for them to be impacted into the future by human activities (Pusey *et al.*, 2004). Barramundi are present in all WT catchments and Proserpine, Pioneer and Plane catchments of the MW region (Pusey *et al.*, 2004; DSITIA 2013b). The maintenance of a viable barramundi fishery links directly to a number of Social and Ecological values – 3 (community lifestyle enhancement), 4 (cultural), 5 (healthy waterways for healthy communities, 8 (iconic species populations) and 11 (diverse and viable communities of freshwater and inshore species) (DSITIA 2013b). The relationship between flow and a viable barramundi fishery has been shown via statistical relationships between year class strength (YCS) and freshwater flow. The following equation describes this relationship: YCS = 0.227 (Log summer flow ML - 4.1011) with summer defined as Dec to Feb. This relationship is based on total discharge over the summer period and measured as end of system flows to each estuary. A ToC was defined using the YCS and population maintenance thresholds developed by Halliday & Robbins (2007). The median YCS under modelled pre-development flows was defined as a threshold above which *L. calcarifer* recruitment was strong. A ToC was determined based upon consecutive years where YCS is weakened by continuous low summer flow totals (with poor recruitment). These ToC's were summarised into three risk levels where low risk is considered any period of <5 years with poor recruitment, moderate risk 5-11 years of poor recruitment and high risk >11 years of poor recruitment.

Fenneropenaeus merguisensis (Banana prawn)

F. merguisensis are a short-lived marine and estuarine prawn species widely distributed through the Indo-West Pacific region and in the estuaries of all WT and MW regions (Dall et al. 1990). Mangrove-lined creeks are the preferred habitat of post-larvae and juveniles. Freshwater flow stimulates the downstream movement of juveniles and sub-adults. Further freshwater flows mare required for prawn recruitment and growth and increased flows into estuaries appear to be linked to high commercial catch rates (Robins and Ye 2007). While models of flow and prawn production have been developed for the Fitzroy River they need refinement for use in the WT and MW regions. However, the presumption could be made that any reductions in end of system discharge (magnitude) would impact the prawn fishery.

Ecosystem Processes

Provision of riffle habitat

Riffles have been identified as habitats that are sensitive to, and at high risk from flow modification, being sensitive to being drowned-out due to flow supplementation or seasonal reservoir releases. They are equally sensitive to being dried out due to water diversion or abstraction resulting in decreased or cessation of flows. Riffles are considered the most productive of riverine habitats, supporting both primary producers e.g. algae, bacteria and macrophytes which in turn support primary and secondary consumers e.g. macroinvertebrates (such as rheophilic species), fish and frogs. Riffles also support many specialist taxa that are adapted to these fast-flowing habitats. Within the WT and MW regions riffles support species reliant on such habitat such as sooty grunter (*Hephaestus fuliginosus*) which spawns close to these habitats, while *Psuedomugil signifer* are generally found inhabiting these habitats in preference to slower-flowing deeper stream sections. Riffles also improve water quality through the re-oxygenation of water through the turbulence created in these habitats. The presence of riffle sequences support a number of social and ecological values scores 2, 3 6, 7, 10 and 11 (including tourism, improved lifestyle, geomorphological processes, conservation of priority species and provision of clean water). The maintenance of medium and low flows over riffles is needed for habitat provision and water quality amelioration. This is provided by maintaining a minimum stream depth from10 – 40 cm during low-flow periods. A ToC could not be derived for riffle habitat provision due to the lack of knowledge around rheophilic taxa’s flow requirements.

Protection of waterholes

Waterholes are a key feature of riverine ecosystems that can become vital during dry periods, brought about through natural drying events or through water abstraction in managed systems. During such drying events they can become the only, or major refugia for obligate aquatic biota. For many fish species these waterholes may be crucial for maintaining local population persistence as they may need to complete their life-cycles entirely in them depending on the duration of drying. Further, waterholes can then become key sources for river habitat that are especially important during dry periods where they may become the most significant habitat for aquatic biota. Where they become true refugia they would also be key habitat foci of amphibians, reptiles and bird species, and a range of other vertebrate species. For the maintenance of refugial waterholes, provision of connecting flows during typically low-flow periods will be important for movement opportunities for biota to move among waterholes. Further, the cease to flow period will be critical for waterhole persistence times (and thus the biota they support).

Table 5-1: Potential hydrological metrics that represent the hydrological indicators presented in Table 1 2. The final collection of hydrological metrics was tested from a subset of this list.

Flow category	Types of indicators	Duration of flow (timing)	Hydrologic metric	Hydrologic Metric definition
Low flows	Duration of low flow events	Maximum change in depth of 5cm over whole stable period (min of 25 d to meet needs of all species)	Low flow spell duration (<75th, <90th, <99th percentile)	Mean duration of flows which remain below a lower threshold defined by the 75th, 90th and 99th percentiles (from the flow duration curve)
			CV Low flow spell duration (<75th, <90th, <99th percentile)	CV of in duration of annual occurrences during which the magnitude of flow remains below a lower threshold (75th, 90th and 99th percentiles)
	Frequency of low flow events		Low flow spell count (<75th, <90th, <99th percentile)	Mean number of annual occurrences during which the magnitude of flow remains below a lower threshold (75th, 90th and 99th percentiles) (from the flow duration curve)
	Timing of low flow event		Perenniality of monthly flows	Percentage contribution to mean annual discharge by mean monthly flow in the six driest months of the year
	Magnitude of flow events		Low flow discharge (<75th, <90th, <99th percentile)	75th, 90th and 99th percentiles from the flow duration curve
	Variability of baseflow		CV of daily flow	
Cease to flow	Duration of low flow events	Minimum period of zero flow	CV Number of zero flow days	CV in annual number of days with zero flow
	Timing of low flow event		Julian date of annual minimum	CV in Julian date of the 1-day annual minimum flow over 1 year
Low to Medium flows	Duration of low to medium event		Low flow spell duration (<50th percentile)	Mean duration of flows which remain below a lower threshold defined by the 50th percentile
	Frequency of low-medium medium flows		Medium flow spell count (<50th percentile)	Mean number of annual occurrences during which the magnitude of flow remains below a lower threshold (50thepercentile) (from the flow duration curve)
High flows	Magnitude of high flow events		Flood magnitude (1, 2, 5, 10, 15 and 20 year ARI)	Magnitude of flood events with ARI's of 1, 2, 5, 10, 15 and 20 years
	Duration of high flow events		CV of high flow spell count (<75th, <90th, <99th percentile)	CV in annual occurrences during which the flow remains above a higher threshold (<75th, <90th, <99th percentile)

6) Appendix 2: Summary of available data, supplied data and analysis completed

Table 6-1: Summary of available data, supplied data and analysis completed. The final three columns show the observed flow data that have been retrieved (Obs) and the modelled IQQM data that have been received from Queensland Government, including pre-development (PD) and full development (FD). Rows highlighted yellow are those for which data was provided by the Queensland Government.

Region	Basin	Gauge number	DNRM Gauges	Open	Start	End	Record Length (years)	Area (Km2)	DTM (km)	Obs	PD	FD
MW	Don	121001A	DonR@IdaCk	Y	1/03/1957		60.4	604	43.3	x		
MW	Don	1210002A	ElliotR@Guthalungra	Y	12/03/1973		44.3	273	7.5	x		
MW	Don	1210003A	DonR@Reeves	Y	14/03/1984		33.3	1016	23.5	x		
MW	Don	1210004A	EuriCk@Koonandah	Y	18/11/1998		18.7	429	7.9	x		
MW	Proserpine	122004A	GregoryR@LowerGregory	Y	24/10/1972		44.7	47	25.7	x		
MW	Proserpine	122003A	ProserpineR@PeterFaustDamTW	N	1/12/1956	1/07/2002	45.6	269	57	x		
MW	Proserpine	122005A	ProserpineR@Proserpine	N	24/07/1991	3/06/2014	22.9	360	30.7	x		
MW	O'Connell	124001B	OConnellR@StaffordsCrossing	Y	3/11/2005		11.7	342	19.5	x		
MW	O'Connell	124002A	StHelensCk@Calen	Y	7/02/1973		44.4	118	22	x		
MW	O'Connell	124003A	AndromaheR@Jochheims	Y	27/01/1976		41.5	230	16.7	x		
MW	O'Connell	124004A	JolimontCk@MountRoy	Y	20/01/1999		18.5	23	17.9	x		
MW	O'Connell	124005A	OConnellR@ForbesRd	Y	31/05/2007		10.1	167	28.7	x		
MW	Pioneer	125002C	PioneerR@Sarichs	Y	17/02/1958		58.4	757	57.7	x	x	
MW	Pioneer	125004B	CattleCk@Gargett	Y	3/07/1986		30	326	11	x	x	
MW	Pioneer	125005A	BlacksCk@Whitefords	Y	12/12/1973		42.8	509	64.9	x	x	
MW	Pioneer	125006A	FinchHattonCk@GorgeRd	Y	28/01/1976		40.9	35	3.2	x		
MW	Pioneer	125007A	PioneerR@MiraniWeirTW	Y	9/11/1977		38.7	1211	45.7	x	x	
MW	Pioneer	125009A	CattleCk@HighmansBridge	Y	19/06/2002		14.1	198	25	x		
MW	Pioneer	1250013A	PioneerR@DumbletonWeirHW	Y	26/02/1988		28.5	1485	16.7	x		

Region	Basin	Gauge number	DNRM Gauges	Open	Start	End	Record Length (years)	Area (Km2)	DTM (km)	Obs	PD	FD
MW	Pioneer	1250016A	PioneerR@DumbletonPump StationWeirTW	Y	22/12/2005		10.7	1488	16.6	x		
MW	Plane	126001A	SandyCk@Homebush	Y	17/08/1966		50.9	326	32.7	x		
MW	Plane	126003A	CarmilaCk@Carmila	Y	8/11/1973		43.7	84	11.8	x		
WT	Daintree	108002A	DaintreeR@Bairds	Y	25/09/1968		48.8	911	33.9	x		
WT	Daintree	108003A	BloomfieldR@ChinaCamp	Y	16/01/1970		47.5	264	13.5	x		
WT	Daintree	108008A	WhyanbeelCk@UpstreamLittle FallsCk	Y	12/10/1990		26.8	15	11.6	x		
WT	Mossman	109001A	MossmanR@Mossman	Y	1/08/1948		69	106	6	x	x	x
WT	Barron	110001D	BarronR@Myola	Y	1/10/1982		34.8	1945	27.1	x	x	x
WT	Barron	110002A	BarronR@Mareeba	Y	19/07/1915		102	836	70.2	x		
WT	Barron	110003A	Barron@PicnicCrossing	Y	1/10/1925		91.8	228	126.7	x		
WT	Barron	110011B	FlaggyCk@CattleYards	Y	1/10/1955		61.8	150	13	x		
WT	Barron	110017A	KauriCk@MainRd	Y	5/09/1991		25.9	15	2	x		
WT	Barron	110018A	MazlinCk@RailwayBridge	Y	5/09/1991		25.9	53	4.6	x		
WT	Barron	110019A	Petersonck@RailwayBridge	Y	21/07/1992		25	20	4.8	x		
WT	Barron	110020A	BarronR@Bilwon	Y	9/07/1992		25	1258	49.3	x		
WT	Barron	110021A	BarronR@GoonaraCk	Y	20/12/1994		22.6	127	143.7	x		
WT	Barron	110022A	LesliesCk@BarronJunction	Y	25/06/2004		13.1	56	0.1	x		
WT	Barron	110024A	GwynneCk@Schoorls	Y	2/11/2006		10.7	16	6	x		
WT	Barron	110025A	RockyCk@ChannelRd	Y	27/10/2006		10.7	32	10.1	x		
WT	Barron	110026A	SpringCk@ChannelSyphon	Y	16/02/2008		9.4	27	1.8	x		
WT	Barron	110104A	FreshwaterCk@RedlynchEstate	Y	7/10/1999		17.8	70	14.7	x		
WT	Mulgrave_Russell	111005A	MulgraveR@TheFisheries	Y	28/10/1966		50.7	357	48.9	x	x	x
WT	Mulgrave_Russell	111007A	MulgraveR@PeetsBridge	Y	29/02/1972		45.4	520	38	x		

Region	Basin	Gauge number	DNRM Gauges	Open	Start	End	Record Length (years)	Area (Km2)	DTM (km)	Obs	PD	FD
WT	Mulgrave_Russell	111010B	HillsCk@HamiltonRdBridge	Y	23/12/2001		15.6	14	5.7	x		
WT	Mulgrave_Russell	111101D	RussellR@Bucklands	Y	23/01/1980		37.5	315	22.5	x	x	x
WT	Mulgrave_Russell	111105A	BabindaCk@TheBoulders	Y	24/10/1966		50.7	39	16.4	x		
WT	Johnstone	112002A	FisherCk@Nerada	Y	30/09/1928		88.8	16	2.9	x		
WT	Johnstone	112003A	NorthJonstoneR@GlenAllyn	Y	1/10/1958		58.8	165	96.5	x		
WT	Johnstone	112004A	NorthJohnstoneR@TungOil	Y	1/10/1966		50.8	925	28.5	x	x	x
WT	Johnstone	112005A	TaylorCk@Warraker	Y	24/05/1991		26.1	1	0.7			
WT	Johnstone	112006B	RankinCk@Ross	Y	11/08/2011		5.9	31	3			
WT	Johnstone	112101B	SouthJohnstoneR@Upstream	Y	1/10/1974		42.8	400	18.5	x	x	x
WT	Johnstone	112102A	LiverpoolCk@UpperJapoonvale	Y	25/05/1970		47.1	78	39.4			
WT	Johnstone	112103B	LiverpoolCk@Silkwood	Y	15/09/2011		5.8	242	20.4			
WT	Tully	113004A	CochableCk@Powerline	Y	21/12/1966		50.6	95	4			
WT	Tully	113006A	TullyR@Euramo	Y	11/04/1972		45.3	1450	17.5	x	x	x
WT	Tully	113015A	TullyR@TullyGorgeNationalPark	Y	23/11/2009		7.6	480	74			
WT	Murray	114001A	MurrayR@UpperMurray	Y	26/05/1970		47.1	156	60.8	x	x	x
WT	Murray	114002B	MeungaCk@Sings	Y	12/08/2010		6.9	153	9.3			
WT	Herbert	116001F	HerbertR@Ingham	Y	22/10/2009		7.7	8581	30.5	x	x	x
WT	Herbert	116004C	HerbertR@GlenEagle	Y	1/10/1959		57.8	5236	179			
WT	Herbert	116006B	HerbertR@Abergowrie	Y	15/09/1969		47.8	7454	71.8			
WT	Herbert	116008B	GowrieCk@Abergowrie	Y	1/10/1953		63.8	124	6.9			
WT	Herbert	116010B	BlencoCk@BlencoFalls	Y	1/10/1960		56.8	226	4			
WT	Herbert	116011A	Millstream@Ravenshoe	Y	18/07/1960		57	89	37.6			
WT	Herbert	116012A	CameronCk@8.7km	Y	1/10/1961		55.8	360	8.2			
WT	Herbert	116013A	Millstream@ArcherCk	Y	24/12/1961		55.6	308	13.2			
WT	Herbert	116014A	WildR@SilverValley	Y	1/12/1961		55.6	591	283.1			

Region	Basin	Gauge number	DNRM Gauges	Open	Start	End	Record Length (years)	Area (Km2)	DTM (km)	Obs	PD	FD
WT	Herbert	116015A	BlunderCk@Wooroora	Y	20/10/1966		50.7	127	36.8			
WT	Herbert	116016A	RuddCk@Gunnawarra	Y	1/10/1970		46.8	1450	10			
WT	Herbert	116017A	StoneR@RunningCk	Y	30/06/1970		47	157	30			

7) Appendix 3: User guide for the Flow Indicator Excel tool

Introduction

This section provides an overview of how to use the flow indicator calculation tool. The tool itself works across multiple worksheets to integrate the rainfall and flow data, to calculate the final score.

General notes

Cells in blue can be edited by the user. For normal use with no changes to the current parameter settings, the user would

1. Overwrite the flow data and rainfall data in the "Data" worksheet.
2. Press F9 to perform a recalculation
3. Go to the "report" worksheet to see the results

The notes worksheet

The notes worksheet is where all the global parameters for the tool are set and where users can alter parameter settings if desired (Figure 7-1).

Reporting year month start:

The tool is based on an annual reporting cycle and since the reef report card reporting cycle is based on financial year, the default value for start month is 7. This cell can be changed (to any number from 1-12) to test an alternative annual cycle for reporting.

Flow metrics:

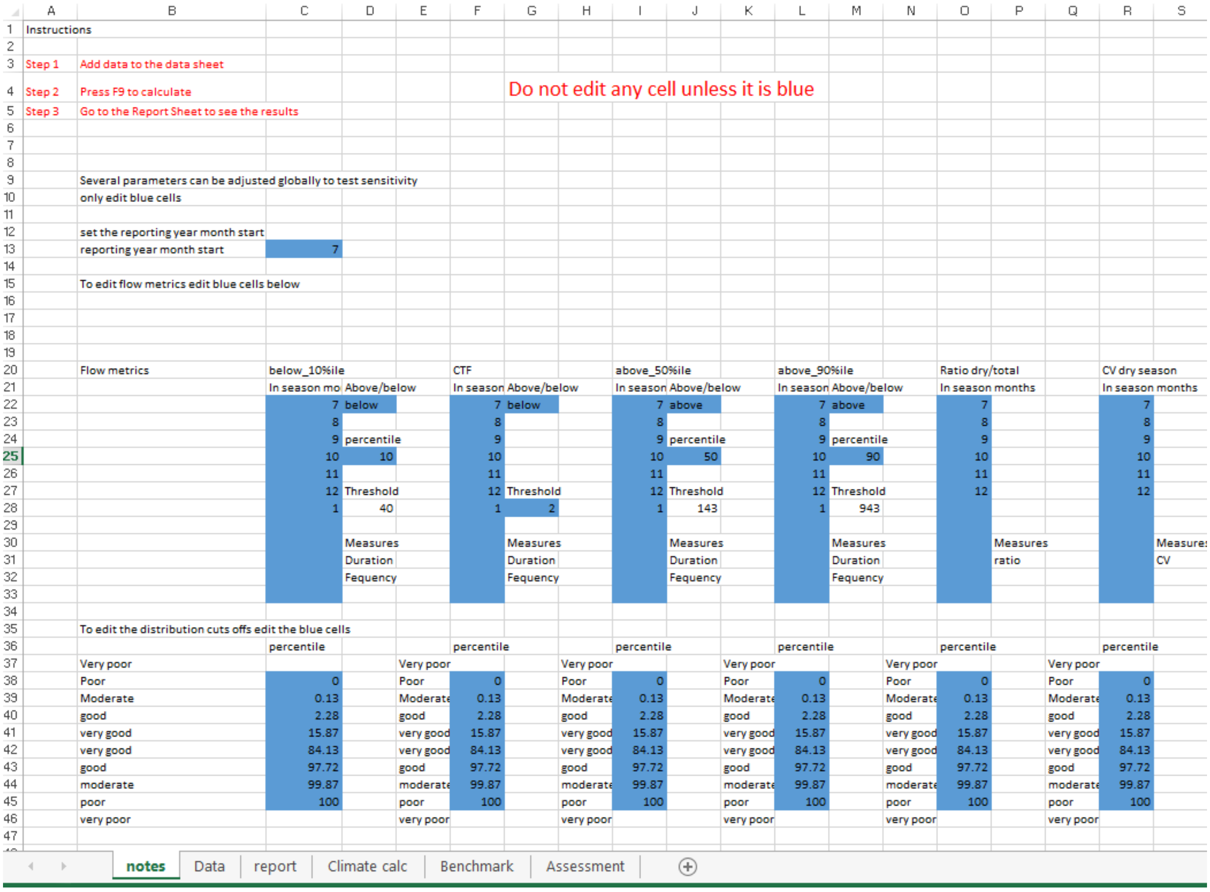
For each of the flow metrics the months over which the metric should be applied is the first column. For example the flow below 10th%ile is a dry season metrics and the default months to consider are July-January. For another site, it may be more appropriate to use June-December.

The flow threshold as a percentile value can also be altered if desired.

The flow threshold approach "above/below" can be altered to switch the metric type from an above threshold approach to a below threshold approach.

Distribution cutoffs:

The distribution cutoffs for setting up the scoring table benchmarks can be edited. The values are percentiles.

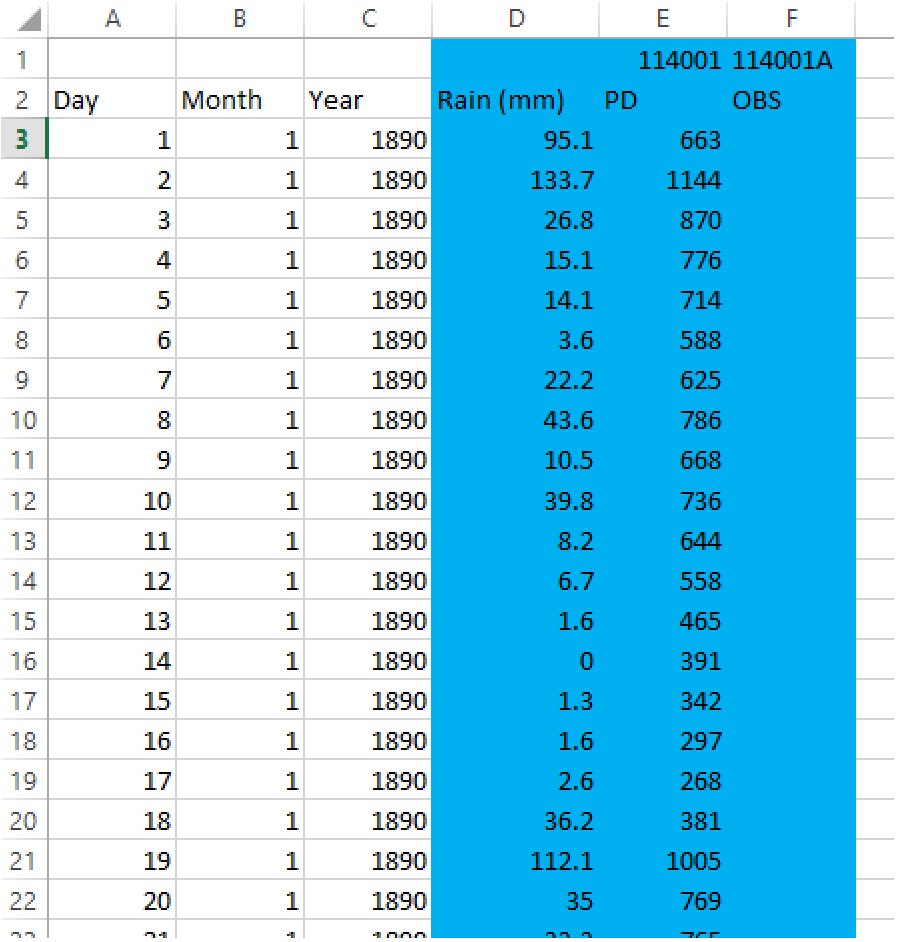


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	Instructions																		
2																			
3	Step 1	Add data to the data sheet																	
4	Step 2	Press F9 to calculate					Do not edit any cell unless it is blue												
5	Step 3	Go to the Report Sheet to see the results																	
6																			
7																			
8																			
9		Several parameters can be adjusted globally to test sensitivity																	
10		only edit blue cells																	
11																			
12		set the reporting year month start																	
13		reporting year month start	7																
14																			
15		To edit flow metrics edit blue cells below																	
16																			
17																			
18																			
19																			
20		Flow metrics	below_10%ile			CTF			above_50%ile			above_90%ile			Ratio dry/total			CV dry season	
21			In season mo	Above/below		In season	Above/below		In season	Above/below		In season	Above/below		In season months			In season months	
22			7	below		7	below		7	above		7	above		7			7	
23			8			8			8			8			8			8	
24			9	percentile		9			9	percentile		9	percentile		9			9	
25			10	10		10			10	50		10	90		10			10	
26			11			11			11			11			11			11	
27			12	Threshold		12	Threshold		12	Threshold		12	Threshold		12			12	
28			1	40		1	2		1	143		1	943						
29																			
30				Measures			Measures			Measures			Measures			Measures			Measure
31				Duration			Duration			Duration			Duration			ratio			CV
32				Fequency			Fequency			Fequency			Fequency						
33																			
34																			
35		To edit the distribution cuts offs edit the blue cells																	
36			percentile			percentile			percentile			percentile			percentile			percentile	
37		Very poor			Very poor			Very poor			Very poor			Very poor			Very poor		
38		Poor	0		Poor	0		Poor	0		Poor	0		Poor	0		Poor	0	
39		Moderate	0.13		Moderate	0.13		Moderate	0.13		Moderate	0.13		Moderate	0.13		Moderate	0.13	
40		good	2.28		good	2.28		good	2.28		good	2.28		good	2.28		good	2.28	
41		very good	15.87		very good	15.87		very good	15.87		very good	15.87		very good	15.87		very good	15.87	
42		very good	84.13		very good	84.13		very good	84.13		very good	84.13		very good	84.13		very good	84.13	
43		good	97.72		good	97.72		good	97.72		good	97.72		good	97.72		good	97.72	
44		moderate	99.87		moderate	99.87		moderate	99.87		moderate	99.87		moderate	99.87		moderate	99.87	
45		poor	100		poor	100		poor	100		poor	100		poor	100		poor	100	
46		very poor			very poor			very poor			very poor			very poor			very poor		
47																			

Figure 7-1: Screenshot of the "notes" sheet in the flow indicator tool. Cells in blue can be modified by the user to alter parameters of interest, such as the start of the water year (reporting year month start) or the months over which flow metrics are calculated etc.

The "Data" worksheet

The data worksheet is where the input rainfall data, pre-development (benchmark) and observed flow data is loaded. It is critical that this data be loaded on the correct rows, which corresponds to the date values in columns A, B and C. Regardless of the number of locations used to characterise rainfall, the rainfall input data needs to be a single column of integrated rainfall.

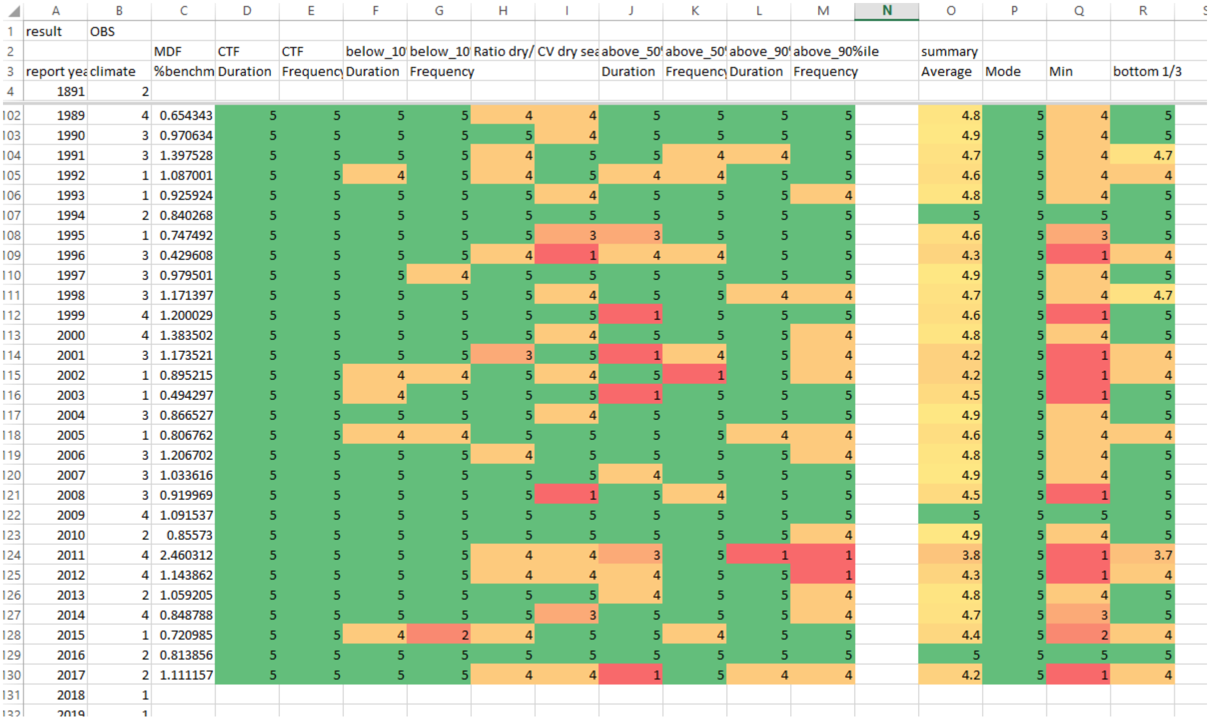


	A	B	C	D	E	F
1					114001	114001A
2	Day	Month	Year	Rain (mm)	PD	OBS
3	1	1	1890	95.1	663	
4	2	1	1890	133.7	1144	
5	3	1	1890	26.8	870	
6	4	1	1890	15.1	776	
7	5	1	1890	14.1	714	
8	6	1	1890	3.6	588	
9	7	1	1890	22.2	625	
10	8	1	1890	43.6	786	
11	9	1	1890	10.5	668	
12	10	1	1890	39.8	736	
13	11	1	1890	8.2	644	
14	12	1	1890	6.7	558	
15	13	1	1890	1.6	465	
16	14	1	1890	0	391	
17	15	1	1890	1.3	342	
18	16	1	1890	1.6	297	
19	17	1	1890	2.6	268	
20	18	1	1890	36.2	381	
21	19	1	1890	112.1	1005	
22	20	1	1890	35	769	

Figure 7-2: Screenshot of the Data worksheet showing the cells that can be changed by the user. Column D, the Rainfall data, needs to be a single integrated variable regardless of number of sites used for the rainfall data chosen by the user.

The "Report" worksheet

The report worksheet is where the results are displayed for all metrics and the different aggregation approaches for the catchments (Figure 7-3).



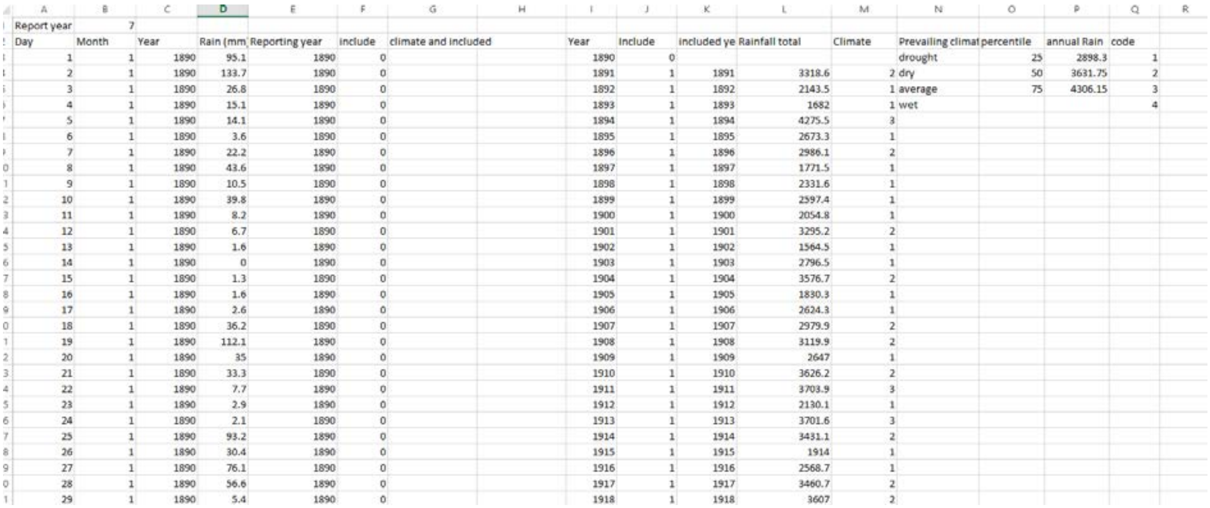
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	result	OBS																
2			MDF	CTF	CTF	below_10	below_10	Ratio dry/	CV dry sea	above_50	above_50	above_90	above_90%ile		summary			
3	report yea	climate	%benchm	Duration	Frequency	Duration	Frequency			Duration	Frequency	Duration	Frequency		Average	Mode	Min	bottom 1/3
4	1891	2																
102	1989	4	0.654343	5	5	5	5	4	4	5	5	5	5		4.8	5	4	5
103	1990	3	0.970634	5	5	5	5	5	4	5	5	5	5		4.9	5	4	5
104	1991	3	1.397528	5	5	5	5	4	5	5	4	4	5		4.7	5	4	4.7
105	1992	1	1.087001	5	5	4	5	4	5	4	4	5	5		4.6	5	4	4
106	1993	1	0.925924	5	5	5	5	5	4	5	5	5	4		4.8	5	4	5
107	1994	2	0.840268	5	5	5	5	5	5	5	5	5	5		5	5	5	5
108	1995	1	0.747492	5	5	5	5	5	3	3	5	5	5		4.6	5	3	5
109	1996	3	0.429608	5	5	5	5	4	1	4	4	5	5		4.3	5	1	4
110	1997	3	0.979501	5	5	5	4	5	5	5	5	5	5		4.9	5	4	5
111	1998	3	1.171397	5	5	5	5	5	4	5	5	4	4		4.7	5	4	4.7
112	1999	4	1.200029	5	5	5	5	5	5	1	5	5	5		4.6	5	1	5
113	2000	4	1.383502	5	5	5	5	5	4	5	5	5	4		4.8	5	4	5
114	2001	3	1.173521	5	5	5	5	3	5	1	4	5	4		4.2	5	1	4
115	2002	1	0.895215	5	5	4	4	5	4	5	1	5	4		4.2	5	1	4
116	2003	1	0.494297	5	5	4	5	5	5	1	5	5	5		4.5	5	1	5
117	2004	3	0.866527	5	5	5	5	5	4	5	5	5	5		4.9	5	4	5
118	2005	1	0.806762	5	5	4	4	5	5	5	5	4	4		4.6	5	4	4
119	2006	3	1.206702	5	5	5	5	4	5	5	5	5	4		4.8	5	4	5
120	2007	3	1.033616	5	5	5	5	5	5	4	5	5	5		4.9	5	4	5
121	2008	3	0.919969	5	5	5	5	5	1	5	4	5	5		4.5	5	1	5
122	2009	4	1.091537	5	5	5	5	5	5	5	5	5	5		5	5	5	5
123	2010	2	0.85573	5	5	5	5	5	5	5	5	5	4		4.9	5	4	5
124	2011	4	2.460312	5	5	5	5	4	4	3	5	1	1		3.8	5	1	3.7
125	2012	4	1.143862	5	5	5	5	4	4	4	5	5	1		4.3	5	1	4
126	2013	2	1.059205	5	5	5	5	5	5	4	5	5	4		4.8	5	4	5
127	2014	4	0.848788	5	5	5	5	5	3	5	5	5	4		4.7	5	3	5
128	2015	1	0.720985	5	5	4	2	4	5	5	4	5	5		4.4	5	2	4
129	2016	2	0.813856	5	5	5	5	5	5	5	5	5	5		5	5	5	5
130	2017	2	1.111157	5	5	5	5	4	4	1	5	4	4		4.2	5	1	4
131	2018	1																
132	2019	1																

Figure 7-3: Screenshot of the report worksheet showing the results of all of the metrics and the four aggregation approaches for the catchment

The "Climate Calc" worksheet

The climate calc worksheet copies the rainfall data from the "Data" tab and then determines the percentile distribution on an annual basis (Figure 7-4).

To alter the number of prevailing seasons (for example where the benchmark period is short) one can make the climate code for all prevailing climates the same (e.g. 1) so that all years are treated as having the same prevailing climate.

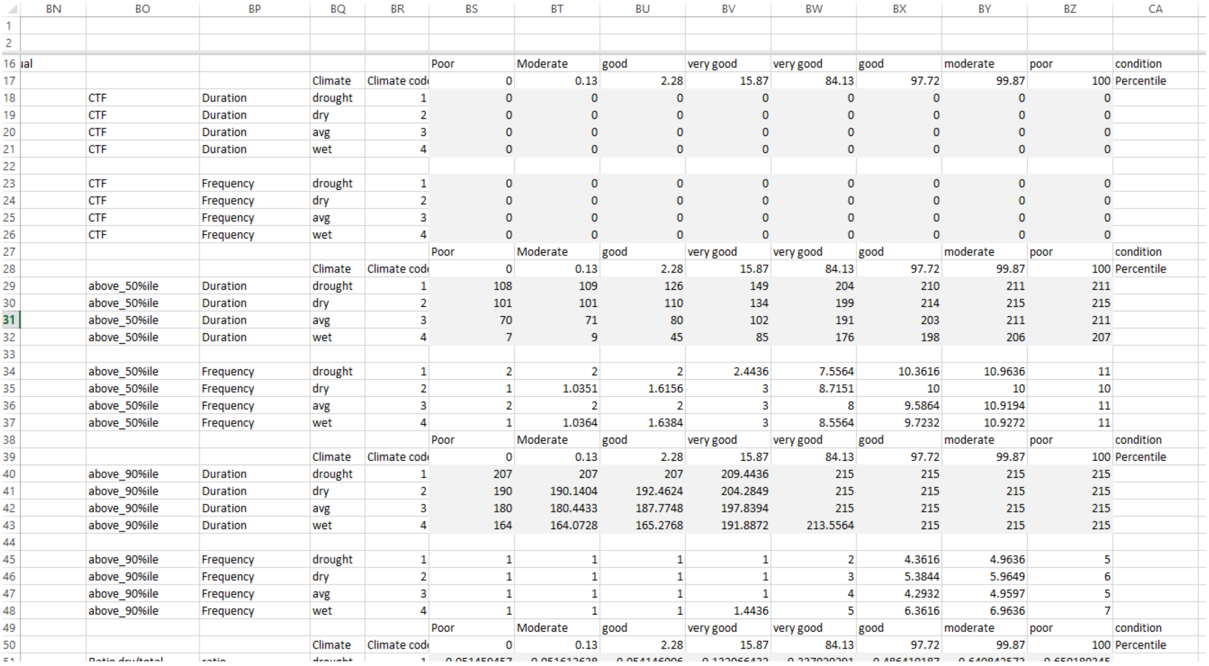


A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Report year	7																
Day	Month	Year	Rain (mm	Reporting year	include	climate and included		Year	Include	included ye	Rainfall total	Climate	Prevailing climat	percentile	annual Rain	code	
1	1	1890	95.1	1890	0			1890	0				drought	25	2898.3	1	
2	1	1890	133.7	1890	0			1891	1	1891	3318.6	2	dry	50	3631.75	2	
3	1	1890	26.8	1890	0			1892	1	1892	2143.5	1	average	75	4306.15	3	
4	1	1890	15.1	1890	0			1893	1	1893	1682	1	wet			4	
5	1	1890	14.1	1890	0			1894	1	1894	4275.5	3					
6	1	1890	3.6	1890	0			1895	1	1895	2673.3	1					
7	1	1890	22.2	1890	0			1896	1	1896	2986.1	2					
8	1	1890	43.6	1890	0			1897	1	1897	1771.5	1					
9	1	1890	10.5	1890	0			1898	1	1898	2331.6	1					
10	1	1890	39.8	1890	0			1899	1	1899	2597.4	1					
11	1	1890	8.2	1890	0			1900	1	1900	2054.8	1					
12	1	1890	6.7	1890	0			1901	1	1901	3295.2	2					
13	1	1890	1.6	1890	0			1902	1	1902	1564.5	1					
14	1	1890	0	1890	0			1903	1	1903	2796.5	1					
15	1	1890	1.3	1890	0			1904	1	1904	3576.7	2					
16	1	1890	1.6	1890	0			1905	1	1905	1830.3	1					
17	1	1890	2.6	1890	0			1906	1	1906	2624.3	1					
18	1	1890	36.2	1890	0			1907	1	1907	2979.9	2					
19	1	1890	112.1	1890	0			1908	1	1908	3119.9	2					
20	1	1890	35	1890	0			1909	1	1909	2647	1					
21	1	1890	33.3	1890	0			1910	1	1910	3626.2	2					
22	1	1890	7.7	1890	0			1911	1	1911	3703.9	3					
23	1	1890	2.9	1890	0			1912	1	1912	2130.1	1					
24	1	1890	2.1	1890	0			1913	1	1913	3701.6	3					
25	1	1890	93.2	1890	0			1914	1	1914	3431.1	2					
26	1	1890	30.4	1890	0			1915	1	1915	1914	1					
27	1	1890	76.1	1890	0			1916	1	1916	2568.7	1					
28	1	1890	56.6	1890	0			1917	1	1917	3460.7	2					
29	1	1890	5.4	1890	0			1918	1	1918	3607	2					

Figure 7-4: Screenshot of the climate calc worksheet to determine the percentile distribution on an annual basis

The “Benchmark” worksheet

The benchmark worksheet (Figure 7-5) is where the flow metrics are calculated for the benchmark flow series (from the Data worksheet). The summary benchmark tables are in columns BS-BZ, these are used to determine the scores for the observed data.



	BN	BO	BP	BQ	BR	BS	BT	BU	BV	BW	BX	BY	BZ	CA
1														
2														
16	al					Poor	Moderate	good	very good	very good	good	moderate	poor	condition
17				Climate	Climate cod	0	0.13	2.28	15.87	84.13	97.72	99.87	100	Percentile
18		CTF	Duration	drought	1	0	0	0	0	0	0	0	0	
19		CTF	Duration	dry	2	0	0	0	0	0	0	0	0	
20		CTF	Duration	avg	3	0	0	0	0	0	0	0	0	
21		CTF	Duration	wet	4	0	0	0	0	0	0	0	0	
22														
23		CTF	Frequency	drought	1	0	0	0	0	0	0	0	0	
24		CTF	Frequency	dry	2	0	0	0	0	0	0	0	0	
25		CTF	Frequency	avg	3	0	0	0	0	0	0	0	0	
26		CTF	Frequency	wet	4	0	0	0	0	0	0	0	0	
27						Poor	Moderate	good	very good	very good	good	moderate	poor	condition
28				Climate	Climate cod	0	0.13	2.28	15.87	84.13	97.72	99.87	100	Percentile
29		above_50%ile	Duration	drought	1	108	109	126	149	204	210	211	211	
30		above_50%ile	Duration	dry	2	101	101	110	134	199	214	215	215	
31		above_50%ile	Duration	avg	3	70	71	80	102	191	203	211	211	
32		above_50%ile	Duration	wet	4	7	9	45	85	176	198	206	207	
33														
34		above_50%ile	Frequency	drought	1	2	2	2	2.4436	7.5564	10.3616	10.9636	11	
35		above_50%ile	Frequency	dry	2	1	1.0351	1.6156	3	8.7151	10	10	10	
36		above_50%ile	Frequency	avg	3	2	2	2	3	8	9.5864	10.9194	11	
37		above_50%ile	Frequency	wet	4	1	1.0364	1.6384	3	8.5564	9.7232	10.9272	11	
38						Poor	Moderate	good	very good	very good	good	moderate	poor	condition
39				Climate	Climate cod	0	0.13	2.28	15.87	84.13	97.72	99.87	100	Percentile
40		above_90%ile	Duration	drought	1	207	207	207	209.4436	215	215	215	215	
41		above_90%ile	Duration	dry	2	190	190.1404	192.4624	204.2849	215	215	215	215	
42		above_90%ile	Duration	avg	3	180	180.4433	187.7748	197.8394	215	215	215	215	
43		above_90%ile	Duration	wet	4	164	164.0728	165.2768	191.8872	213.5564	215	215	215	
44														
45		above_90%ile	Frequency	drought	1	1	1	1	1	2	4.3616	4.9636	5	
46		above_90%ile	Frequency	dry	2	1	1	1	1	3	5.3844	5.9649	6	
47		above_90%ile	Frequency	avg	3	1	1	1	1	4	4.2932	4.9597	5	
48		above_90%ile	Frequency	wet	4	1	1	1	1.4436	5	6.3616	6.9636	7	
49						Poor	Moderate	good	very good	very good	good	moderate	poor	condition
50				Climate	Climate cod	0	0.13	2.28	15.87	84.13	97.72	99.87	100	Percentile

Figure 7-5: Screenshot of the Benchmark worksheet where benchmarks of flow metrics are calculated for each climate period

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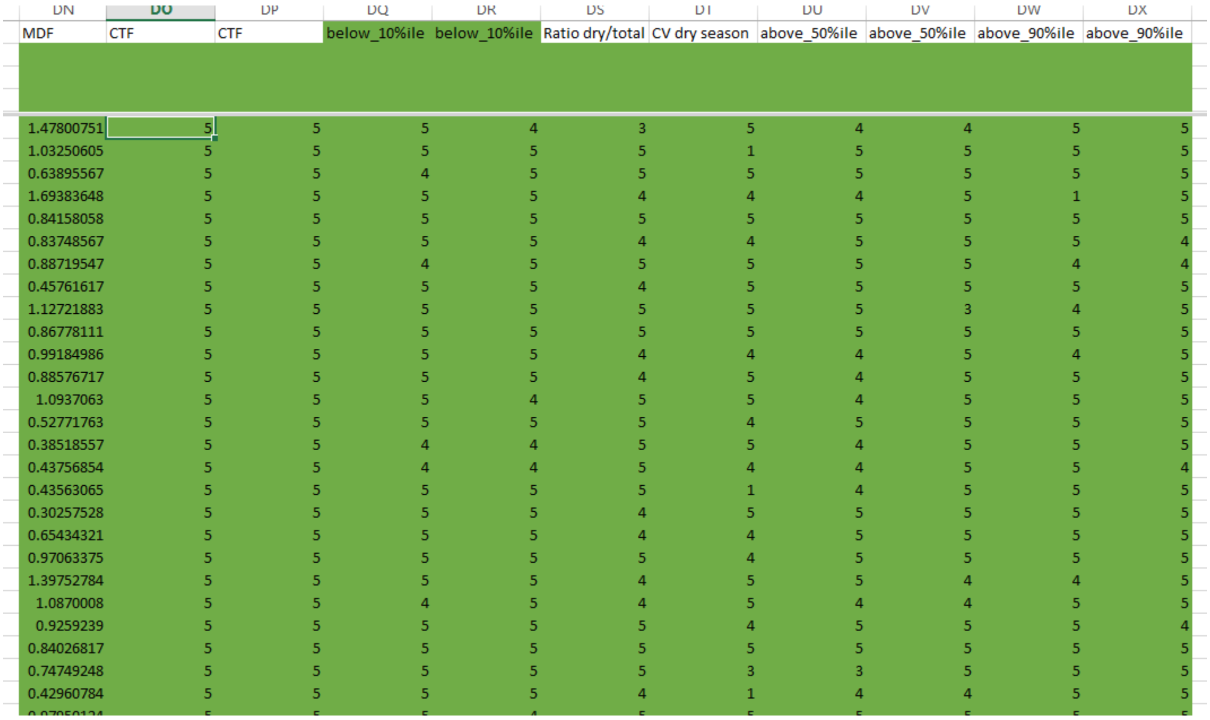
The “Assessment” worksheet

The assessment worksheet (Figure 7-6) is where the flow metrics for the observed flow record are calculated, compared with the distribution from the benchmark worksheet and a score is allocated.



DN	DO	DP	DQ	DR	DS	DT	DU	DV	DW	DX
MDF	CTF	CTF	below_10%ile	below_10%ile	Ratio dry/total	CV dry season	above_50%ile	above_50%ile	above_90%ile	above_90%ile
1.47800751	5	5	5	4	3	5	4	4	5	5
1.03250605	5	5	5	5	5	1	5	5	5	5
0.63895567	5	5	4	5	5	5	5	5	5	5
1.69383648	5	5	5	5	4	4	4	5	1	5
0.84158058	5	5	5	5	5	5	5	5	5	5
0.83748567	5	5	5	5	4	4	5	5	5	4
0.88719547	5	5	4	5	5	5	5	5	4	4
0.45761617	5	5	5	5	4	5	5	5	5	5
1.12721883	5	5	5	5	5	5	5	3	4	5
0.86778111	5	5	5	5	5	5	5	5	5	5
0.99184986	5	5	5	5	4	4	4	5	4	5
0.88576717	5	5	5	5	4	5	4	5	5	5
1.0937063	5	5	5	4	5	5	4	5	5	5
0.52771763	5	5	5	5	5	4	5	5	5	5
0.38518557	5	5	4	4	5	5	4	5	5	5
0.43756854	5	5	4	4	5	4	4	5	5	4
0.43563065	5	5	5	5	5	1	4	5	5	5
0.30257528	5	5	5	5	4	5	5	5	5	5
0.65434321	5	5	5	5	4	4	5	5	5	5
0.97063375	5	5	5	5	5	4	5	5	5	5
1.39752784	5	5	5	5	4	5	5	4	4	5
1.0870008	5	5	4	5	4	5	4	4	5	5
0.9259239	5	5	5	5	5	4	5	5	5	4
0.84026817	5	5	5	5	5	5	5	5	5	5
0.74749248	5	5	5	5	5	3	3	5	5	5
0.42960784	5	5	5	5	4	1	4	4	5	5

Figure 7-6: Screenshot of the Assessment worksheet