Classification and comparison of natural and altered flow regimes to support an Australian trial of the Ecological Limits of Hydrologic Alteration (ELOHA) framework

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KEYWORDS

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ABSTRACT

The Ecological Limits of Hydrologic Alteration (ELOHA) is a new framework designed to develop environmental flow prescriptions for many streams and rivers in a user-defined geographic region or jurisdiction. This study presents hydrologic classifications and comparisons of natural and altered flows in southeast Queensland, Australia, to support the ecological steps of a field trial of the ELOHA framework. We extended existing protocols for flow classification by assessing the stability of flow classes. Model-based clustering distinguished six Reference classes (based on modelled predevelopment flow data) and five Historic classes (based on stream gauge data). The principal flow regime change was loss of some of the original (natural) flow diversity accompanied by the emergence of a perennial flow class in the Historic classification comprised mostly of gauges with flow regimes influenced by dams. However, similarities between Reference and Historic classifications indicate that hydrologic changes in southeast Queensland have not totally obscured Reference (pre-development) characteristics. Duration of low flow spells has undergone the greatest absolute change from Reference values.

Dams had substantial but variable impacts on downstream flow regimes. Each dam created a unique downstream flow signature, indicating that environmental flow guidance for each regulated river must be tailored to the particulars of flow alterations, the associated ecological impacts and the desired future ecological state of the aquatic ecosystem. Other stressors were implicated in flow regime change, highlighting the need to consider the potential influence of factors other than prominent water infrastructure on flow regime alterations and associated ecological responses.

INTRODUCTION

Land use change, river impoundment, surface and groundwater abstraction and artificial inter/intra-basin water transfers profoundly alter the natural flow regimes of rivers and streams (Nilsson *et al*., 2005; Lehner *et al*., 2011). A recent synthesis of threats to the world's rivers has found that impoundments and alteration of river flows threaten aquatic biodiversity and ecosystem services by directly degrading and reducing river and floodplain habitat, with 65% of global river discharge and aquatic habitat under moderate to high threat (Vörösmarty *et al*., 2010). Protection and restoration of threatened and damaged river ecosystems through provision of environmental flows are now cornerstones of river and catchment management, but remain a global challenge given increasing human and climatic pressures on freshwater resources (Bernhardt and Palmer 2007; Palmer *et al*., 2008). Environmental flows can be defined as the "quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems" (Brisbane Declaration, 2007). Although the environmental flow requirements of species and ecosystems have been estimated for numerous streams/rivers in over 50 countries (Tharme, 2003), thousands of systems remain unstudied, or at best are managed with very little understanding of their individual or common ecological water requirements (Arthington *et al*., 2006).

The Ecological Limits of Hydrologic Alteration (ELOHA) is a new framework designed to develop environmental flow prescriptions for many streams/rivers in a user defined geographic region or jurisdiction (Poff *et al*., 2010). This framework takes into account the hydrologic, geomorphic and ecological similarities and difference among rivers, and seeks to quantify their patterns of response to flow regime alterations as the basis for development of environmental flow guidelines or quantitative rules for each particular type (flow class) of stream or river (Arthington *et al*., 2006). In the ELOHA framework a flow class is a group of sites with similar ecologically relevant hydrologic characteristics. If flow alteration–ecological response relationships prove to be distinctive for particular types of streams or rivers, then it may be possible to extrapolate environmental flow relationships and rules developed from studies on streams representative of each flow class to all members of that class. Applied across a region with several distinctive river classes, the ELOHA approach has potential to reduce the demand for numerous individual environmental flow assessments. A scientifically acceptable process for extrapolation of environmental flow rules or management standards from river to river has been a frequent request from water managers (Arthington, 2012).

The first step in applications of the ELOHA framework is flow classification as a means to understand how natural flow regimes of a chosen region vary geographically and how they have been modified by human activity (Poff *et al*., 2010). Several studies have presented flow classifications to underpin subsequent ELOHA applications (Belmar *et al*., 2011; Reidy Liermann *et al*., 2012; Zhang *et al.*, 2012). These examples provide an array of approaches and statistical methods to classify hydrogeomorphic conditions and flow regimes for regions varying from large river basins (Huai River, China; Segura Basin, Spain) to entire provinces (Washington State, USA). The present study complements these analyses through development of flow classifications and novel comparisons of natural and altered flow regimes in southeast Queensland, Australia, as the basis for a field trial of the ELOHA framework.

The water resources of southeast Queensland are under pressure from intermittent drought, population increases, and predicted future climate change, including reduced rainfall but more frequent extreme flood events (CSIRO, 2007). Strategies to secure reliable supplies of fresh water for urban and peri-urban populations, industry, and agriculture across southeast Queensland have relied on impoundments, weirs and barrages, inter-basin transfers and groundwater abstraction. Hence there exists an array of opportunities to study the effects of water infrastructure and management practices on stream and river flow regimes, linked to the ecological consequences of altered flow patterns, especially downstream of dams. A previous study involving a large impoundment, Lake Wivenhoe situated on the Brisbane River, has provided guidance on environmental flows (Arthington *et al*., 1999; Greer *et al*., 1999), but the majority of impounded systems in the region have received only cursory assessment of their ecological condition in relation to water infrastructure and flow regulation (Brizga *et al*., 2006).

The objectives of this paper are to: (1) identify flow regime classes in southeast Queensland based on classification of 35 flow metrics representing the five key facets of the flow regime (Poff *et al*., 1997), (2) identify a subset of flow metrics that best discriminate the flow classes identified (Olden and Poff, 2003), (3) characterise the types and degrees of flow regime alteration that have arisen as a consequence of dams and water management practices in the study area, and (4) identify major gradients of hydrologic alteration across the study area to support development of hydro-ecological relationships as proposed in the ELOHA framework (Poff *et al*., 2010). Individual flow classifications are presented for two flow scenarios: a modelled pre-development (near natural) flow scenario and a historic flow scenario based on gauged records of stream flow. The classification based on the modelled pre-development flow data allows the characteristics and variability of near-natural flow regimes within the study area to be described, while the classification based on the historic flow data is intended to highlight changes in the flow regimes of localities affected by dams, weirs and other factors such as land use change. Time series of pre-dam flow data were insufficient to undertake before-after comparisons of flow regimes at most localities in the region, hence the reliance on modelled pre-development data, now a common practice in studies of this type (Olden *et al*., 2012). Comparison of the two classifications has the potential to reveal the types and degrees of flow regime alteration and any shifts of stream sites into a different flow class (e.g. Zhang *et al*., 2012). These flow classifications and subsequent quantification of flow regime alterations represent the first step in the ELOHA framework - the building of the 'hydrological foundation' to underpin analysis of hydro-ecological relationships in rivers with natural flow regimes and in rivers where flow regimes have been altered by human activities. Ecological responses to flow variability and to flow regime alterations across southeast Queensland, and their implications for application of the science component of the ELOHA framework, are not addressed in this study.

METHODS

Study area

The river systems of southeast Queensland are dominated by perennial, intermittent and highly intermittent systems (Kennard *et al*., 2010a). Seven major river catchments with a total area of 32 000 km^2 occur within the region (Figure 1; Table I). The climate of the region is sub-tropical (Pusey *et al*., 2004) and discharge generally peaks in late summer to early autumn, with periods of low discharge occurring from late winter to early spring (August-November). The occasional influence of temperate weather systems that produce winter rain in southern Australia may produce significant rainfall in southeast Queensland from autumn to mid-winter (Pusey *et al*., 2004). The occurrence and intensity of rainfall is irregular and hence the flow regimes of rivers and streams in the region are highly variable (Pusey *et al*., 2004). A distinct longitudinal (east-west) rainfall gradient exists in southeast Queensland, with average annual rainfall varying from 1400 mm on the coast to 800 mm in the western part of the study area (Bridges *et al*., 1990; Young and Dillewaard, 1999). Coastal (eastern) catchments therefore have higher mean annual runoff per unit of catchment area than inland (western) catchments.

Twenty-four dams with a crest height greater than 15 m occur within southeast Queensland (ANCOLD, 2002). Many of these dams were constructed in the early to mid-1970s and vary considerably in volume and proportion of mean annual runoff stored (ANCOLD, 2002; Table I). The total storage capacity of dams and weirs is approximately 38% of the combined (natural) mean annual runoff of the principal river catchments of the study area (Table I).

Flow data and metrics

Flow data were obtained from the Queensland Department of Environment and Resource Management as modelled pre-development data derived from an "Integrated Quantity Quality Model" (IQQM, Simons *et al*., 1996) and stream gauge data (Appendix 1). Flow data were arranged by water years (October-September) to avoid splitting the summer flood season across consecutive years (Gordon *et al*., 2005).

IQQM data represented reference (near natural) condition and was used to produce a pre-development flow classification. Flow data were obtained for 88 IQQM nodes, representing specific locations in the river network often corresponding to currently operating or decommissioned gauges and tributary junctions. All IQQM nodes had a minimum 100 years of continuous flow record within the period 1889-2003 and all IQQM nodes were used in the pre-development classification. Flow metrics calculated from IQQM pre-development flow data are designated *Reference metrics* and the classification based on Reference metrics is termed the *Reference classification*. Flow metrics calculated from gauged flow data are designated *Historic metrics* and the classification based on Historic metrics is termed the *Historic classification*.

Stream gauge data represent historic flow conditions, i.e. the actual discharge recorded through time at an individual stream gauge, which may be influenced by changes to land use, water resource development (dams and weirs) and unsupplemented extraction, i.e. extraction of natural river flows. Gauge data were used to produce a classification of these actual (Historic) flow regimes. Fifty-nine gauges were used in the Historic classification. Our criteria for inclusion of gauges in the Historic classification were a minimum of fifteen years of flow record within the period 1975-2000, not necessarily concurrent (Kennard *et al*., 2010b), and missing periods of flow record could be infilled adequately (Nature Conservancy, 2009). The flow regimes of seven gauges used in the Historic classification were influenced by dams (Appendix 1). Five of these gauges commenced operation after dam construction and hence the entire flow record was considered for metric calculation. The flow records of two currently operating gauges included pre-dam and post-dam flow regimes. Flow metrics for these gauges were calculated using post-dam flow data only. The mean length of flow record (± standard deviation) for gauges included in the Historic classification was 24.7 ± 6.5 years.

Flow metrics available in the Indicators of Hydrologic Alteration (IHA) software package were used to characterise Reference and Historic flow regimes (Nature Conservancy, 2009; Table II). These metrics represent the five ecologically relevant components of the flow regime and minimise metric redundancy (Poff *et al*., 1997; Olden and Poff, 2003; Poff *et al*., 2010). The Median of Annual Maximum Flows and Specific Mean Annual Maximum Flows were also calculated to better represent high flow conditions (Olden and Poff, 2003). The magnitude of floods with Average Recurrence Intervals (ARIs) of 1, 2 and 10 years were also calculated as potentially important indicators of frequency of inundation for riparian vegetation (Pettit *et al*., 2001; Wintle and Kirkpatrick, 2007) and other ecological processes. Colwell's Indices were also calculated as indicators of flow predictability, constancy and seasonality (Colwell, 1974). Since it is not necessary to use the entire IHA metric set for flow classification (Olden and Poff, 2003) the number of metrics representing flow magnitude was reduced by excluding mean monthly discharge metrics for February, April, June, August, October and December, with data for the remaining months adequately representing seasonal flow magnitudes. Magnitude metrics were standardised by upstream catchment area to downweight the influence of these metrics on the Reference and Historic classifications (Kennard *et al*., 2010a). The final suite of 35 minimally redundant metrics described facets of the flow regime known to be both ecologically relevant from previous studies (Pusey *et al*., 1993; Mackay *et al*., 2003; Kennard *et al*., 2007), sensitive to hydrologic alterations caused by human activities (Richter *et al*., 1996; Bunn and Arthington, 2002) and potentially amenable to management through ecologically sensitive dam operations and constraints on abstraction. Flow metrics were calculated using the Time Series Analysis module of the River Analysis Package (Marsh *et al*., 2003).

Statistical methods

Principal components analysis (PCA) based on a correlation matrix was used to investigate redundancy in Reference and Historic metric datasets (Olden and Poff, 2003). Retention of components was determined by inspection of scree plots, eigenvalues and metric loadings on individual principal components.

Classification was undertaken using model-based hierarchical agglomerative clustering based on Gaussian finite mixture models, as implemented in the Mclust package for R (Fraley and Raftery, 2008; R Development Core Team, 2010). This is a soft classification procedure where each IQQM node or gauge (site) is assigned a probability of membership for each of the classes identified by the classification (Olden *et al*., 2012). Model-based clustering assumes that the observed data come from a population comprised of several subpopulations (Raftery and Dean, 2006). In the context of flow classification each subpopulation represents a flow class. Each subpopulation is modelled separately with probability density functions and hence the entire population is comprised of a mixture of models. We used models suitable for multidimensional data (Fraley and Raftery, 2008). The optimal classification is the model and number of clusters that maximises the Bayes Information Criterion (BIC). We used the Hubert-

Arabie adjusted Rand Index to compare Reference and Historic classifications (Kennard *et al*., 2010a). This index is a measure of agreement between two classifications. The index uses a contingency table approach to determine how frequently pairs of objects are placed in the same cluster (Steinley, 2004). The value of the index ranges between 0 (no agreement between any pairs of objects) and 1 (complete agreement).

The clustvarsel package for R was used to identify a subset of flow metrics in which all flow metrics contain classification information (Raftery and Dean, 2006; Dean and Raftery, 2009). The clustvarsel algorithm first identifies a flow metric that has the most evidence of univariate clustering, then identifies the second clustering variable that has the most evidence of bivariate clustering and then selects the next clustering variable as the one that shows the best evidence for multivariate clustering, while including the first two variables (Raftery and Dean, 2006). The algorithm then searches for a flow metric to drop from the subset, based on change in Bayesian Information Criterion (BIC). The procedure is repeated until no metric can be found to include or drop from the classification (Raftery and Dean, 2006).

The stability of the flow classes identified in the Reference and Historic flow classifications was assessed using the clusterboot function in the fpc package for R (Hennig 2010). Stability refers to the capacity of a "valid" cluster to be retained in a classification if the original dataset is changed in a non-essential manner and re-classified (Hennig, 2007). We used the subset option in the fpc package for R (Hennig, 2010) to select 100 random subsets representing 75% of the original data, for both Reference and Historic data sets. Each subset was classified and each cluster was compared with the most similar cluster in the original classification using the Jaccard coefficient. This procedure was repeated and the mean Jaccard similarity for each cluster used as an index of flow class stability. Valid, stable classes should have a mean Jaccard similarity of 0.85 or greater (Hennig, 2010).

Assessing flow regime alteration in southeast Queensland

Three methods were used to assess the extent of flow regime alteration by dams and other factors in the study area. Firstly, the Gower dissimilarity coefficient (Gower, 1971) was used to compare Reference and Historic flow regimes. The Gower metric ranges from 0 to 1, where 1 indicates total dissimilarity in Reference and Historic flow regimes. These comparisons were limited to IQQM nodes with a corresponding stream gauge (n = 49). All 35 flow metrics were used to calculate the Gower coefficient.

Secondly, a random forest model was used to allocate gauges to Reference classes (Brieman, 2001). This analysis was limited to IQQM nodes with a corresponding stream gauge (n = 49). It was assumed that if there was little or no hydrologic change between Reference and

Historic regimes then the Reference random forest model should be able to predict the correct Reference class for an individual stream gauge, based on the Reference class of the corresponding IQQM node. A random subsample of predictor variables was used to determine splitting at each node for each tree. Functions within the randomForest package for R (Liaw and Weiner, 2009) were used to construct the random forest model. The number of flow metrics used at each split was determined using the tuneRF function. This function constructs random forests and compares the out-of-bag (OOB) error rate when the number of metrics used at each split is varied. One thousand trees were constructed (Breiman, 2001).

Thirdly, Reference and Historic values for each of the 35 flow metrics were compared to examine how individual flow metrics changed through time Change in individual flow metrics was expressed as the percentage difference of the Historic value from the Reference value. Selected metrics were then plotted to demonstrate gradients of flow alteration that could be tested for their ecological relevance in subsequent analyses.

RESULTS

Reference classification

PCA of Reference flow metrics explained 88.0% of the variation in the dataset with five components identified (not shown). As all metrics had loadings less than -0.5 and greater than 0.5 on at least one component, all metrics were retained for classification.

Classification of Reference metrics identified six Reference classes as the best solution (Appendix 1). The probability of class membership was greater than 99.5% for all IQQM nodes. All Reference classes had distinctly seasonal flow regimes with peak flows occurring in late summer (Figure 2a). Six flow metrics (as defined and abbreviated in Table II) were identified as best discriminating between Reference classes. These were MA1dayMin, MA1dayMax, MDF_Mar, MDF_Sep, MedAnnMax and MeanZeroDay (Figure 3). The principal gradient separating Reference classes was discharge magnitude, with classes 5 and 6 having substantially higher discharge magnitude per unit of catchment area than Reference classes 1-4 (Figure 3a-e). Reference classes 1-4 were similar hydrologically and differed principally in the mean number of zero flow days per year (Figure 3a-f).

Reference class 1 consisted of 26 tributary and main channel IQQM nodes from all river catchments in the study area (Appendix 1) and hence had a wide geographic distribution throughout southeast Queensland. The average number of zero flow days per year (MeanZeroDay) was low (median approximately 15 days per year, Figure 3f) as was discharge magnitude (Figure 3a-e). Peak discharge occurred in late summer (February) but high flows persisted into early autumn (Figure 2a). Reference class 2 consisted of 17 IQQM nodes located mostly in tributaries in the southern third of the study area (Figure 1; Appendix 1). The members of this flow class varied substantially in terms of the mean number of zero flow days per year (MeanZeroDay), although the median value for this metric was comparable to Reference class 1 (Figure 2f). The flow duration curve for Reference class 2 indicates that this flow class is intermittent (no flow 2% of the time, Figure 2b). Reference class 3 included five IQQM nodes from three different catchments, located mostly in the northern and southern extremities of the study area. The shape of the flow duration curve for Reference class 3 indicates flow perenniality and a greater contribution of base flow to total discharge when compared with other Reference classes (Figure 2b). This is due to groundwater input (Teewah Creek), large upstream catchment area (Mary River), and the occurrence of upstream tributaries and headwaters in high rainfall areas (Christmas Creek and Logan River).

IQQM nodes in Reference classes 4-6 show distinct geographic relationships in class membership. Reference class 4 included 17 IQQM nodes located in two river catchments. These nodes were located in the drier western parts of the Brisbane and Mary River catchments and had the lowest discharge per unit of catchment area of the six Reference classes (Figure 3f). The median number of zero flow days per year (60) was the highest of the six Reference classes. Reference class 5 included 18 IQQM nodes from coastal (eastern) parts of the study area, and was similar to Reference class 1 in having a late summer-early autumn dominated flow regime (Figure 2a). Reference class 6 consisted of five nodes from five different catchments. Three of the nodes in this class (South Maroochy River, Stanley River and Obi Obi Creek) have headwaters on adjacent mountain ranges (Conondale and Blackall Ranges) and are potentially influenced by similar rainfall patterns. Reference class 6 had the highest discharge magnitude per unit of catchment area but Reference class 5 had higher values for median annual maximum discharge (MedAnnMax, Figure 3b).

Historic classification

Preliminary PCA indicated that 143033 Oxley Creek was an outlier in terms of low spell duration (a single low flow spell equivalent to the length of the flow record used to calculate flow metrics) and this gauge was subsequently excluded (*n* for Historic classification = 58).

PCA of Historic metrics (not shown) extracted six components with eigenvalues greater than one, explaining 89.8% of the variation in the dataset. However, only one metric (JDMin) loaded on component 5 and only two metrics (JDMax and CVDaily) loaded on component 6. These components were therefore considered unreliable and not included in the Historic flow classification (Tabachnik and Fidell, 1989). Classification of Historic metrics identified five Historic classes (Appendix 1). Fifty-six of the fifty-eight gauges used in the classification had a probability of class membership of 100% while the remaining two gauges had a probability of class membership greater than 98.5%.

Six flow metrics were identified as best discriminating between Historic classes (Figure 3g-l). These flow metrics described discharge magnitude (MA1dayMin, MA30dayMin, ARI_10yr, MeanZeroDays), high spell duration (based on 25th percentile) and flow constancy. MA1dayMin and MeanZeroDays were amongst those metrics that best discriminated between Reference classes (Figure 3a,f). The seasonal pattern of flow varied substantially amongst the five Historic classes however most Historic classes had peaks in discharge in late summer and autumn (Figure 2c).

Historic class 1 consisted of six gauges in three river catchments. The flow regimes of five gauges in this class (Brisbane River, Logan River, Burnett Creek) were directly influenced by flow supplementation from dams. Consequently, this flow class had an artificially perennial flow regime (Figure 2d). Teewah Creek is the only gauge in this flow class not subjected to flow alteration but has a relatively high groundwater contribution to base flow (Brizga *et al*., 2005). The effect of flow regulation on Historic class 1 is further shown by the relatively high discharge during natural seasonal periods of low flow in late winter-spring (Figure 2c). Gauges in Historic class 1 had relatively high values for MA1dayMin and CONSTAN but relatively low values for ARI_1yr and ARI_10yr.

Historic class 2 included 13 gauges located mostly in the western part of the study area and in terms of class composition was comparable to Reference class 4 (Appendix 1). Peak discharge occurred in late summer but a substantial secondary discharge peak also occurred in late autumn (Figure 2c). Historic class 2 was characterised by a high percentage of zero flow days per year (median value 100 days, Figure 3j), high median value for high spell duration and very low values for metrics describing low discharge magnitude (see MA1dayMin and MA30dayMin in Figure 3g-h). Historic class 3 included 18 gauges distributed across the study area (Appendix 1). Peak discharge occurred in late summer but a secondary peak in discharge occurred in autumn (Figure 2c). Compared with other Historic classes this class was relatively invariant in terms of the six discriminating metrics (Figure 3). Flow recession was rapid at the low flow end of the flow duration curve (>90% percentile flow, Figure 2d).

Historic class 4 included 12 gauges located mostly in the southern half of the study area (Appendix 1). Members of Historic class 4 varied considerably for MeanZeroDay. Historic class 4 was similar to Historic class 3 in terms of MA1dayMin, MA90dayMin, HSDur and CONSTAN (Figure 3). Historic class 5 included nine gauges located in coastal parts of the study area and resembled Reference class 5 in terms of class membership (Appendix 1).

Discharge was distinctly late summer dominated (Figure 2c). Gauges in Historic class 5 had high discharge magnitude per unit catchment area and low discharge constancy (Figure 3g-l).

Cluster-wise stability of Reference and Historic classes

Assessment of cluster-wise stability showed that Reference class 6 was a highly stable cluster (mean Jaccard similarity >0.85) and Reference class 5 was a stable cluster (mean Jaccard similarity 0.75-0.85; Figure 4a). The mean Jaccard similarities for Reference class 1 (0.68) and Reference class 4 (0.62) indicated pattern in the Reference metric dataset but that class membership was uncertain (Hennig, 2007). Reference class 3 had the lowest cluster-wise stability (mean Jaccard similarity < 0.3). Cluster-wise stability did not appear to be related to cluster size (see sample sizes in Figure 4a).

The Historic classification yielded one stable cluster (Historic class 2, mean Jaccard similarity 0.75-0.85, Figure 4b). The cluster-wise stability score for Historic class 5 indicated pattern in the data but uncertain cluster membership. Historic classes 1, 3 and 4 had mean Jaccard similarities between 0.5-0.6 and hence were considered unstable clusters (Hennig, 2007).

Comparison of Reference and Historic classifications

The adjusted Rand Index was used to compare the Reference and Historic flow classifications (Appendix 1). The adjusted Rand Index for this comparison (0.382) suggests low agreement between theses classifications, as might be expected in a region with substantial flow regime change brought about by dams and other factors. In summary, changes in class membership are as follows. Reference class 1 was split across Historic classes 3 and 4. Reference class 2 was split across Historic classes 1, 2 and 3. Reference class 3 was split across Historic classes 1 and 3. Reference class 4 was split across Historic classes 2 and 4. Reference class 5 was similar to Historic class 5 in terms of class membership but most South Coast sites were added to Historic classes 3 and 4. Reference class 6 consisted of IQQM nodes without equivalent stream gauges (Appendix 1).

Flow regime alteration within southeast Queensland

The Gower metric was used to compare Reference and Historic flow regimes on the basis of the 35 flow metrics used for classification (Table II; Figure 5). These comparisons were limited to IQQM nodes with a corresponding stream gauge (n = 49). All gauges in southeast Queensland included in this analysis have been subject to some degree of flow regime change, and in general, the greatest flow regime changes from Reference (pre-development) have occurred downstream of dams. However, the presence of dams does not necessarily imply extensive flow regime change. For example, gauges 138107 (Six Mile Creek) and 138104 (Obi Obi Creek) are both downstream of dams but the flow regimes recorded at these gauges have not undergone substantial change from Reference, as shown by the Gower metric (Figure 5). Furthermore, three of the 11 gauges with the greatest flow regime change (Running Creek, South Pine River, Mudgeeraba Creek) were not downstream of a dam or weir.

As a further measure of the extent of flow regime alteration in the study area the Reference random forest model was used to predict Reference class membership for stream gauges. It was assumed that if the flow regime of an individual stream gauge had undergone little or no change from Reference then that gauge should be allocated to the same Reference flow class as the corresponding IQQM node. Forty of the 49 gauges included in this analysis were allocated to the correct Reference class (Figure 6). The high rate of successful classification (79.6%) is in contrast to the adjusted Rand Index, which suggested low concordance between classifications. Five of the gauges misclassified by the random forest model were downstream of a dam and three misclassified gauges had a dam on an upstream tributary (Appendix 1). However, two gauges downstream of Wivenhoe Dam on the Brisbane River (143001 and 143005) were allocated to the correct Reference class (Figure 6). Probabilities of class membership for gauges that were allocated to the correct Reference class varied between 59.8-99.5% (Figure 6).

Changes in individual flow metrics associated with flow regime change

Comparison of Reference and Historic values for individual flow metrics showed that the absolute magnitude of change from Reference was 10% or less for 37% of the 35 flow metrics, and 20% or less for 57% of the flow metrics (Figure 7). The extent to which individual flow metrics changed from Reference varied amongst gauges. Low spell duration (LSDur) underwent the greatest change from Reference, with most gauges experiencing low flow spells of longer duration compared to Reference (Figure 7). Mean rates of rise and fall also increased substantially when compared to Reference values. In contrast, moving averages of the 3-90 flow minima (MA3-90dayMin) decreased in value relative to the Reference value, as did metrics describing mean monthly discharge.

Four broad categories of flow regime change by dams are evident in southeast Queensland (Figure 8). The first group includes Hinze, Baroon Pocket and Six Mile Creek Dams. Flow regimes downstream of Baroon Pocket and Six Mile Creek Dams have undergone relatively minor overall change. For example, downstream of Baroon Pocket Dam (Obi Obi Creek) 25 of 35 flow metrics changed by less than 10% and the largest change in any flow metric was less than 50% (Figure 8). Downstream of Six Mile Creek Dam 14 of 35 flow metrics have changed by 10% or less. At this site rates of rise and fall have increased to a moderate extent while LSDur has increased substantially from Reference (>100%). Hinze Dam (Nerang River) is grouped with Barron Pocket and Six Mile Creek Dams. Flow metric changes for Hinze Dam were generally in the range of -10 to -50 % (i.e., Reference values greater than Historic values) but substantial increases in CVDaily and CONSTAN have occurred (i.e., Historic values greater than Reference values).

The second group of dams includes Borumba Dam (Yabba Creek) and Maroon Dam (Burnett Creek). The flow regimes downstream of these dams show substantial changes in low and high spell durations and JDMax (the timing of the annual maximum discharge). Additional flow regime changes downstream of Borumba Dam include substantial increases in MeanZeroDay and BFI (base flow index). Additional flow regime changes downstream of Maroon Dam include a substantial increase in MA1dayMin and a moderate increase (50-100%) in MDF_Sep (Figure 7). These categories are characterised by relatively *minor* reductions in flow metric values (as shown by yellow and blue cells in Figure 8).

The third group of dams includes both gauges on the Brisbane River downstream of Wivenhoe Dam and the fourth group includes only Moogerah Dam (on Reynolds Creek, Figure 1). Both of these groups share moderate to large *increases* in PREDICT, CONSTAN, BFI and MA7-90dayMin, as shown by the red colours in Figure 8. Additional flow regime changes downstream of Wivenhoe Dam include substantial increases in MA1-3dayMin and moderate increases in spell durations at the gauge closest to the dam (but not evident further downstream at Savages Crossing, gauge number 143001). Further flow regime changes downstream of Moogerah Dam include substantial increases in MA1-90dayMax, MDF_Sep and JDMax, and moderate increase in spell durations.

Figure 9 shows the percentage change in flow metrics between Reference and Historic flow regimes for those metrics identified by *clustvarsel* as best discriminating between Historic classes. These plots represent gradients of flow regime change for individual metrics across the study area. In general the gauges on the extremes of the gradients represented in Figure 9 have flow regimes influenced by dams or weirs. An exception is ARI_10yr. Many of the gauges with a positive change in ARI_10yr (i.e. Historic value exceeds Reference value) are not downstream of dams and weirs, and may suggest factors such as land use changes are influencing this metric (e.g. Siriwardena *et al*., 2006). Changes in MA1dayMin and MA30dayMin represent decreases (Reference value exceeds Historic) but the extreme changes in these metrics have been increases. MA1dayMin has undergone the greatest change (shown by Brisbane River and Burnett Creek gauges (below dams) but the North Maroochy River has also undergone a substantial increase in MA1dayMin despite not being subject to flow regime alteration by dams or weirs. HSDur and CONSTAN have tended towards substantial increases compared to reference values. CVDaily has decreased in value for most gauges, indicating mean daily flows are less variable at some locations.

DISCUSSION

Environmental flows are widely recognised as a central tool helping countries to protect freshwater biodiversity, resiliency and the ecological goods and services provided by healthy aquatic ecosystems (Naiman *et al*., 2008; Arthington *et al*., 2010). The ELOHA framework proposes a series of analyses that can lead to improved understanding and quantification of ecological responses to altered flow regimes in rivers of different hydrological and ecological character. Hydrologic classification is the first step in application of the ELOHA framework (Poff *et al.,* 2010). In theory, flow classes identified by classification may be regarded as management units that potentially share ecological attributes, and therefore could be managed in similar ways with regard to the design and allocation of environmental flows (Kennard *et al*., 2010a).

Flow classifications

This study has presented flow classifications and comparisons of natural and altered flows in southeast Queensland, Australia, to support the ecological steps of ELOHA.

Model-based clustering distinguished six Reference classes (based on modelled pre-development flow data) and five Historic classes (based on stream gauge data). The Reference classification identified flow magnitude and the number of zero flow days as the major pre-development hydrologic gradients in southeast Queensland, reflecting geographic patterns of rainfall in the region (Bridges *et al*., 1990; Young and Dilleward, 1999). The adjusted Rand Index value (0.382) suggested low concordance between the two classification schemes. In broad terms, the principal flow regime change (from Reference to Historic) in southeast Queensland appears to be loss of some of the original (natural) flow diversity accompanied by the emergence of a perennial flow class in the Historic classification comprised mostly of gauges with flow regimes influenced by dams.

In contrast to the adjusted Rand Index, several lines of evidence indicate many similarities between classification schemes. Firstly, elements of the Reference classification (RC) were evident in the Historic classification (HC). Two Reference classes had equivalent Historic classes – a flow class comprised of mostly Maroochy catchment sites (RC5 and HC5) and a flow class comprised of sites in the drier (western) region of southeast Queensland (RC4 and

HC2). The members of these flow classes were spatially cohesive and contiguous (Kennard *et al*., 2010a) and hence the geographic influences evident in the Reference classification persisted in the Historic classification. Other Historic classes were comprised of spatially disjunct gauges (e.g. HC3 and HC4), implying that caution should be used in extrapolating flow regime characteristics to ungauged areas of southeast Queensland (Kennard *et al*., 2010a) i.e., it cannot be assumed that rivers or streams in close geographic proximity belong to the same flow class. Secondly, two flow metrics (MeanZeroDay and MA1dayMin) were identified as distinguishing between flow classes for both classification schemes. Thirdly, the Reference random forest model successfully allocated 79.6% of gauges with an equivalent IQQM node to the correct Reference class. Similarities in the Reference and Historic classifications reflect the influence of broad-scale factors such as climate, topography and geology on hydrologic patterns (Kennard *et al*., 2010a). Presumably, substantial flow regime changes would produce relatively high error in allocation of stream gauges to Reference classes. However, only 10 out of 49 gauges used in this analysis were misclassified. Seven of the misclassified gauges were directly downstream of a dam, or were downstream of a dam located on an upstream tributary. The similarities between the Reference and Historic flow regimes demonstrate that hydrologic changes in southeast Queensland have not totally obscured many of the Reference (pre-development) flow characteristics. Zhang *et al*. (2012) also found that despite substantial flow regulation in the Huai River basin (China) by dams and flood levees, prominent hydrologic attributes of the pre-development flow regime were still evident in contemporary flow regimes.

Fourthly, concordance between classification schemes is not surprising given that the absolute magnitude of change between Reference and Historic metrics was less than 20% for over half of the metrics (Figure 7). The duration of low flow spells (LSDur) has undergone the greatest change from Reference condition. Presumably, increased duration of low flow spells is due to unsupplemented extraction, a form of flow regime alteration which is widespread in southeast Queensland (Brizga *et al*., 2006). Rates of water level rise and fall have increased substantially when compared to the Reference values, indicating greater flow variability captured in the gauged flow records. In contrast, the moving averages of the annual 3 day to 90 day minima have undergone decreases in value relative to the Reference flow value, as have mean monthly values. These marked changes could represent the effects of dams on downstream flows, or levels of water extraction from regulated rivers, or effects of dry conditions at many sites over the study period, or all three processes. However, the latter is an unlikely explanation as rainfall for the period 1971-2000 was generally similar to long-term values (Bureau of Meteorology climate summaries, http://www.bom.gov.au/climate). Increased duration of low flow spells and increased discharge intermittency have implications for the survival and persistence of aquatic biota (Bunn and Arthington, 2002; Lake, 2011). As well as marked changes, even relatively low levels of change in some flow metrics could have significant impacts on certain ecological indicators and processes, and this is precisely what the ecological steps of the ELOHA framework seek to determine. Dams in the study area probably have little capacity to alter medium and high flow characteristics, suggesting that flow regime changes have been restricted to low flow features of the hydrograph.

Flow regime changes downstream of dams

Dams had substantial impacts on downstream flow regimes. Comparisons of Reference and Historic flow regimes using the Gower dissimilarity coefficient showed that the greatest flow regime changes generally occurred in gauges downstream of dams (Nerang River, Reynolds Creek, Yabba Creek, Lockyer Creek, Brisbane River, Burnett Creek; see Figure 8). However, three of the 11 gauges with the greatest flow regime change are not located downstream of dams. These are gauges are situated on Running Creek, Mudgeeraba Creek and the South Pine River where land use changes in surrounding catchment areas are extensive. The gauge (145010 Running Creek) with the highest dissimilarity between Reference and Historic flow regimes (0.25) is not subject to flow regime alteration by dams or weirs. The primary land use change in the Running Creek catchment is agriculture, while urbanisation is the more prominent change for Mudgeeraba Creek and South Pine River. Furthermore, the presence of dams does not necessarily imply marked flow regime change (e.g. Six Mile Creek has a Gower metric of 0.052). These findings highlight the need to consider the potential influence of factors other than prominent water infrastructure on flow regime alterations and associated ecological responses (Siriwardena *et al*., 2006; McManamay *et al*., 2012a).

Four broad types of flow regime alteration by dams were distinguished by classification. However, there was no replication of any particular suite of changes in flow metrics within flow classes, nor across all streams/rivers regardless of flow class. Instead, a range of different changes has occurred below dams, presumably according to the characteristics of the catchments and individual dams, water release strategies and downstream water abstraction practices. It appears that each dam has generated a unique flow alteration signature. If every individual dam has a different effect on downstream hydrology and the flow metrics describing that flow regime, ecological impacts might be expected to differ also among regulated sites. However, similarities of ecological response might still become evident if certain flow metrics have a particularly powerful influence on biological systems (Bunn and Arthington, 2002; Poff and Zimmerman, 2010).

Our finding that individual dams in southeast Queensland have altered flow regimes in different ways contrasts with Poff *et al*. (2007) who found that dams in the United States had uniformly reduced flow regime diversity. There was no evidence in this study to show that this was the case in southeast Queensland. Rather, each of the major dams in the study area alters the downstream flow regime in a slightly different manner, although four broad types of flow regime alteration by dams were evident. Our finding supports McManamay *et al*. (2012a) who found that dams in the southeastern United States created a relatively high diversity of flow regimes, when compared with unregulated flow regimes, as indicated by the distribution of unregulated and regulated stream gauges in ordination (PCA) space.

Implications for application of the ELOHA framework

Flow classification is the first step in applications of the ELOHA framework. Flow classification identifies sites with similar flow regime characteristics that may also share biotic and ecological characteristics (Poff *et al*., 2010; Kennard *et al*., 2010a). Hence, intensive biological sampling of streams with similar flow regime characteristics and types and degrees of flow alteration may not be necessary, provided that data are available for some of the streams in a given flow class (Poff *et al*., 2010). The fundamental importance of this step in the application of the ELOHA framework requires that flow classifications be validated (Olden *et al*., 2012), since the flow classes identified by classification could form the basis of alternative stream management strategies (McManamay *et al*., 2012b) that vary in financial and ecological outcomes.

Flow classification is becoming more commonplace as a tool in ecohydrologic studies and environmental flow investigations (Olden *et al.,* 2012). Numerous classification methods are available and recent work has provided ecologists with guidance for important issues associated with flow classification (Olden and Poff, 2003; Kennard *et al*., 2010a,b; Olden *et al*., 2012). However, many practical issues associated with classification and cluster validation have not been investigated. For example, different classification algorithms may be suited to datasets with particular characteristics (Milligan and Cooper, 1985). Similarly, the results of cluster validation methods may be affected by the properties of the clusters, such as cluster size (Milligan and Cooper, 1985). Some cluster validation indices are based on the premise that good clusters will be small (i.e. relative small distances between members of a single class) and discrete (i.e. the distances between members of different classes will be large). It is perhaps unreasonable to expect that flow classes will form discrete groups since sites within a flow classification scheme may be expected to share flow regime attributes with sites in other classes (Olden *et al*., 2012; Figure 3). We trialled cluster-wise stability (Hennig, 2007) to validate Reference and Historic classes identified by model-based clustering. Cluster instability may arise from inherent instabilities in the data, a lack of robustness in the clustering method or the use of a sound clustering method being applied to an unsuitable dataset (Hennig, 2007). Cluster-wise stability provides a method of ranking flow classes for biological investigation. The most stable flow classes can be prioritised for ELOHA-style investigations over flow classes with uncertain membership, especially unstable flow classes with data-poor members. For classifications presented here, only one flow class (RC 6) was considered to be highly stable, and two classes (RC 5 and HC 2) were rated as stable. These represent spatially contiguous (RC5, HC2) and spatially disjunct (RC 6) classes, suggesting that high cluster-wise stability was not associated with the geographic proximity of sites within classes. Given the paucity of flow data often available, flow classes with high cluster-wise stability could be prioritised for development of models to predict flow class membership for ungauged sites (Sanborn and Bledsoe, 2006) or assessment of climate change impacts upon flow regimes (Barron *et al*., 2012).

An important consideration for hydrologic classification is the merit of a “statistical” classification, where statistical assumptions are fulfilled, *versus* an “ecological” classification where metrics are included for their ecological significance, whether or not they are considered statistically redundant (see Monk *et al.*, 2007). The Historic classification did not include CVDaily, JDMin and JDMax as these flow metrics were considered redundant by PCA. Yet these flow metrics have clear ecological relevance and may change considerably due to flow regime alteration by dams (Arthington *et al*., 1999; Bunn and Arthington, 2002; Kennard *et al*., 2007). In this study flow classification was combined with investigation of change in individual flow metrics, which offers a compromise in situations where individual flow metrics have been excluded on the basis of statistical considerations. Classification of flow regimes provides a framework for inferring the ecological outcomes of flow regime change, however the magnitude of change in an individual flow metric for a given site or suite of sites may be of more ecological and managerial relevance than whether sites change flow classes following water resource development (Mackay *et al*., 2012). Future studies in southeast Queensland may identify a subset of the 35 metrics used in this study that minimise statistical redundancy but capture known ecological relationships, thereby avoiding statistical assumptions that may weaken classification models (Monk et al 2007).

CONCLUSIONS

The ELOHA framework proposes a series of analyses that can lead to improved understanding and quantification of ecological responses to altered flow regimes in rivers of different hydrological and ecological character. Flow regime classification is the first step in applications of the ELOHA framework (Poff *et al*., 2010). In theory, flow classes identified by classification may be regarded as management units that potentially share ecological (as well as hydrologic) attributes, and therefore could be managed in similar ways with regard to the design and allocation of environmental flows. This study has presented hydrologic classifications and comparisons of natural and altered flows in southeast Queensland, Australia, to support the subsequent ecological steps of the ELOHA framework. Model-based clustering distinguished six Reference classes (based on modelled predevelopment flow data) and five Historic classes (based on stream gauge data).

Comparison of Reference (modelled pre-development data) and Historic (steam gauge data) classifications revealed the impacts of dams and other probable stressors such as land use on flow regimes. Four broad types of flow regime alteration by dams were distinguished. However, there was no replication of any particular suite of changes in flow metrics within flow classes, nor across all streams/rivers regardless of flow class. It appears that each dam has generated a unique flow alteration signature. If every individual dam has a different effect on downstream flow characteristics, ecological impacts might be expected to differ also among regulated sites. However, similarities of ecological response might still become evident if certain flow metrics have a particularly powerful influence on biological systems (Bunn and Arthington, 2002; Poff and Zimmerman, 2010). In either case, environmental flow guidance for each regulated river must be tailored to the particulars of flow alterations, the associated ecological impacts and the desired future ecological state of the aquatic ecosystem.

Assessment of cluster validity is an important step in hydrologic classification and deserving of more attention from researchers, given the potential financial and ecological implications for environmental flow management. In the present study not all hydrological classes were amenable to close inspection of their ecological affinities nor necessarily suitable for development of hydro-ecological relationships peculiar to their class. Nevertheless, this study has developed solid understanding of regional hydrologic variability and gradients, and quantified the impacts of dams and other factors on flow regimes in sufficient detail to proceed with testing the ecological steps of the ELOHA framework.

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Table I. Characteristics of principal river catchments in the study area (QDPI 1993; Long and Lloyd 1997; QDNRM 2001, 2002, 2005a,b). The South Coast catchment includes Coomera River, Nerang River, Little Nerang Creek, Back Creek, Pimpama River, Mudgeeraba Creek, Currumbin Creek and Tallebudgera Creek. Mean annual runoff estimates obtained from Australian Natural Resources Atlas (http://www.anra.gov.au/topics/water/availability/qld).

Catchment	Catchment area (km^2)	Mean annual runoff (natural)	Volume of water in storages
Mary	9 595	2.04×10^9 m^3	1.36×10^8 m^3
Noosa	1 915	1.07×10^9 m^3	0
Maroochy-Mooloolah	861	6.74×10^8 m^3	3.00×10^7 m^3
Pine-Caboolture	1282	3.80×10^8 m^3	2.32×10^8 m^3
Brisbane	13 560	1.11×10^9 m^3	1.87×10^9 m^3
Logan	3 073	3.89×10^8 m^3	4.47×10^7 m^3
Albert	782	1.86×10^8 m^3	3.00×10^4 m^3
South Coast	1 302	6.58×10^8 m^3	1.73×10^8 m^3

Table II**.** Flow metrics used in the classification of flow regimes. Magnitude metrics (except for Sp_MeanAnnMax) were standardised by upstream catchment area.

Flow regime component	Metrics	Acronym
Magnitude	Mean daily flow January	MDF_Jan
	Mean daily flow March	MDF_Mar
	Mean daily flow May	MDF_May
	Mean daily flow July	MDF_Jul
	Mean daily flow September	MDF_Sep
	Mean daily flow November	MDF_ Nov
	Annual minima, 1 day mean	MA1dayMin
	Annual minima, 3 day means	MA3dayMin
	Annual minima, 7 day means	MA7dayMin
	Annual minima, 30 day means	MA30dayMin
	Annual minima, 90 day means	MA90dayMin
	Annual maxima, 1 day mean	MA1dayMax
	Annual maxima, 3 day means	MA3dayMax
	Annual maxima, 7 day means	MA7dayMax
	Annual maxima, 30 day means	MA30dayMax
	Annual maxima, 90 day means	MA90dayMax
	Baseflow Index	BFI
	Mean number of zero flow days per year	MeanZeroDay
	Magnitude of the 1 year ARI flood	ARI_1yr
	Magnitude of the 2 year ARI flood	ARI_2yr
	Magnitude of the 10 year ARI flood	ARI_10yr
	Specific Mean Annual Maximum Discharge [2]	Sp_MeanAnnMax

Flow regime component	Metrics	Acronym
	Median of Annual Maximum Discharge	MedAnnMax
Timing	Julian date of annual 1 day maximum discharge	JDMax
	Julian date of annual 1 day minimum discharge	JDMin
	Predictability of mean daily discharge	PREDICT
	Constancy of mean daily discharge	CONSTAN
	Seasonality of mean daily discharge	SEASON
Frequency and duration	Number of high pulses within each year [3]	HSNum
	Number of low pulses within each year [3]	LSNum
	Duration of high pulses within each year	HSDur
	Duration of low pulses within each year	LSDur
Rate of change and variability	Mean rate of discharge rise	RateRise
	Mean rate of discharge fall	RateFall
	CV of mean daily discharge	CVDaily

[1] Calculated as the mean annual maximum flow divided by catchment area.

[2] Based on 75^{th} (low spell threshold) and 25^{th} percentiles (high spell threshold).

[3] Seasonality calculated as (Contingency/Predictability).

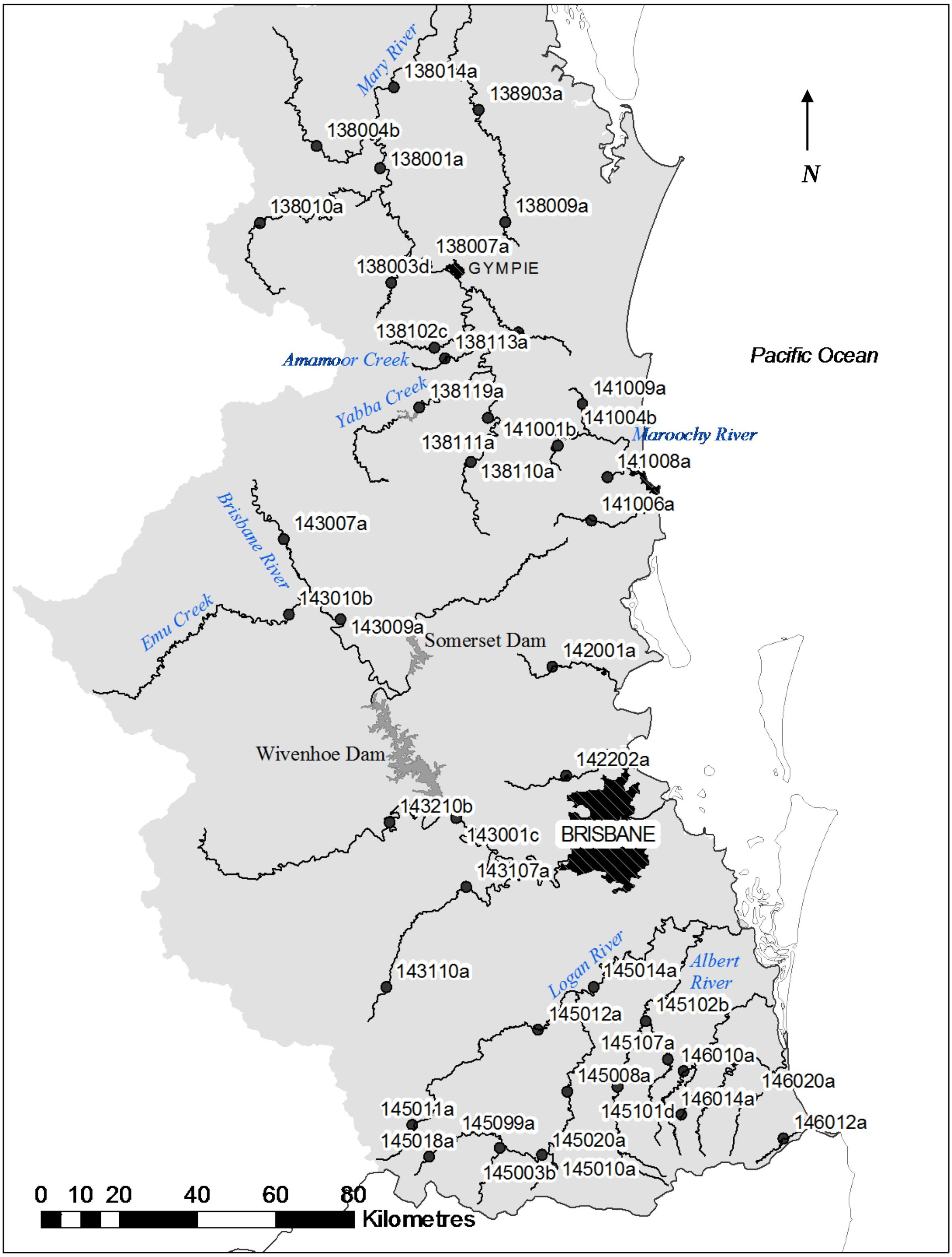


Figure 1. Locations and names of stream gauges used in the classification of southeast Queensland flow regimes.

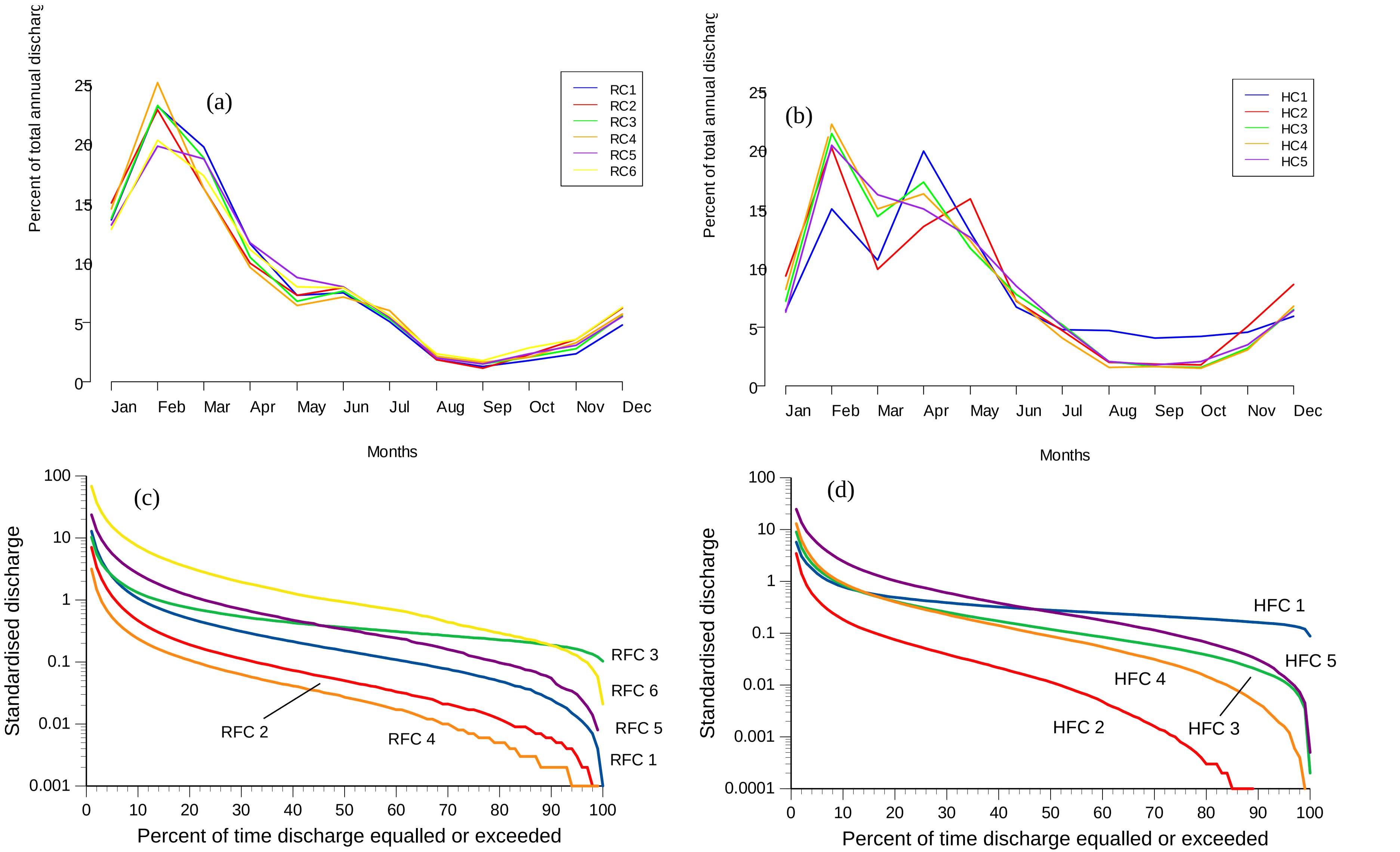


Figure 2. Flow regime characteristics of Reference and Historic classes. Flow seasonality for (a) Reference classes and (b) Historic classes. Numbers indicate flow classes. Flow duration curves for (c) Reference classes and (d) Historic classes.

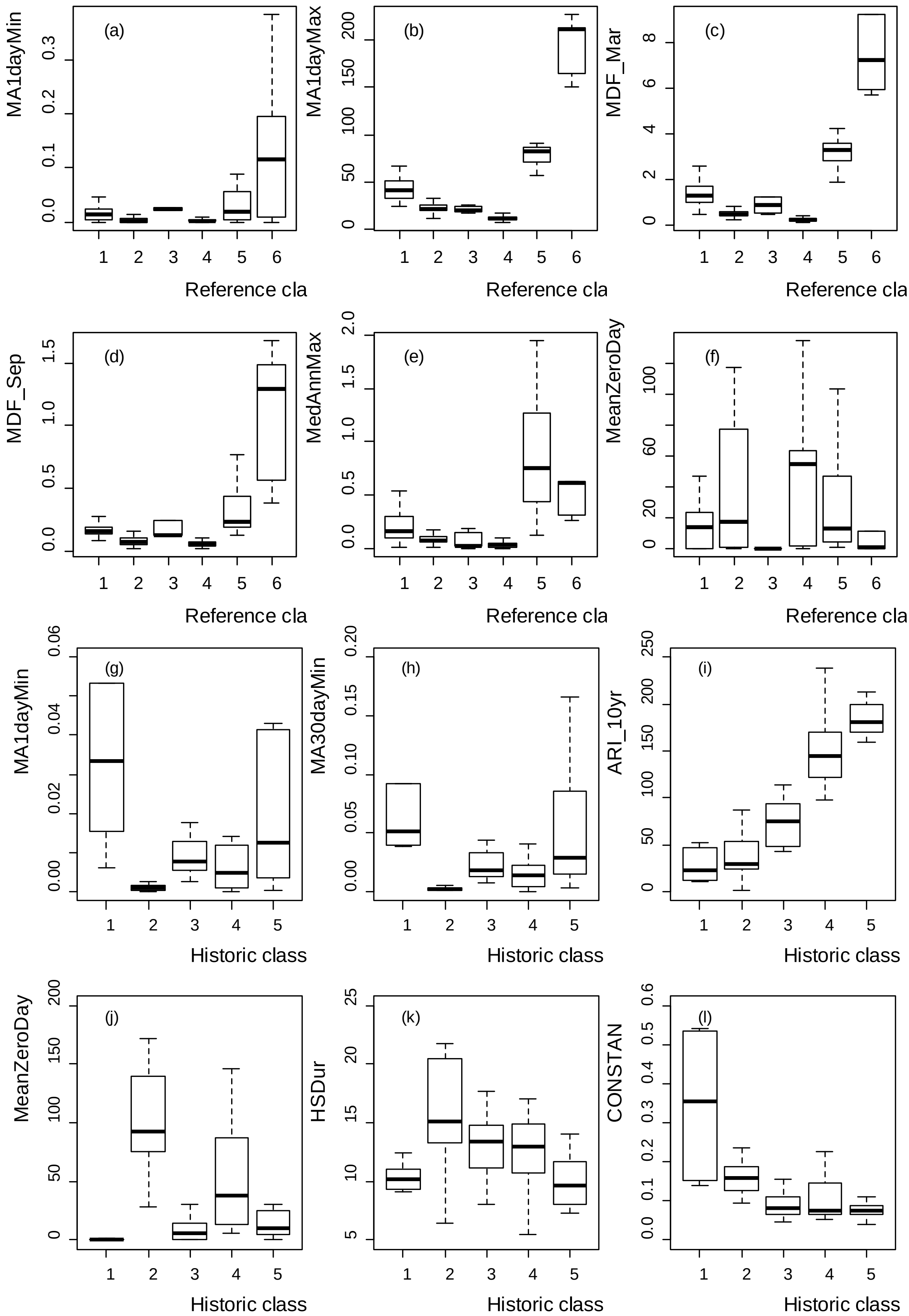


Figure 3. Box and whisker plots of flow metrics selected by the clustvarsel function as best discriminating between Reference flow classes (a-f) and Historic flow classes (g-l). See Table II for definition of flow metrics.

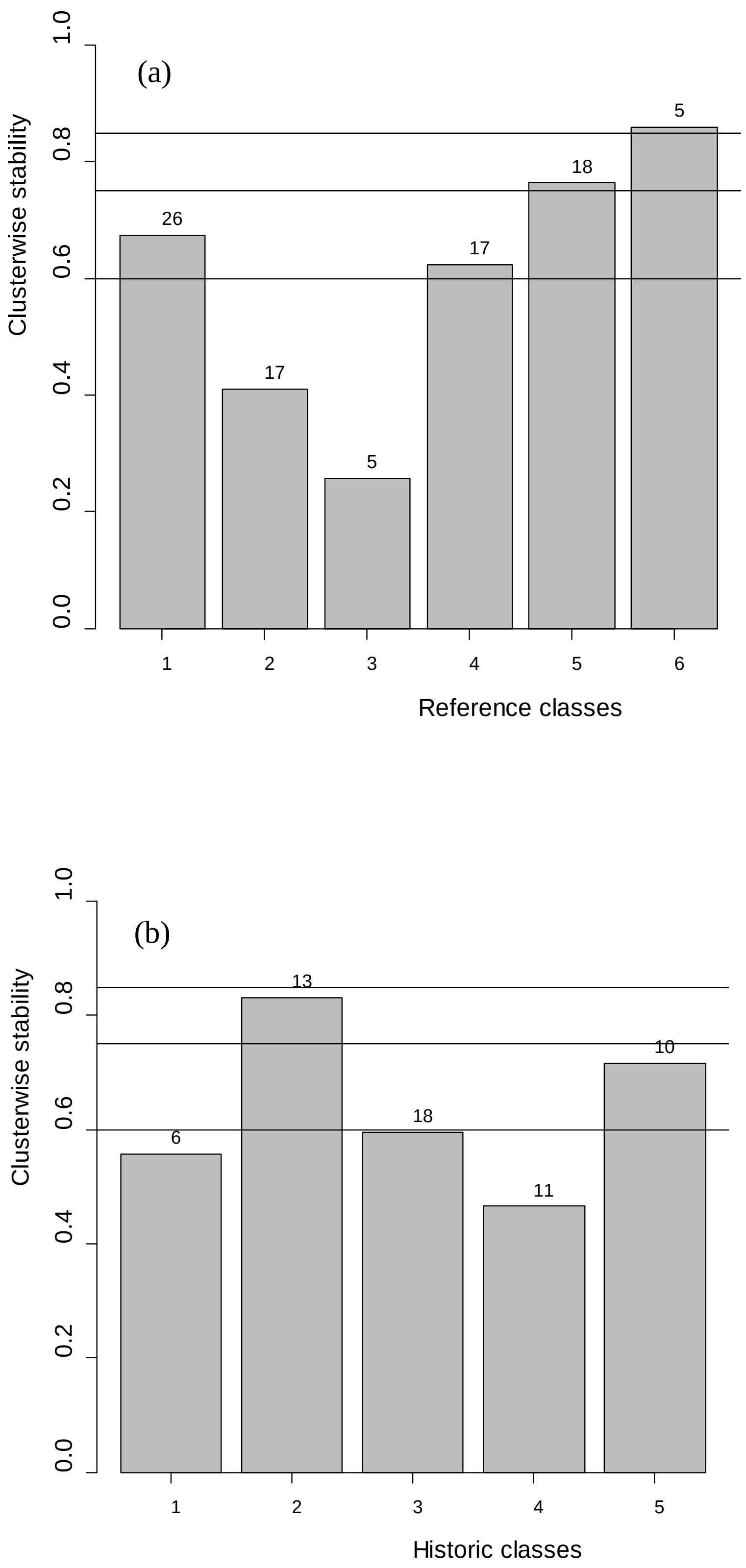


Figure 4. Clusterwise stability (as mean Jaccard similarity) for (a) Reference classes and (b) Historic classes, as calculated by the clusterboot function in the fpc package for R. Horizontal lines indicate thresholds of cluster stability. Clusterwise values between 0.6-0.75 indicate patterns but uncertain cluster membership (bottom line). Clusterwise values between 0.75-0.85 indicate stable clusters (middle line) and values above 0.85 (top line) indicate highly stable clusters (Hennig 2010).

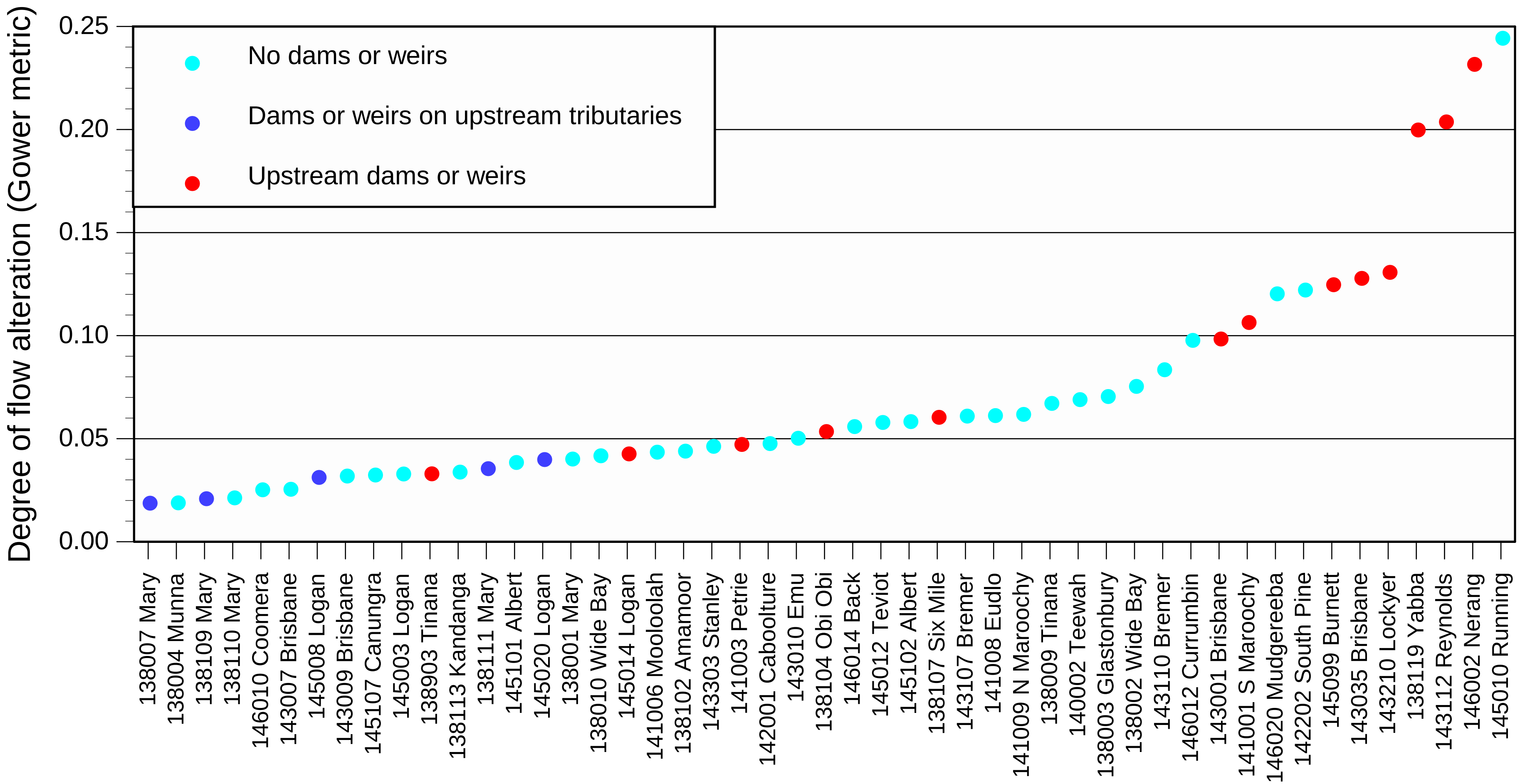


Figure 5. Comparison of Reference and Historic flow regimes using the Gower dissimilarity coefficient based on comparisons of 35 flow metrics. Higher values for the Gower metric indicate greater divergence of the Historic flow regime from the Reference flow regime. Only IQQM nodes with a currently operating stream gauge shown.

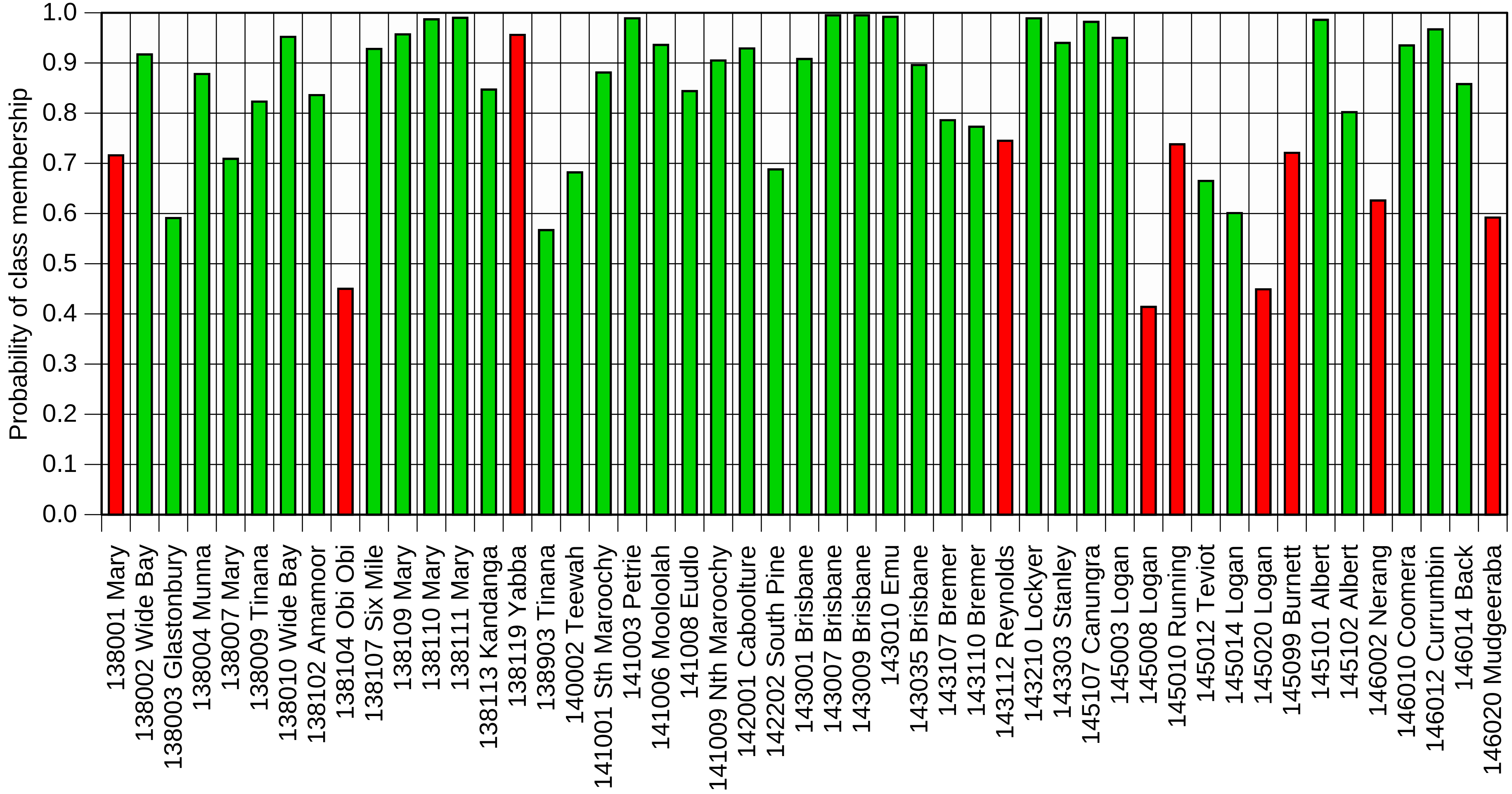


Figure 6. Probability of Reference class membership for gauges as determined by the Reference random forest model. Shown are gauges with a corresponding IQQM node. A green bar indicates allocation to the correct Reference class. A red bar indicates allocation to an erroneous flow class. See Appendix 1 for full gauge names.

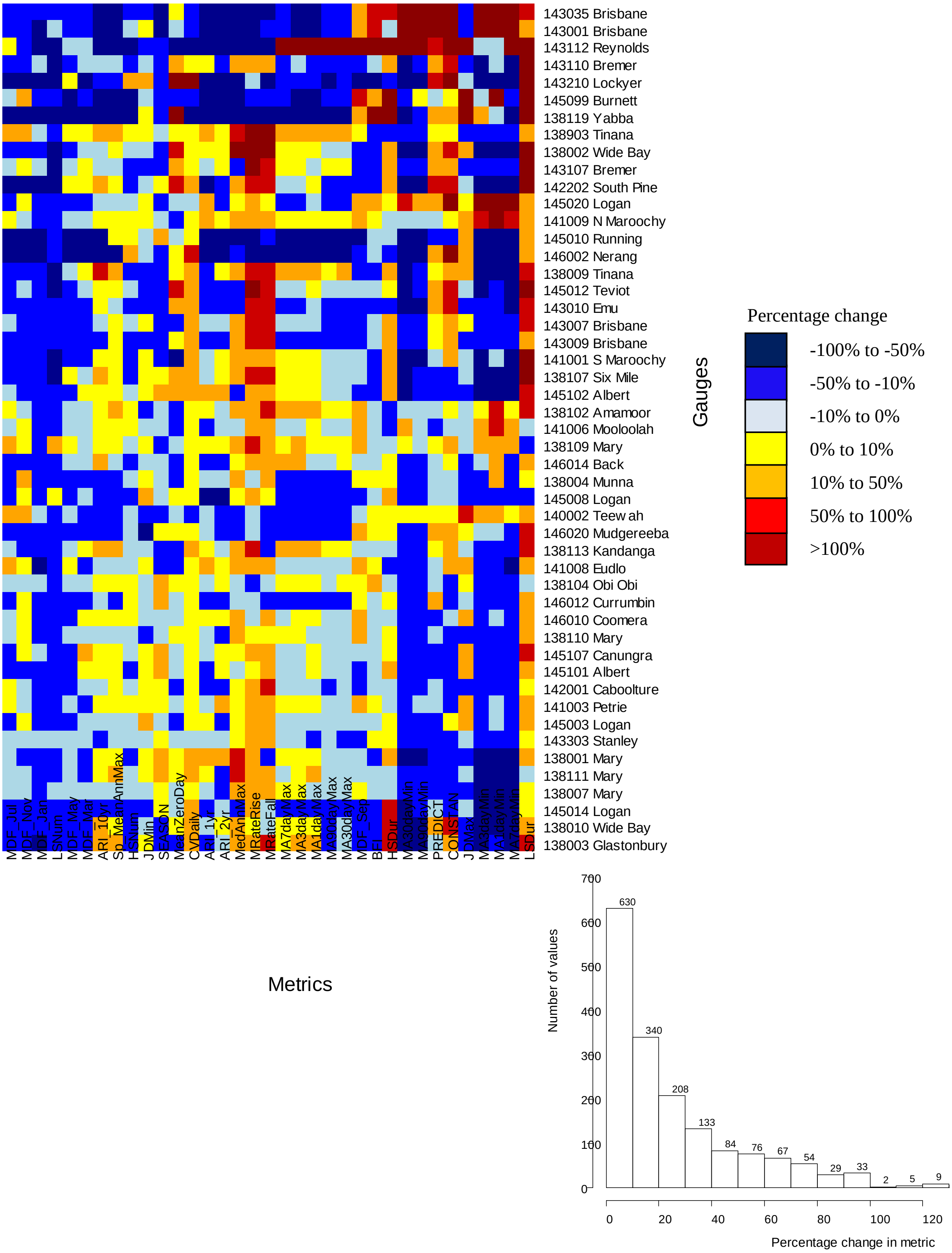


Figure 7. Heat map showing the percentage change in flow metrics between Reference and Historic flow regimes, expressed as (Historic value-Reference value)/Reference value. MeanZeroDay is expressed as the difference between Reference and Historic values due to division by zero. Histogram shows absolute percentage change in flow metrics for changes of 0-125% only (total *n*=1715). Numbers above bars are *n* for each category.

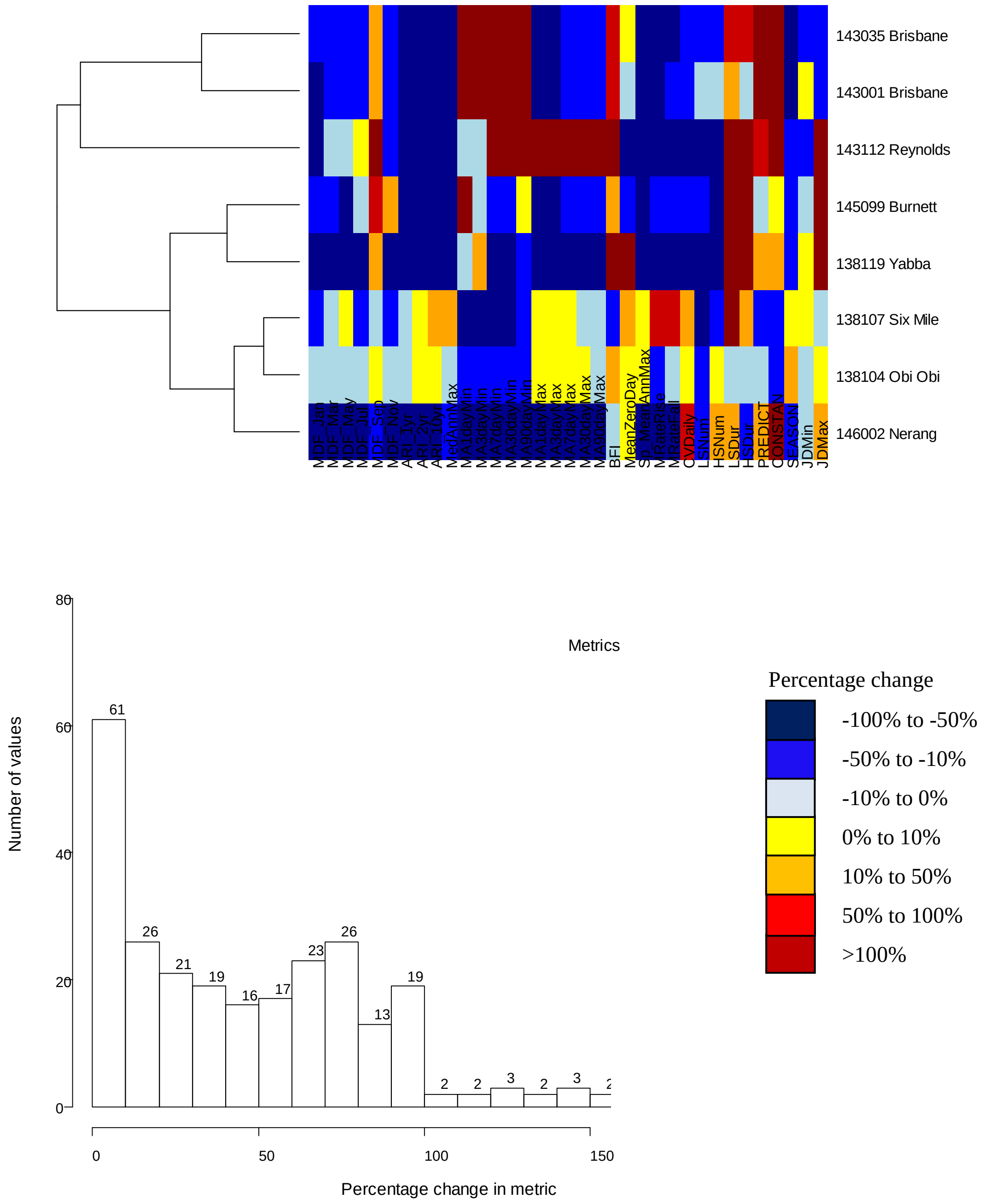


Figure 8. Heat map showing the percentage difference between Reference and Historic flow metrics, expressed as (Historic-Reference)/Reference, for gauges downstream of a dam. MeanZeroDay is expressed as the difference between Reference and Historic values due to division by zero. Histogram shows absolute percentage change in flow metrics for changes of 0-125% only (total *n*=280). Numbers above bars are *n* for each category. The dendrogram was constructed using Euclidean distance and the complete linkage algorithm.

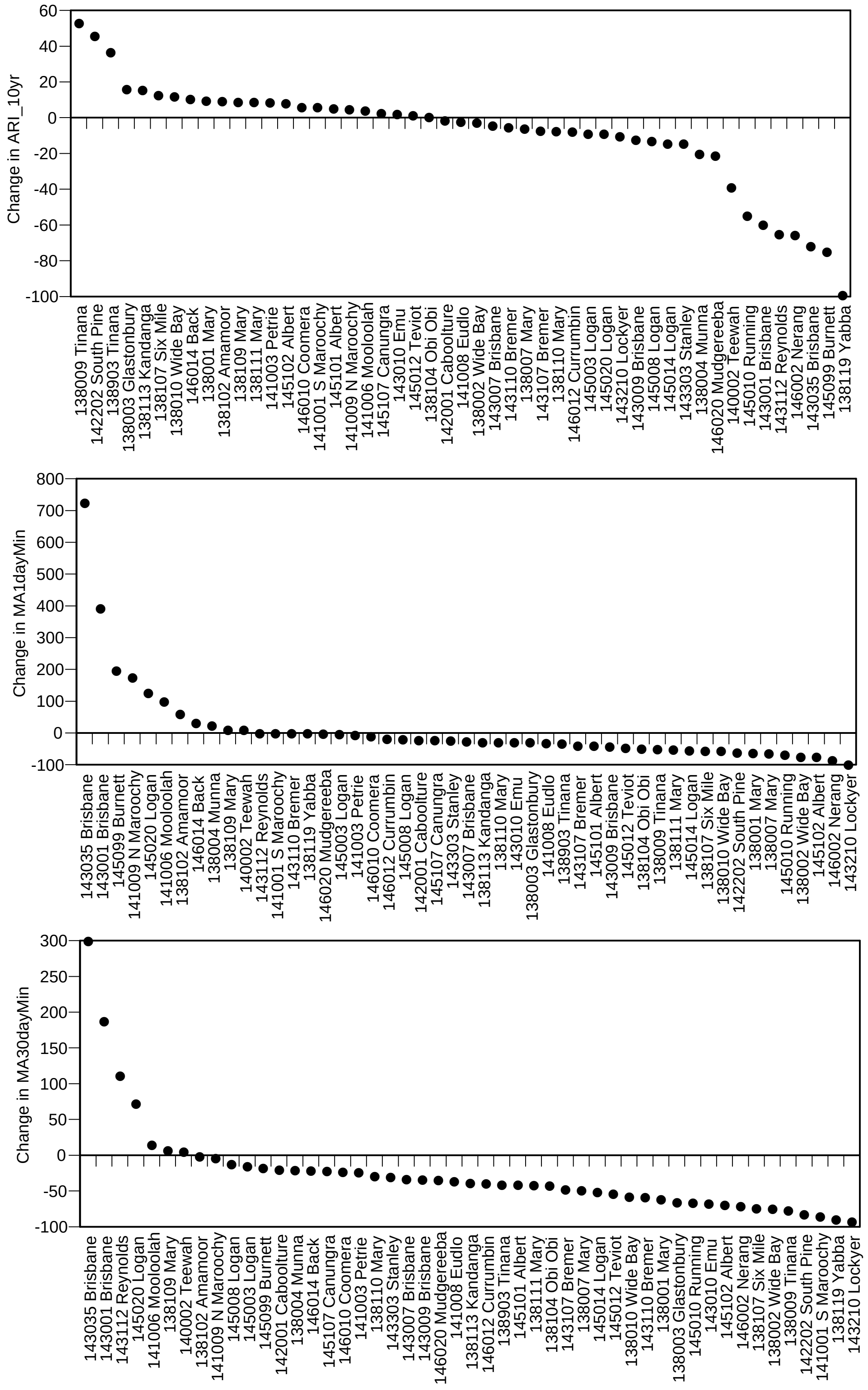
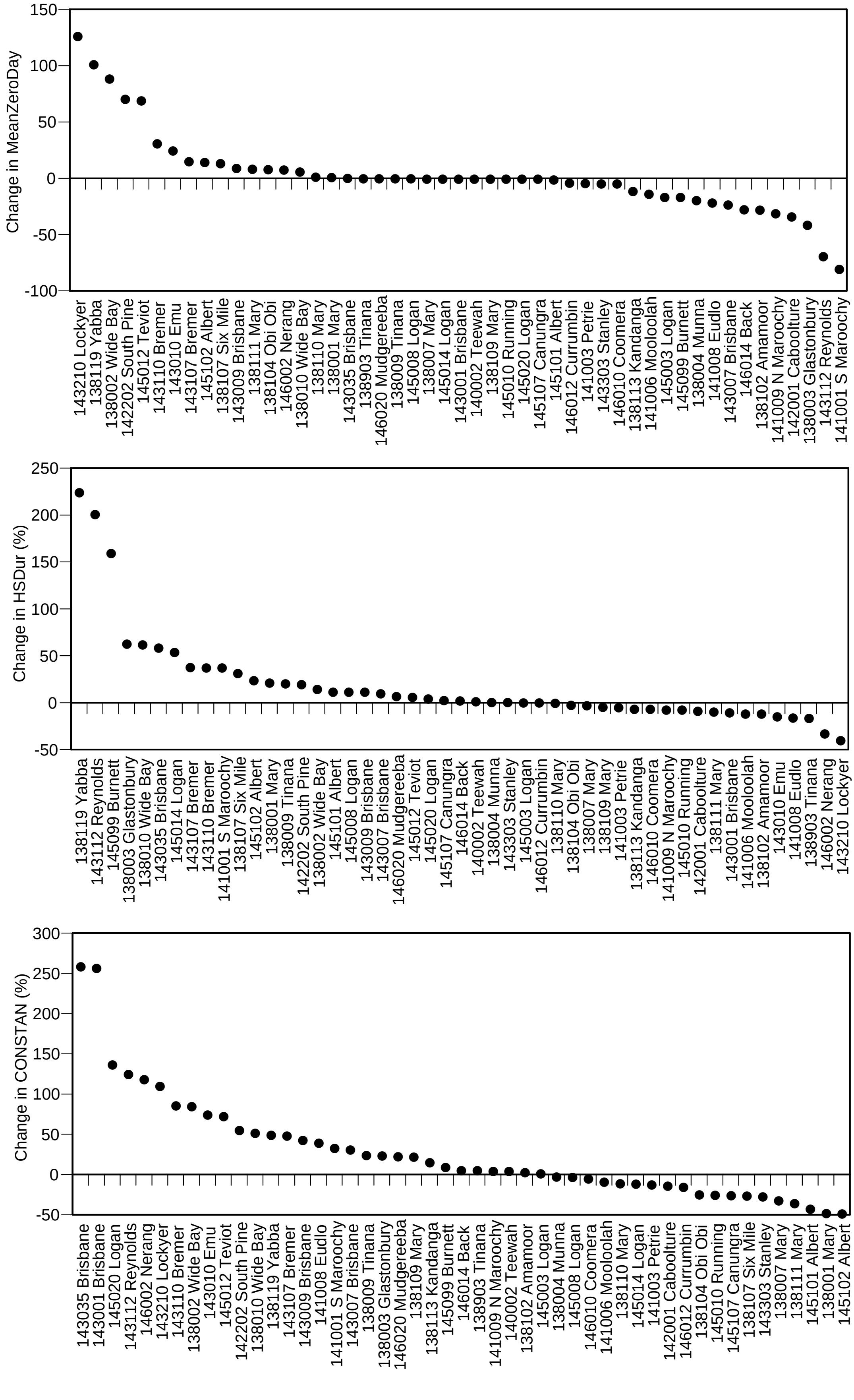


Figure 9. Percentage change in hydrologic metric values for metrics identified by clustvarsel as discriminating between Historic classes. MeanZeroDay is calculated as the difference between Historic and Reference values due to zero values. A positive difference indicates the Historic value is greater than the Reference value.

Figure 9 continued.



Appendix 1. IQQM nodes and stream gauges used in the hydrologic classification of streams in southeast Queensland. "Type of flow regime alteration" describes whether dams or weirs are present upstream of the gauge. A dam or weir located immediately upstream of the gauge is named (construction date in brackets); "Upstream dam" and "Upstream weir" indicate the presence of one or more dams or weirs on tributaries upstream of the gauge. ‡ indicates IQQM node without comparable stream gauge in Historic classification (due to absence of a gauge or poor quality gauge record). "IaBT" indicates intrabasin water transfer scheme. Dam construction dates obtained from ANCOLD (2002).

River/Catchment	IQQM nodes and stream gauges	Catchment area (km^2)	Reference class	Historic class	Type of flow regime alteration
Mary	138001a Mary River at Miva	4755	3	3	Upstream dams
	138002c Wide Bay Creek at Brooyar	655	4	2	None
	138003d Glastonbury Creek at Glastonbury	113	2	3	None
	138004b Munna Creek at Marodian	1193	4	2	None
	138007a Mary River at Fishermans Pocket	3068	1	3	Upstream dams
	138009a Tinana Creek at Tagigan Road	100	1	3	None
	138010a Wide Bay Creek at Kilkivan	322	4	2	None
	138014a Mary River at Home Park	6845	No class	3	Upstream dams
	138101b Mary River at Kenilworth‡	720	1	No class	None
	138102c Amamoor Creek at Zachariah Lane	133	1	4	None
	138104a Obi Obi Creek at Kidaman	174	1	3	Baroon Pocket Dam (1989)
	138105c Yabba Creek at Imbil‡	623	2	No class	Upstream dam
	138106a Obi Obi Creek at Baroon Pocket‡	67	5	No class	None
	138107b Six Mile Creek at Cooran	186	1	4	Six Mile Creek Dam (1964)
	Six Mile Creek at Cooroy‡	45	5	No class	None
	138109a Mary River at Dagun Pocket	2097	1	3	Upstream dams
	138110a Mary River at Bellbird Creek	486	1	4	None
	138111a Mary River at Moy Pocket	820	1	3	Upstream dams
	138113a Kandanga Creek at Hygait	143	1	4	None
	138119b Yabba Creek at Borumba Dam Release	498	2	2	Borumba Dam (1964)
	138120a Obi Obi Creek at Gardners Falls	26	6	No class	Weir
	138903a Tinana Creek at Bauple East	783	2	3	Upstream weirs

River/Catchment	IQQM nodes and stream gauges	Catchment area (km^2)	Reference class	Historic class	Type of flow regime alteration
Noosa	140002a Teewah Creek at Coops Corner	53	3	1	None
	Kin Kin Creek at Mouth‡	268	1	No class	None
Maroochy	141001b South Maroochy River at Kiamba	33	5	No class	Weir
	141002a South Maroochy River Kureelpa‡	20	6	No class	None
	141003c Petrie Creek at Warana Bridge	38	5	5	Weirs
	141004b South Maroochy River at Yandina	75	No class	5	Wappa Dam (1961)
	141006a Mooloolah River at Mooloolah	39	5	No class	None
	141008a Eudlo Creek at Kiels Mountain	62	5	5	None
	141009a North Maroochy River at Eumundi	38	5	5	None
	Rocky Creek at Cooloolabin Dam‡	8	5	No class	None
	Mooloolah River at Addlington Creek‡	79	1	No class	None
	South Maroochy River at Wappa Dam	70	5	No class	None
Pine-Caboolture	142001a Caboolture River at Upper Caboolture	94	1	4	None
	North Pine River at North Pine Dam Outflow‡	346	1	No class	None
	142101a North Pine River at Youngs Crossing‡	403	1	No class	None
	142103a North Pine River at Laceys Crossing‡	118	1	No class	None
	142202a South Pine River at Drapers Crossing	156	1	4	None
Brisbane	143001c Brisbane River at Savages Crossing	10 180	4	1	Wivenhoe Dam (1985)
	143018a Brisbane River at Avoca Vale‡	1498	4	No class	None
	143007a Brisbane River at Linville	2009	4	2	None
	143009a Brisbane River at Gregors Crossing	3866	4	2	None
	Brisbane River at Watts Bridge	4602	4	No class	None
	143010b Emu Creek at Boat Mountain	915	4	2	None
	Emu Creek outflows to Brisbane River‡	995	4	No class	None
	143015b Cooyar Creek at dam site	963	No class	2	None
	143028a Ithaca Creek at Jason Street	10	No class	4	None
	143032a Moggill Creek at Upper Brookfield	23	No class	4	None
	143033a Oxley Creek at New Beith	60	No class	No class	None
	143035a Brisbane River at Wivenhoe Dam	7023	4	1	Wivenhoe Dam (1985)
	143112a Reynolds Creek at Moogerah Dam	227	2	1	Moogerah Dam (1961)

River/Catchment	IQQM nodes and stream gauges	Catchment area (km^2)	Reference class	Historic class	Type of flow regime alteration
	143107a Bremer River at Walloon	620	2	2	None
	143108a Warrill Creek at Amberley	914		3	Weirs/IaBT
	Warrill Creek at Kalbar‡	468	2	No class	None
	Warrill Creek at Toohills Crossing‡	120	1	No class	None
	143110a Bremer River at Adams Bridge	125	2	2	None
	Lockyer Creek at Helidon‡	357	4	No class	None
	143210b Lockyer Creek at Rifle Range Road	2490	4	2	Weirs
	143303a Stanley River at Peachester	104	5	5	None
	Stanley River at Woodford Weir Inflows‡	65	6	No class	None
	143306a Reedy Creek at Upstream Byron Creek	56	No class	2	None
	Laidley Creek at Node 301‡	167	1	No class	None
	Laidley Creek at Lockyer Creek junction‡	465	2	No class	None
	Buaraba Creek at 15.8km‡	251	2	No class	None
	Buaraba Creek at Vineyards‡	347	2	No class	None
	Buaraba Creek at Lockyer Creek junction‡	390	2	No class	None
	143307a Byron Creek at Causeway	79	No class	4	None
	Murphy Creek at Alice Creek junction‡	228	4	No class	None
	143921a Cressbrook Creek at Rosentretters‡	447	4	No class	None
	Cressbrook Creek at Cressbrook Dam Outflows‡	325	4	No class	None
	Cressbrook Creek Outflows to Brisbane River‡	620	4	No class	None
Logan-Albert	145003b Logan River at Forest Home	175	1	3	None
	145008a Logan River at Round Mountain	1262	3	1	Upstream dam
	145010a Running Creek at Deickmann Bridge	128	5	3	None
	145011a Teviot Brook at Croftby	83	No class	3	None
	145012a Teviot Brook at The Overflow	503	2	2	None
	Teviot Brook at Logan River Junction‡	694	2	No class	None
	145014a Logan River at Yarrahappini	2416	2	3	Weirs
	145018a Burnett Creek upstream of Maroon Dam	82	No class	3	None
	145020a Logan River at Rathdowney	533	2	1	Upstream dam
	145099a Burnett Creek at Maroon Dam Tailwater	106	2	1	Maroon Dam (1974)

River/Catchment	IQQM nodes and stream gauges	Catchment area (km^2)	Reference class	Historic class	Type of flow regime alteration
	145101d Albert River at Lumeah No. 2	169	1	3	None
	145102b Albert River at Bromfleet	544	1	3	None
	145107a Canungra Creek at Main Road Bridge	101	1	3	None
	Christmas Creek at Rudds Lane‡	157	3	No class	None
	Albert River at Glendower‡	305	1	No class	None
	Logan River at Bromelton Rocks‡	98	6	No class	None
	Logan River at Teviot Brook Junction‡	1698	3	No class	None
South Coast	146002b Nerang River at Glenhurst	240	5	3	Hinze Dam (1976)[1]
	146004a Little Nerang Creek at Neranwood‡	40	5	No class	None
	146009a Little Nerang Creek at 4.0km‡	53	5	No class	None
	146010a Coomera River at Maybury	88	1	4	None
	146011a Nerang River at Whipbird‡	122	5	No class	None
	146012a Currumbin Creek at Nicolls Bridge	30	5	5	None
	146014a Back Creek at Beechmont	7	5	5	None
	146020a Mudgeeraba Creek at Springbrook Road	36	5	4	None
	Mudgeeraba Creek at Nerang‡	82	6	No class	None
	146095a Tallebudgera Creek at Tallebudgera Creek Rd	56	1	No class	Weir

[1] Hinze Dam was raised in 1989 – this year taken as the construction date for calculating flow metrics.