Hydrological Estimates for Auckland

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Hydrological Estimates for Auckland

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NIWA Project: AC12505

Executive summary

For this project 485 flow records containing at least five years of mean daily flow data were assembled. These records were used to create regression (random forest) models to calculate several hydrological indices. Calculated values of the same hydrological indices were also extracted from NIWA's national TopNet model and databases available from the previously completed Hydrology of Ungauged Catchment (HUC) projects. Calculated values for each method were then compared with observed values using scatterplots and by calculating root-mean-square deviance. Results indicated that:

- the HUC method is the best currently available method for calculating mean flow for application to Auckland region;
- the Random Forest method is the best currently available for calculating 7-day mean annual low flow (MALF) for application to the Auckland region;
- the Random Forest method for calculating 7-day one-in-five low flow (Q_5) is the best currently available method for application to the Auckland region;
- the Random Forest method for calculating the proportion of flow in February is the best currently available method for application to the Auckland region.
- the Random Forest method for calculating FDCs over all-time and for each month of the year is the best currently available method for application to the Auckland region.

These data were used to demonstrate how calculated hydrological values at all rivers in a region can be used to inform river management decisions. For example, maps were used to illustrate that the proportion of time in February that is lower than the 7-day MALF varies across a region. This has implications for both reliability of supply to water users and for ecological effects when setting minimum flow and total allocations as a proportion of 7-day MALF.

Table of contents

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1.0 Introduction

1.1 Project brief

Auckland Council (AC) requires estimates of several hydrological indices for locations on all rivers in the Auckland region. Specifically AC requires estimates of:

- mean flow over all time (Q_{bar});
- mean flow in each month (e.g., Q_{jan});
- mean annual 7-day low flow (MALF);
- the 20th percentile of the annual 7-day minima (Q_5);
- the shape of the flow duration curve over all time;
- the shape of the flow duration curve in each month; and
- quantification of uncertainties for each of the above.

This information will aid in setting limits to water allocation in Auckland.

1.2 Background

The National Policy Statement for Freshwater Management requires Regional Councils to set limits for water quality and quantity. Relevant limits that provide for life supporting capacity of rivers whilst providing for economic development would need to include at least minimum flows (the flow below which no water can be abstracted) and total allocations (the total water that can be abstracted) for all rivers. Establishment of minimum flow and total allocation limits would provide clarity concerning environmental objectives and for water users with regard to water availability and reliability.

We understand that for highly allocated catchments in Auckland, AC undertakes catchment specific assessments. In catchments where demand for abstraction is high, water quantity limits are already/will be set using catchment specific information such as ecological, physical habitat and hydrological studies for that catchment. In the remaining catchments, where demand for water abstraction is lower, default or interim limits are required. A likely method for setting interim default limits is to use “rules of thumb” that are based on hydrological indices such as the mean annual low flow (MALF). This is the approach that is taken by the proposed National Environmental Standard for Flows and Levels (NES). Interim default limits may be altered in future subject to more detailed studies.

The flow duration curve (FDC) is a tool used to describe hydrological regimes and flow variability at a particular site. The FDC represents the relationship between magnitude and frequency of flow by defining the proportion of time for which any discharge is equalled or exceeded. The position of a minimum flow on the FDC will define the proportion of time for which full restriction of abstractions will apply. The minimum flow plus the allocation rate is known as the management flow. The position of the management flow on the FDC defines the proportion of time that some level of restriction will apply. The position of the minimum flow on the FDC and the allocation rate defines the proportion of the time that the river could be held at the minimum flow.

Both the shape of the FDC and the position of MALF on the FDC vary between sites. Therefore, spatially-distributed representations of these indices are essential to assess the consequences of any set of proposed limits across a region. These representations will also allow comparisons of the in-stream and out-of-stream consequences of applying different options for limits.

Where long-term hydrological records are available, hydrological indices such as MALF, mean flow and the FDC can be estimated and used to set minimum flows and total allocations. However, long-term records are only available for locations with continuously recording flow gauges. There is, therefore, a need to estimate hydrological indices at ungauged locations.

Hydrological indices can be calculated for ungauged locations using various methods. When estimates of hydrological indices are made it is often useful to quantify the uncertainties associated with each calculated index for each method of calculation. This is achieved by assessing correspondence between calculated values and those observed at gauging stations. Quantification of uncertainties allows comparison between calculation methods, and may also assist in planning decisions and help to improve monitoring networks.

1.3 Aims

The main aim of this work is to provide the best available estimates of MALF, Q_5, Q_{bar} and the shape of the FDC at all ungauged locations in the region to assist in water planning and management. A secondary aim is to provide quantification of the uncertainties associated with these estimates. This information is intended to be used in the future for regional level planning and management of water resources, rather than to set specific limits at particular individual locations.

2.0 Data

2.1 Hydrological data

Our analysis required time-series of mean daily flows and information describing the characteristics of the catchment draining to each gauging station. For this project we collated all available daily flow time-series from some regional councils (NRC, AC, WRC, GWRC, and ECan) alongside daily flow time-series from NIWA's national database. See Figure 2-1 for locations of gauging stations.

Figure 2-1: Locations of gauging stations.

2.2 Catchment data

We obtained the location of each gauging station on the NZ river network by finding the REC (River Environment Classification; Snelder and Biggs, 2002) reach number for the reach containing each gauging station. We then extracted information from the REC and FWENZ (Freshwaters Environments of New Zealand; Leathwick et al., 2010) databases describing various characteristics of the catchment upstream of each gauging station (e.g. catchment area, geology, topography, climate).

We used flow records that covered a minimum period of 5 years and that were, to the best of our knowledge, not affected by large engineering projects such as dams, diversions or substantial abstractions.

3.0 Methods

3.1 Observed indices

For each flow time-series we calculated several hydrological indices (Table 3-1). Calculations of MALF and Q_5 were based on a water year starting on the 1^{st} of October. Only water years with 335 days of data were included in our analysis (years with more than 30 days of missing data were excluded). MALF was calculated as being the mean of the 7-day annual low flows.

We fitted a range of distributions (normal, log normal, exponential, Gumbel, Generalised Extreme Value; see Table 3-2) to each 7-day annual low flow series and then calculated the 20^{th} percentile of this fitted distribution to calculate values for Q_5 under each distribution. In order to assess sensitivity to the choice of distribution, we compared values of Q_5 after having assumed several different distributions. Any Q_5 values calculated to be less than zero were set to zero. All low flow indices were standardised by dividing by the catchment area to provide metrics of specific low flow.

Table 3-1: Hydrological Indices derived from observed mean daily flows.

Index	Description	Method of calculation
Q_{bar}	Mean flow over all time	Mean of all daily flows ($m^3\ s^{-1}$)
Q_{month}	Proportion of flow in each month of the year (e.g., Q_{jan} = proportion of flow in January)	Mean of all daily flows for each calendar month after having divided by the overall mean flow (no units)
MALF	Mean of minimum 7-day flow in each year	Mean of minimum flow for each water year after having applied a running 7-day mean to the daily flows ($m^3\ s^{-1}$)
Q_5	20^{th} percentile of the annual 7-day minima	20^{th} percentile of minimum flow for each water year after having applied a running 7-day mean to the daily flows
FDC	Probability distribution of daily flow	Interpolation of the cumulative frequency distribution of daily flows on to 101 points (0 to 100 in steps of 1)
FDC_{month}	Probability distribution of daily flow for each month	Interpolation of the cumulative frequency distribution of daily flows for each calendar month on to 101 points (0 to 100 in steps of 1)

Table 3-2: Definitions of probability distribution functions used to model flow duration curves (after Laio et al., 2009).

Distribution description	Acronym	Cumulative distribution function (*G*) or Probability distribution function (*g*)	Equation No
Gumbel or extreme value type I	GUMBEL	$G(x,\vartheta)=\exp[-\exp(-(x-\vartheta_1)/\vartheta_2)]$	Equation 1
Normal or Gaussian	NORM	$g(x,\vartheta)=(1/\sqrt{2\pi}\vartheta_2)\exp[-1/2((x-\vartheta_1)/\vartheta_2)^2]$	Equation 2
Generalized extreme value	GEV	$G(x,\vartheta)=\exp[-(1-(\vartheta_3(x-\vartheta_1))/\vartheta_2)^{1/\vartheta_3}]$	Equation 3
Log transformed NORM	LN	Log transformation of Equation 2	Equation 4
Gamma or Pearson type III	P3	$g(x,\vartheta)=[1/(\lvert\vartheta_2\rvert\Gamma(\vartheta_3))]((x-\vartheta_1)/\vartheta_2)^{(\vartheta_3-1)}\exp(-[(x-\vartheta_1)/\vartheta_2])$	Equation 5
Frechet or log transformed Gumbel	EV2	Log transformation of Equation 1	Equation 6
Log transformed P3	LP3	Log transformation of Equation XX	Equation 7

For each time-series, we fitted a GEV distribution to all available daily flow data and all daily flow data in each month of the year separately. The GEV distribution is described by three parameters. This distribution has shown to represent the range of FDC shapes found across New Zealand. See Booker and Snelder (2012) for further discussion of estimating FDCs at ungauged sites across New Zealand using various statistical techniques to generalise parameters describing various probability distributions.

3.2 Calculated indices

For this study we compared several methods for calculating hydrological indices at ungauged locations. These methods ranged from purely empirical (i.e. statistical modelling) methods to those applying more physically-based approaches (Table 3-3). All methods were able to produce estimates for all reaches that comprise the NZ river network.

Table 3-3: Methods for predicting various hydrological indices.

Index	Method 1 (Regression)	Method 2 (Hydrology of ungauged catchments)	Method 3 (TopNet)
Q_{bar}	Regression from available catchment variables using all available sites.	Long-term mean from Woods et al. (2006): "ratios of potential evapotranspiration with annual precipitation, and a single water balance parameter which is estimated by independent calibration plus regional bias correction."	Calculated from TopNet daily flow time-series.
Q_{month}	Separate regression for each month from available catchment variables using all available sites.	Q_{bar} multiplied by the proportion of flow in each month distinguished by Island-Climate-Topography class of REC.	Calculated from TopNet daily flow time-series.
MALF	Regression from available catchment variables using all available sites.	Recession-based approach of Henderson et al (2004).	Calculated from TopNet daily flow time-series.
Q_5	Regression from available catchment variables using all available sites.	No method available.	Calculated from TopNet daily flow time-series.
FDC	Regression from available catchment variables for each parameter describing a GEV distribution of daily flows using all available sites.	Generated from two parameters describing a log-normal distribution. These parameters are the mean flow and the slope of the log-normal reduced FDC.	Calculated from TopNet daily flow time-series.
FDC_{month}	Regression from available catchment variables for each parameter describing a GEV distribution of daily flows for each calendar month using all available sites.	The estimated log-normal reduced (all time) FDC (as described in cell above) multiplied by the proportion of flow in each month distinguished by Island-Climate-Topography class of REC.	Calculated from TopNet daily flow time-series.

Many hydrological indices are scale-dependent; bigger catchments have larger values of Q_5, MALF and Q_{bar} than smaller catchments. We therefore standardised Q_5, MALF and Q_{bar} by dividing by catchment area (Table 3-4). Each daily flow time-series was standardised by dividing by its long-term mean.

Table 3-4: Transformations of dependent variables.

Index	Method of standardisation	Transformation
Q_{bar}	Divide by catchment area to get specific mean flow ($m^3 s^{-1} km^{-2}$)	Log base 10
Q_{month}	Divide by mean flow over entire record to get proportion of flow in each month (unit less)	None
MALF	Divide by catchment area to get specific MALF ($m^3 s^{-1} km^{-2}$)	Square root
Q_5	Divide by catchment area to get specific 1 in 5 low flow ($m^3 s^{-1} km^{-2}$)	Square root
P_{MALF}	Not applicable	Log base 10
$P_{MALFfeb}$	Not applicable	Log base 10

3.2.1 Method 1; Regression

The three parameters describing a GEV distribution of each FDC were calculated for: a) all flows; and b) all flows in each month. Separate regression models were then fitted to each of these 39 parameters. This meant that all standardised FDCs should be multiplied by mean flow to be returned to units of $m^3 s^{-1}$. We also calculated the position of MALF on both the all-time FDC (P_{MALF}) and the FDC for February ($P_{MALFfeb}$). We then fitted regression models to these two indices.

Some dependent variables exhibited non-normal distributions. It is not desirable to fit some types of regression models when the dependent variable exhibits a non-normal distribution. We therefore applied several transformations to approximate normal distributions for each dependent variable prior to fitting regression models (Table 3-4, Figure 3-1). Distributions of indices describing the proportion of flow in each month of the year did approximate normal distributions, no transformations were applied to these indices (Figure 3-2).

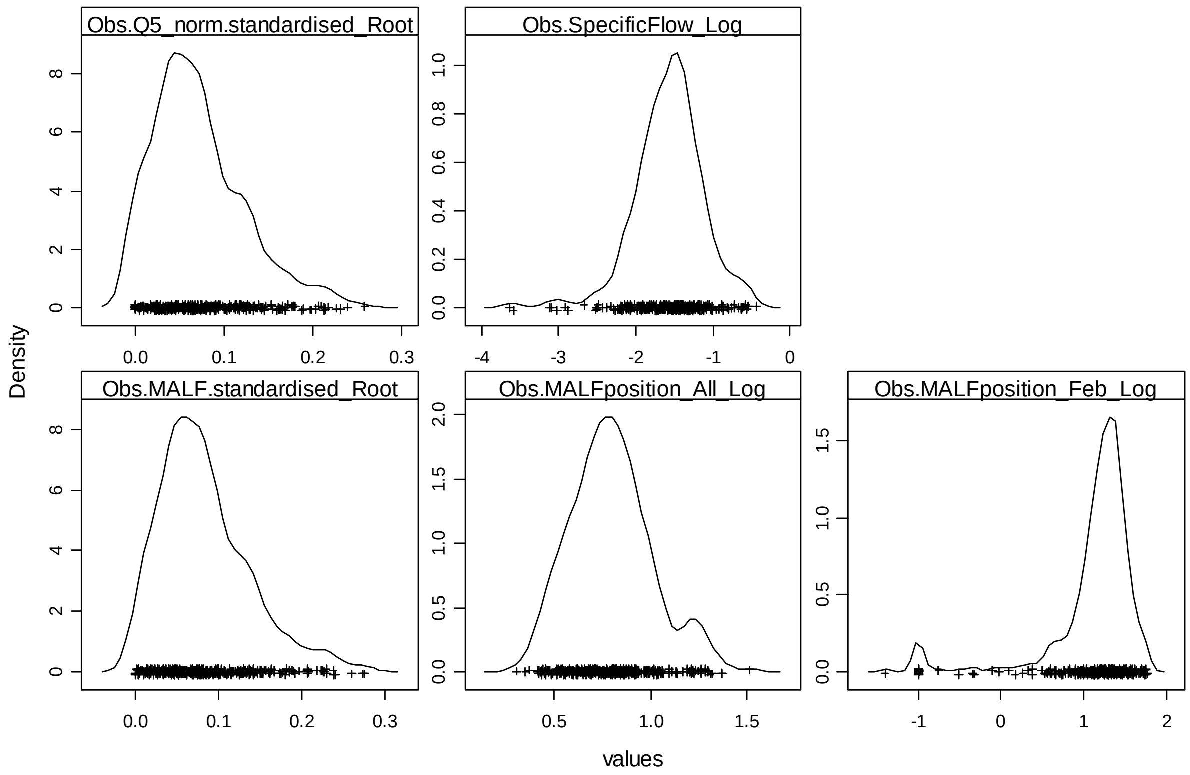

Figure 3-1: Density distributions of observed values after having applied transformations.

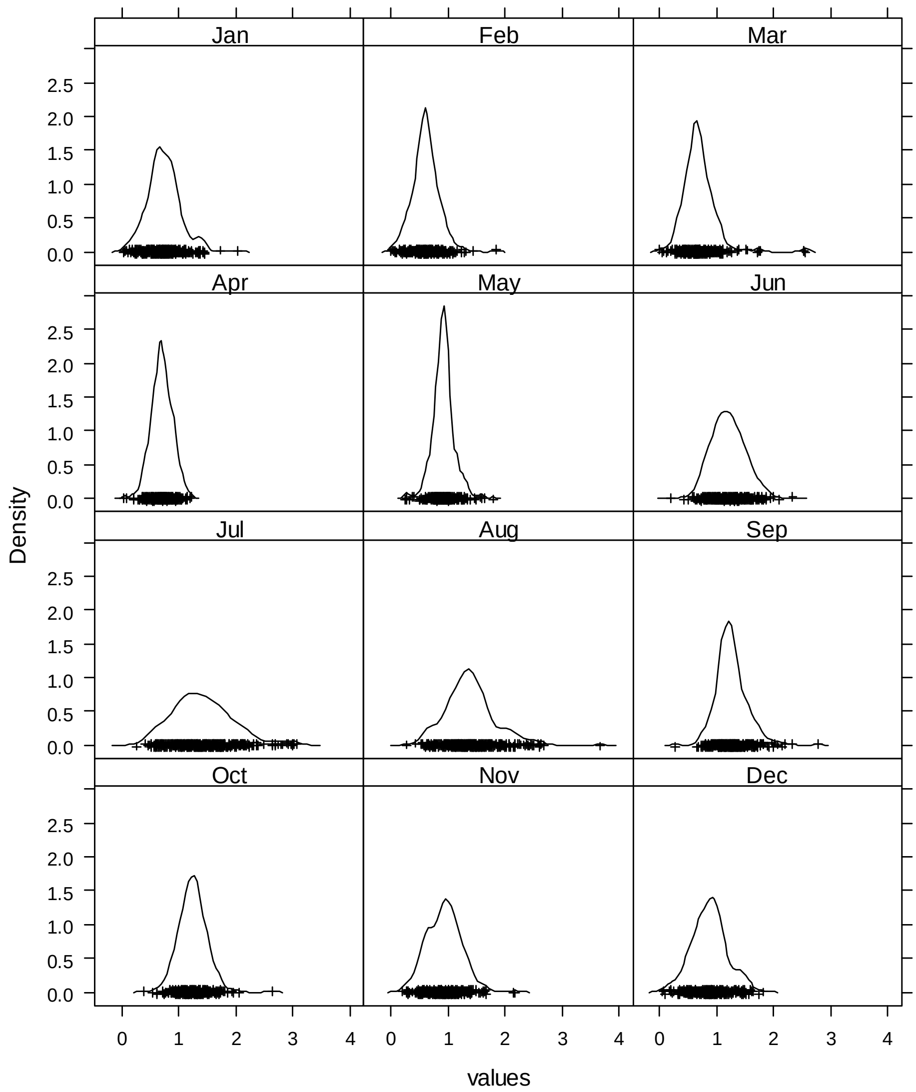

Figure 3-2: Density distribution of the proportion of flow in each month.

A regression technique called Random Forests was used to apply all regressions for Method 1. This method uses machine-learning to combine many regression trees to produce more accurate regressions (Breiman, 2001; Cutler et al., 2007). Random forests were used to model each hydrological index as a function of the explanatory variables (Table 3-5). See Leathwick et al. (2010) for further details of the explanatory variables. A Random Forest model comprises an ensemble of regression trees (a forest) from which a final prediction is based on the predictions averaged over all trees (Breiman, 2001; Cutler, et al., 2007). A random forest model is created by drawing several bootstrap samples from the original training data and fitting a single classification tree to each sample. Independent predictions (i.e. independent of the model fitting procedure) are made for each tree from the observations that were excluded from the bootstrap sample (the OOB samples). These predictions are aggregated over all trees (the OOB predictions) and provide an estimate of the predictive performance of the model for new cases (Breiman, 2001). By-products of the random forest calculations include measures of variable importance, which are evaluated by randomly permuting each predictor variable in turn and predicting the response for the OOB observations. The decrease in prediction performance is the measure of importance of the original variable. Importance represents the contribution to accuracy of independent predictions for each explanatory variable and is equivalent to the error resulting from dropping a term from a linear model. Each random forest was developed by growing 500 trees. As the number of trees (k) increases the generalization error always converges, it was assumed that 500 was sufficiently high to ensure convergence.

Table 3-5: Explanatory variables used in Random Forest models.

Variable name	Description
usArea	Catchment area (m^2)
ORDER	Stream order (Strahler stream order)
usParticleSize_Q	Catchment average of particle size (ordinal scale)
usHard_Q	Catchment average of hardness, induration (ordinal scale)
usCalc_Q	Catchment average of calcium (ordinal scale)
usAlluvium_Q	Catchment average of alluvium (ordinal scale)
usCatElev	Average elevation in the upstream catchment (m)
usAveSlope_Q	Catchment average of slope (m/m)
usAvTWarm_Q	Mean January air temperature (^{O}C)
segTSeas	Seasonally adjusted temperature (dimensionless)
usPET_Q	Annual potential evapotranspiration of catchment (mm)
usAnRainVar_Q	Coefficient of variation of annual catchment rainfall (m)
usRainDays10_Q	Catchment rain days, greater than 10 mm/month (days/year)
usRainDays50_Q	Catchment rain days, greater than 50 mm/month (days/year)
usRainDays200_Q	Catchment rain days, greater than 200 mm/month (days/year)
usBare_Q	Percentage of upstream catchment of bare
usForest_Q	Percentage of upstream catchment of exotic forest plus indigenous forest
usPastoral_Q	Percentage of upstream catchment of pastoral
usScrub_Q	Percentage of upstream catchment of scrub
usTussock_Q	Percentage of upstream catchment of tussock

We fitted all regression models using data from: a) the 379 gauging stations used by Booker and Snelder (2012); and b) all available gauging stations following collation of data for this project.

3.2.2 Method 2; Hydrology of Ungauged Catchments

The approach used to estimate Q_{bar} for Method 2 (HUC) is described in Woods et al (2006). They evaluated four simple models of mean annual runoff throughout New Zealand, predominantly based on precipitation information and estimated evapotranspiration. Model results were compared to observed data and synthesised estimates of catchment runoff. The preferred model of Woods et al. (2006) subtracts an estimate of annual actual evapotranspiration from a precipitation surface. Annual actual evapotranspiration is estimated according to the ratios of potential evapotranspiration with annual precipitation, and a single water balance parameter which is estimated by independent calibration. This method applies a regional bias correction to the results of a previous uncorrected model.

The approach used to estimate Q_{month} for Method 2 (HUC) was based on Source-of-Flow groupings in the REC Table 3-6. For each combination of Source-of-Flow class and island (i.e. North or South Island), a normalised monthly mean flow predictor is available. This predictor is the mean of the normalised mean flow for all measured flow records in New Zealand that belong to that class in that island. For cases where no measured flow is available, expert judgement was applied to make use of data from other classes.

The approach used to estimate MALF for Method 2 (HUC) is described in Henderson et al (2004). Figure 3-3 shows the model and its parameters. These fall into three categories:

1. Climate parameters (T the average length of a dry season, N the number of rain events in that season, P the amount of rain in the dry season);
2. Flow parameters (Q_{mean} the mean flow, Q_0 the average flow at the start of the dry season, α the fraction of that rain that affects the stream flow); and
3. Catchment parameters that describe the way in which water is released from catchments during the dry season (b and T*).

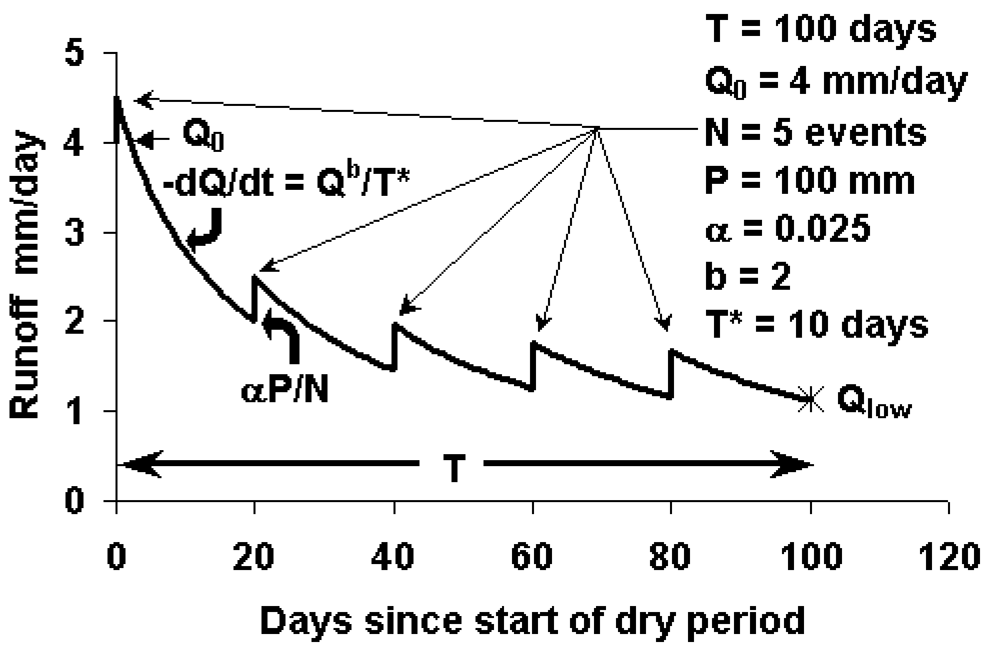

Figure 3-3: Low Flow model and parameters.

Estimates of all of these input parameters have been developed for all of New Zealand. The parameter Q_0 in Figure 3-4 corresponds to Q_{month} at the start of the dry season, i.e. November for most of New Zealand. The predictions are most sensitive to the value of the b parameter, which describes the type of river flow recession. For example, catchments in dry east coast catchments typically have b values near 1, hill country catchments typically have b values near 2, and catchments on the volcanic plateau typically have b values of 3 or larger.

No approach for estimating Q_5 was available for Method 2 (HUC).

The approach used to estimate FDC for Method 2 (HUC) was to assume a log-normal probability distribution as a model of the flow duration curves (Equation (4) of Table 3-2) which has two parameters, θ_1 and θ_2. We further assumed that θ_1 could be estimated as the mean flow (Q_{bar} for Method 2 (HUC)) and that θ_2 would be estimated as a linear function of the b parameter, which is described in the MALF for Method 2 (HUC).

The approach used to estimate FDC_{month} for Method 2 (HUC) was to scale the estimated FDC for Method 2 (HUC) by the estimated Q_{month} for Method 2 (HUC).

Table 3-6: Summary of the defining characteristics, categories and category membership criteria that combine to define Source-of-Flow groupings within the REC. Effective precipitation = annual rainfall – annual potential evapotranspiration. See (Snelder and Biggs, 2002) for a description.

Defining characteristic	Categories	Notation	Category membership criteria
Climate	Warm-extremely-wet Warm-wet Warm-dry Cool-extremely-wet Cool-wet Cool-dry	WX WW WD CX CW CD	Warm: mean annual temperature > 12°C Cool: mean annual temperature < 12°C Extremely Wet: mean annual effective precipitation1 > 1500 mm Wet: mean annual effective precipitation > 500 and < 1500 mm Dry: mean annual effective precipitation < 500 mm
Topography	Glacial-mountain Mountain Hill Low-elevation Lake	GM M H L Lk	GM: M and % permanent ice > 1.5% M: > 50% annual rainfall volume above 1000 m ASL H: 50% rainfall volume between 400 and 1000 m ASL L: 50% rainfall below 400 m ASL Lk: Lake influence index 2 > 0.033

3.2.3 Method 3; TopNet

The approach used to estimate all hydrological indices for Method 3 (TopNet) was to extract daily flows calculated by an uncalibrated TopNet model of New Zealand (Henderson et al., 2011). Topnet is a spatially distributed, time-stepping hydrological model, and is described in detail in Clark et al. (2008). In this case TopNet was run at an hourly timestep over the period 1972-2010, using Strahler-1 sub-catchments from the REC. The typical catchment area of a Strahler-1 catchment is 0.7 km^2.

TopNet has two fundamental components: (i) simulating the water balance over sub-catchments throughout a river basin, and (ii) routing streamflow from each sub-catchment to the basin outlet. The water balance model includes simulating the storages and fluxes of water in the canopy, snowpack, unsaturated and saturated soil zone. TopNet also accounts for time delay in runoff of water within each sub-basin. Runoff from each sub-basin flows into a digital stream network and is routed through the river network.

This TopNet model used daily precipitation and temperature data from the Virtual Climate Station Network (Tait, 2008, Tait et al 2006), which was then disaggregated to hourly using stochastic disaggregation for precipitation. Most of the model parameters were estimated directly from GIS data on topography, soil and vegetation. The development of improved parameter sets for the national TopNet model is continuing.

3.3 Testing

3.3.1 At-site indices

We tested the predictions produced by each method by comparing calculated values with observed values. In order to provide the strictest possible tests, comparisons between observed and calculated values were made after having applied the standardisations and transformations described in Table 3-4.

For regression methods, we applied a leave-one-out cross-validation procedure called jack-knifing to provide an estimate of uncertainty in the predictions at ungauged sites. For each method, this cross-validation procedure is applied by leaving out all data associated with each gauging station and then estimating each index for the left-out gauging station using data from all remaining gauging stations. The results from this procedure produce estimates of each index for each gauging station as if that gauging station were an ungauged site. These jack-knifed comparisons allow an assessment of the uncertainties in each index for ungauged sites.

For each method for each index (Q_{bar}, MALF, Q_5, P_{MALF}, $P_{MALFfeb}$) we plotted observed against calculated values in standardised and transformed space (as described in Table 3-4). We also calculated root-mean-square-deviance (RMSD; Equation 8).

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}\left(M_{obs} - M_{pred}\right)^2}{n}} \qquad \text{Equation 8}$$

RMSD represents a measure of the overall difference between observed and calculated values and is a measure of the uncertainty in calculated values. We also performed a linear regression of observed against calculated values to determine both the statistical significance and how near the relationship between observed values and calculated values was to being 1:1.

Although random forest models were fitted using data from 485 gauging stations, our tests were carried out using data from only 479 gauging stations. This was because four gauging stations had catchments that were much smaller than that of the NZreach that best represented them. In these cases calculated values from the HUC and TopNet methods did not represent the locations at which observations had been made. We removed a further two gauging stations (Whakatane at Whakatane and Aorere at Devils Boots) from our test data set because they were located at locations where the river network has an incorrectly representation of the catchment area because of a break in the upstream catchment (for information; NIWA currently have a project to produce a new river network of New Zealand to solve these issues). Calculated values from the HUC and TopNet at these locations are known to be unrepresentative.

3.3.2 Flow duration curves

For each gauging station we plotted the observed FDC for all time and for each month together with the corresponding FDC calculated using each method to provide a visual comparison. We calculated RMSD for each percentile on all FDCs for each Method.

All tests were repeated for the region and elsewhere in New Zealand to provide an assessment of model performance in the region in comparison to elsewhere.

4.0 Results

See Appendices to this report for hydrographs and flow duration curves derived from observed flow data which were used in this analysis along with calculated values using the various methods.

4.1 Observed indices

Of the gauging stations for which flow data were available for this project and of sufficient length, 41 were located in the Auckland region. These gauging stations spanned a relatively broad range of catchment areas (Figure 4-1). There were no very large catchments from Auckland in our data set because there are no very large catchments in the Auckland region. The relationship between observed mean discharge and catchment area for gauging stations in Auckland was similar to that for all other gauging stations, except that there was a tendency for slightly less mean flow per unit catchment area in Auckland compared to elsewhere in New Zealand.

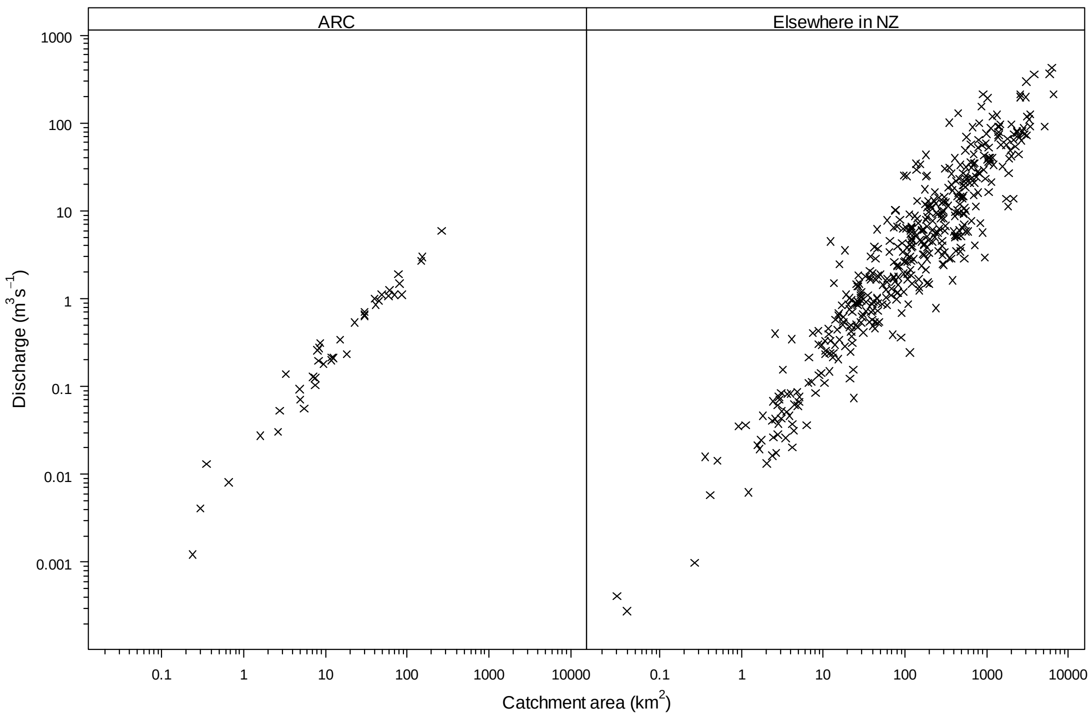

Figure 4-1: Observed mean discharge versus catchment area for observed flow time-series.

Scatterplots of observed low flow indices show that there were only very minor differences in Q5 derived from various probability functions (Figure 4-2). This was the case both for the Auckland region and elsewhere across New Zealand. See Table 3-1 for definitions of indices and Table 3-2 for definitions of probability distribution functions. In the following analysis, we therefore used Q_5 as derived by assuming a normal distribution to the annual low flows.

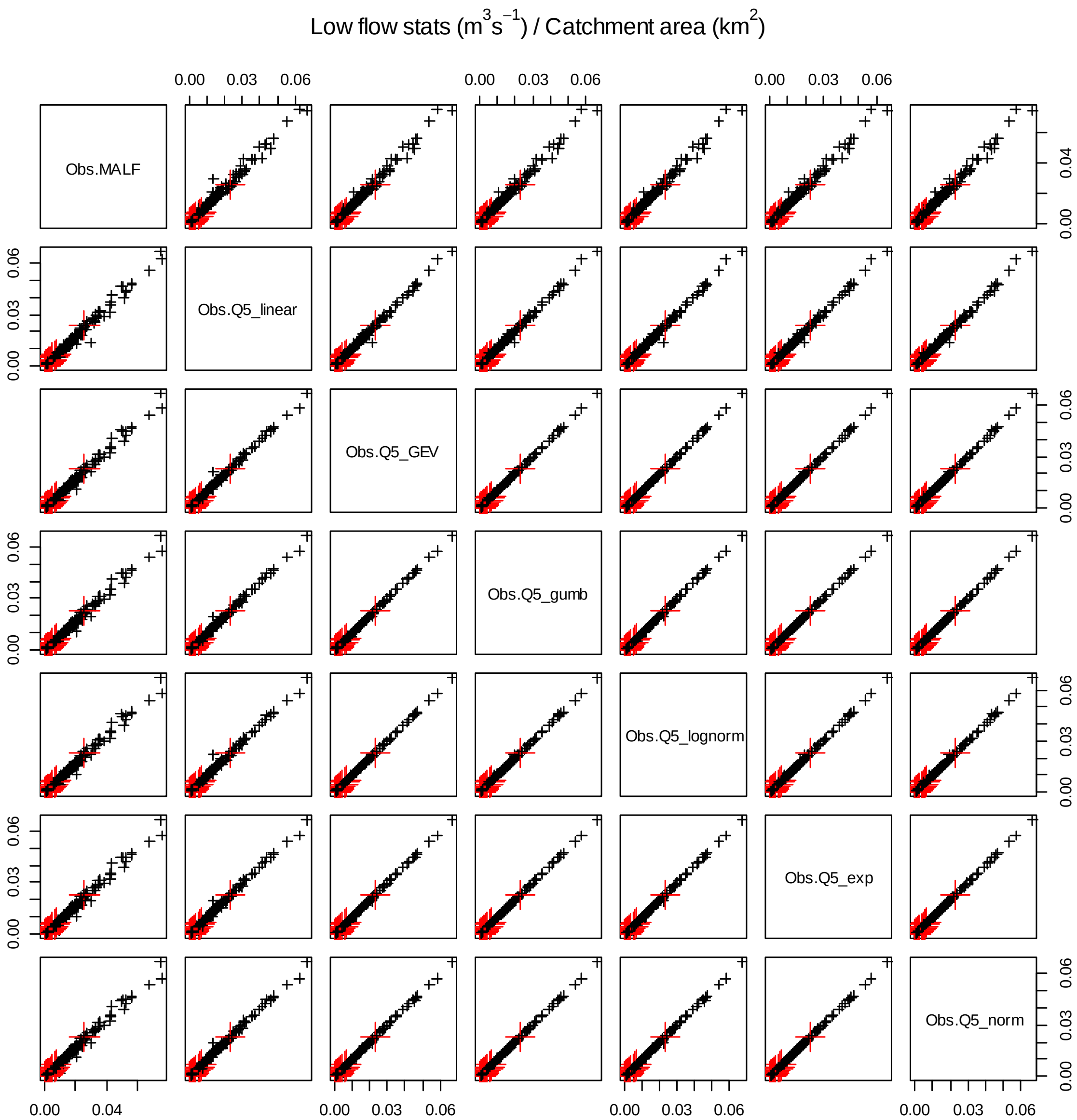

Figure 4-2: Scatterplots of specific low flow indices, including Q5 calculated using a uniform, GEV, Gumbel, lognormal, exponential and normal distribution. Red crosses indicate indices from gauging stations in the Auckland region. Black crosses indicate indices from gauging stations elsewhere in New Zealand.

The position of MALF on the observed FDC varied between sites and between months within sites (Figure 4-3). This indicates that if minimum flows are set relative to MALF, then reliability of supply will not be uniform across sites. Flows in February are less than MALF for longer than in any other month for the majority of sites, including those in the Auckland region. This indicates that, given a minimum flow that does not vary seasonally, February will have the lowest reliability of supply.

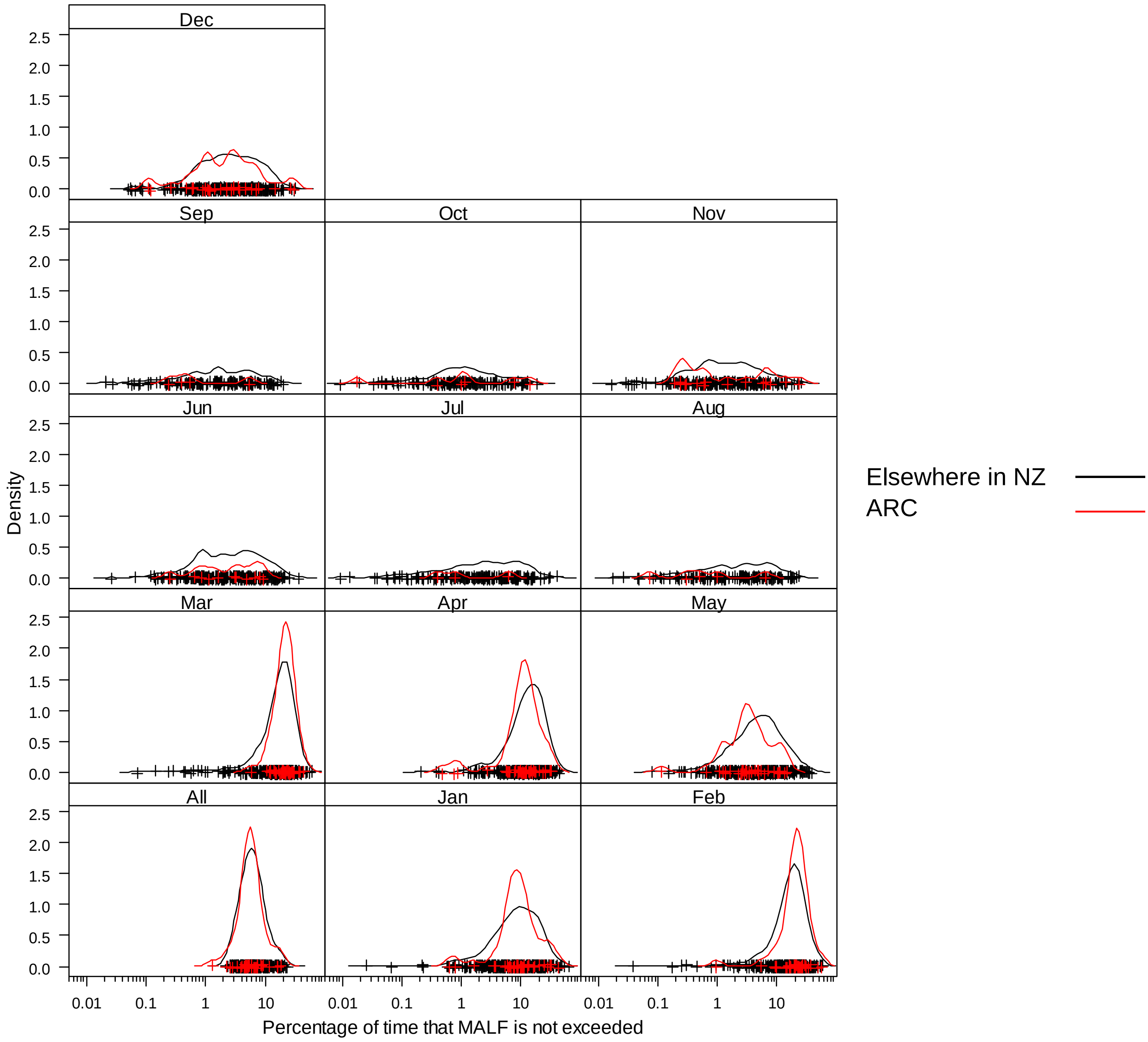

Figure 4-3: Percentage of time that MALF is not exceeded over all time and in each month of the year. Red crosses are for the Auckland region. Black crosses are the elsewhere in New Zealand.

For each time-series of mean daily flows, we fitted the GEV distribution to all daily flows and all daily flows for each month. Results indicated that observed FDCs in the Auckland region were similar in shape to many FDCs observed elsewhere in New Zealand. However, FDCs in the Auckland region did have a tendency to have lower k values and have lower xi values. This generally indicates steeper and less s-shaped FDCs in comparison to elsewhere in New Zealand.

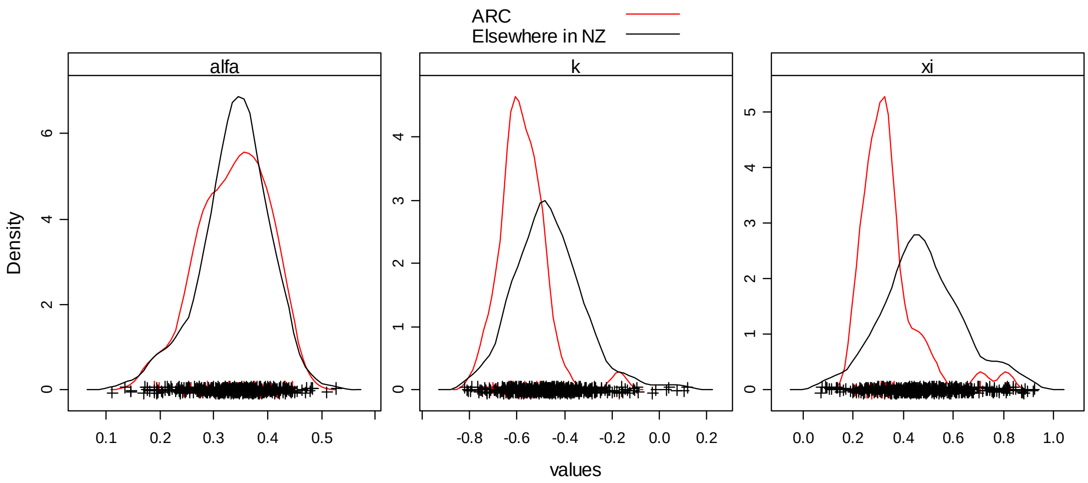

Figure 4-4: Density distributions of parameters describing the GEV distribution of flows over all-time. Red is for the Auckland region. Black is for elsewhere in New Zealand. Alfa, k and xi equate to theta2, theta3, theta1 in Table 3-2.

4.2 Calculated indices

4.2.1 Method 1; Regression

We fitted all regression models using data from: a) the 379 gauging stations used by Booker and Snelder (2012); and b) all available gauging stations following collation of data for this project. In all cases we found that models fitted with all available data performed as well, or better than those fitted using only 379 gauging stations. Therefore the results shown below were all for models fitted using all available data.

Out-of-bag r-squared from random forest models is a measure of prediction accuracy at ungauged locations. Out-of-bag r-squared is therefore a more conservative measure of model fit than traditional r-squared from a linear regression. Out-of-bag r-squared for all indices was generally high (Figure 4-5). Out-of-bag r-squared was particularly high for log mean flow and specific flow. This indicates that these indices were very well predicted. Out-of-bag r-squared was lower for specific MALF and specific Q_5. However, out-of-bag r-squared values of around 0.5 indicates that at least 50% of variance in patterns at ungauged could be explained by these models.

Out-of-bag r-squared was highest for mid-winter (June, July, August), autumn (March, Feb) and mid-summer months (January, December, November) in comparison with the other months (Figure 4-5). This indicates patterns in the proportion of flow in months of the year across New Zealand are more easily discriminated during winter, late autumn and summer than in spring. This may be because patterns in the proportion of flow in winter and summer are stronger across the country because they are driven by long-term climate, whereas patterns in the proportion of flow in spring are less strong.

Out-of-bag r-squared was also reasonably high for GEV parameters describing standardised FDCs for both all-time and for each month of the year (Figure 4-6). The alfa parameter has a strong relationship with the central tendency of each FDC. We standardised all flows before fitting the GEV parameters, therefore there was only relatively weak patterns in alfa and the out-of-bag r-squared for alfa over all-time was relatively low.

Figure 4-7 and Figure 4-8 show the ranking of importance for each independent variable used to fit models to each hydrological index. Results show that different catchment characteristics had more importance for different indices. For example, catchment area had high importance in models of specific flow, whereas potential evapotranspiration had high importance in models of low flows and the proportion of flow in each month. Stream order generally had the lowest importance across the various models.

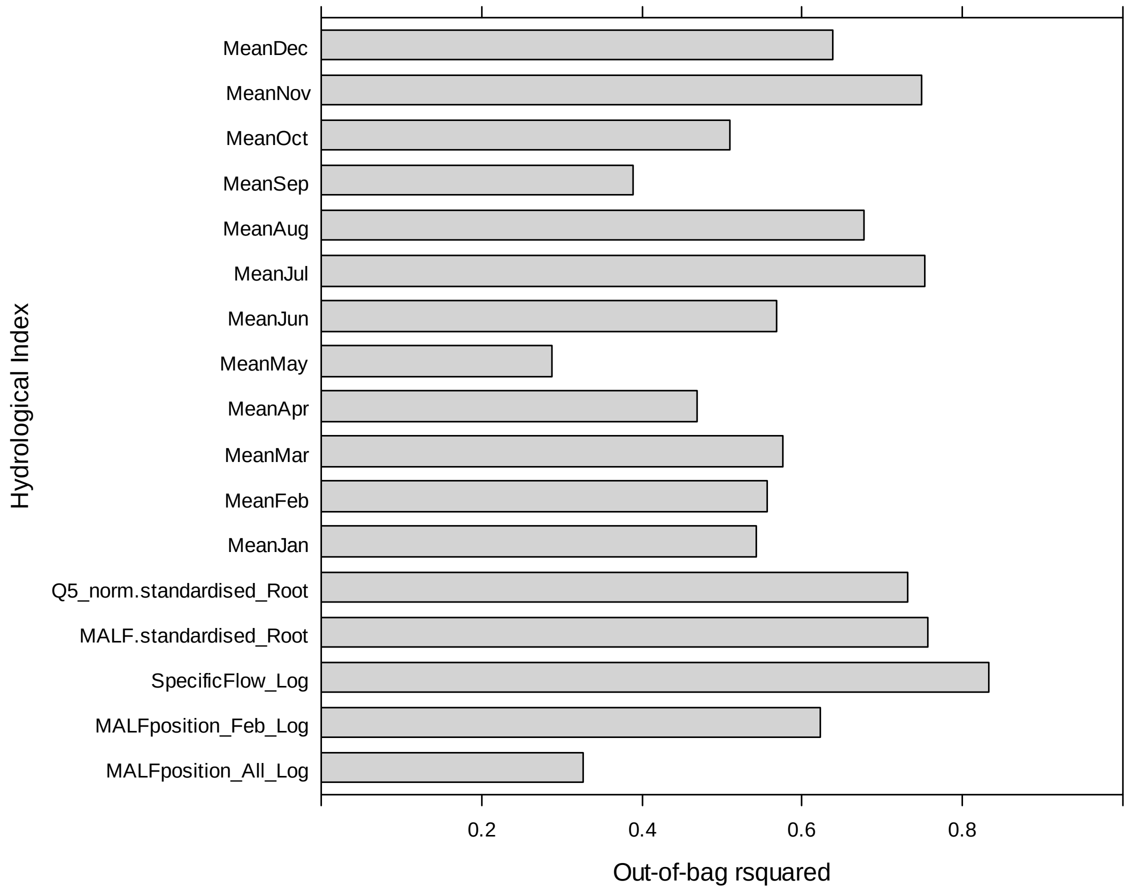

Figure 4-5: Out-of-bag r-squared for random forests of several hydrological indices, fitted using data from catchments throughout New Zealand.

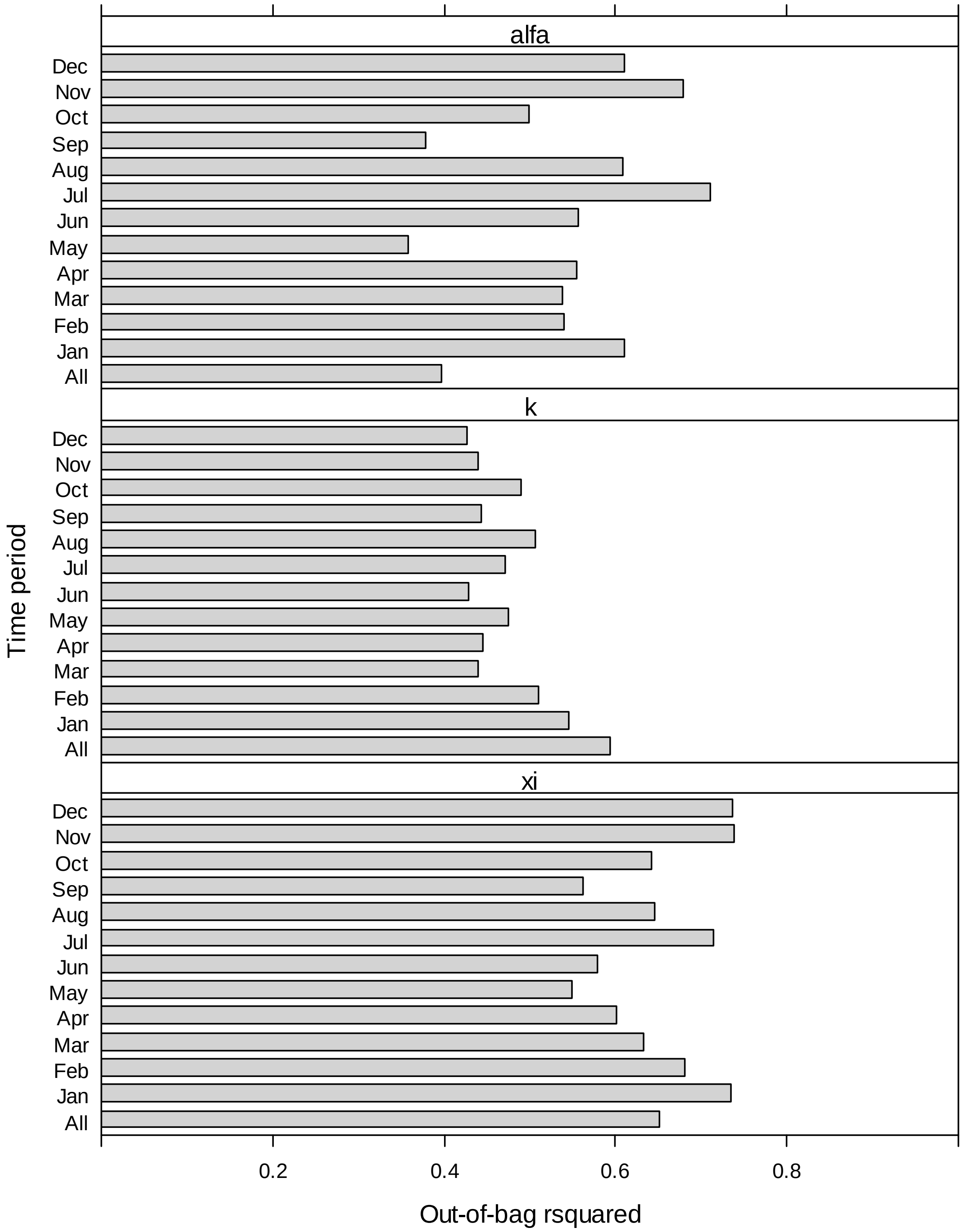

Figure 4-6: Out-of-bag r-squared for random forests of parameters describing a GEV distribution for each month of the year and over all time, fitted using data from catchments throughout New Zealand.

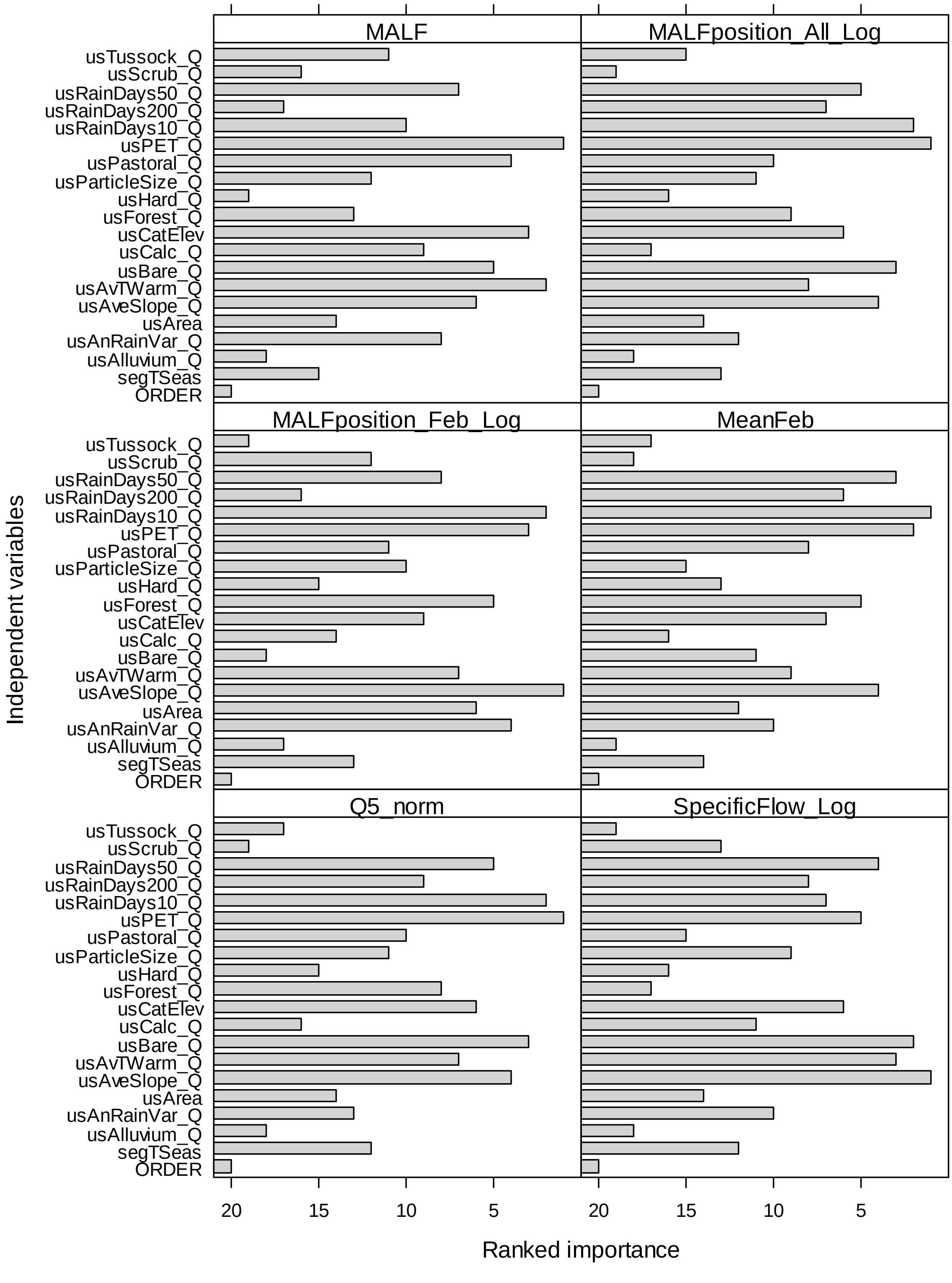

Figure 4-7: Importance in random forests (lowest rank is most important) for several hydrological indices, fitted using data from catchments throughout New Zealand.

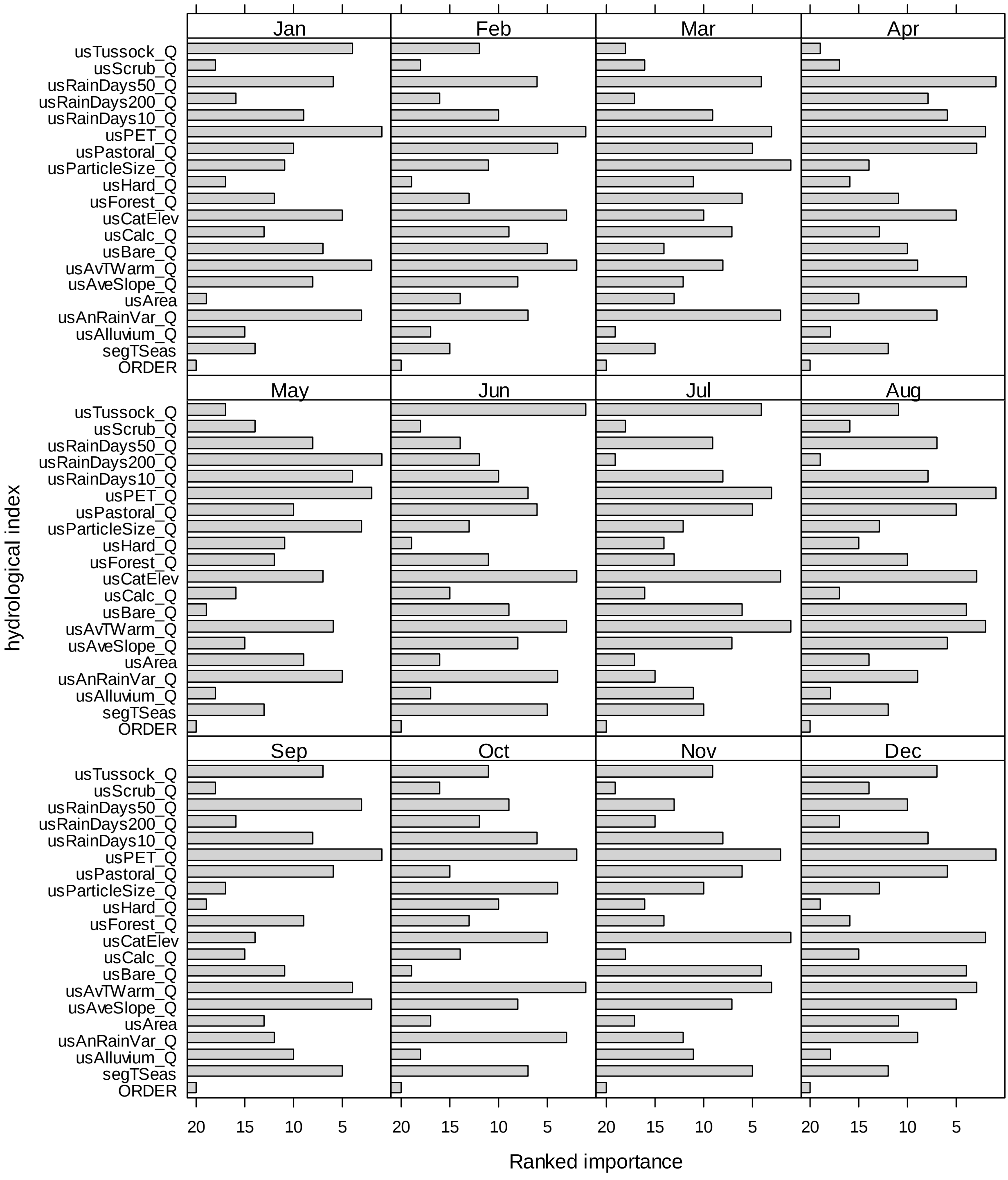

Figure 4-8: Importance in random forests (lowest rank is most important) for mean flow in each month of the year, fitted using data from catchments throughout New Zealand.

4.2.2 Method 2; Hydrology of Ungauged Catchments

See Woods et al., (2006) for more details of the HUC method for mean flow estimation.

4.2.3 Method 3; TopNet

See Clark et al (2008) for more information about TopNet, and Henderson et al (2011) for more information about the national TopNet model of New Zealand.

4.3 Testing

4.3.1 At-site indices

Scatterplots of observed and calculated values give a visual assessment of the performance of each method to predict each hydrological index. Linear regression lines of observed values as a function of calculated values gives an assessment of bias in the calculations. Red lines indicate statistically significant relationships ($p < 0.05$).

Values of specific mean flow were reasonably well produced by all three methods, for both the Auckland region and elsewhere in New Zealand (Figure 4-9). All three methods distinguished the relative difference between Auckland and the rest of New Zealand well. However, there is a relatively narrow range of observed specific mean flow across the Auckland region. This meant that the relatively narrow patterns of specific mean flow within the Auckland region were less well represented. This narrow range in specific mean flow within the Auckland region also makes the regression lines in Figure 4-9 difficult to interpret. The regression lines on Figure 4-9 suggest that, although national patterns are well represented by both the Random Forest and HUC methods, the (narrow) patterns of specific mean flow within the Auckland region were not well represented. Overall, visual inspection of Figure 4-9 suggested that there was little difference between the performance of the Random Forests and HUC methods, and that both these methods performed better than the TopNet method.

Patterns in specific (7-day) MALF flow were reasonably well produced by the Random Forests and HUC methods (Figure 4-10). There is a relatively narrow range of specific MALF across the Auckland region, and all three methods again predicted the relative difference between Auckland and the rest of New Zealand well. Visual inspection and the regression lines in Figure 4-10 suggest that the Random Forests method performed better than the other two methods, both within the Auckland region and across the rest of New Zealand. The HUC method had a tendency to over-predict high values of specific MALF.

Patterns in specific (7-day) Q_5 were reasonably well produced by the Random Forest, but not by TopNet (Figure 4-11). Figure 4-11 suggests that the Random Forest method had a tendency to over-predict low specific Q_5 and under-predict high specific Q_5 within the Auckland region, but not across the rest of New Zealand. No method was available to calculate Q_5 for HUC.

Patterns in the proportion of flow in February were reasonably well produced by the Random Forest, but not by either the HUC method or by the TopNet method (Figure 4-12). This was the case both for the Auckland region and for locations elsewhere in New Zealand.

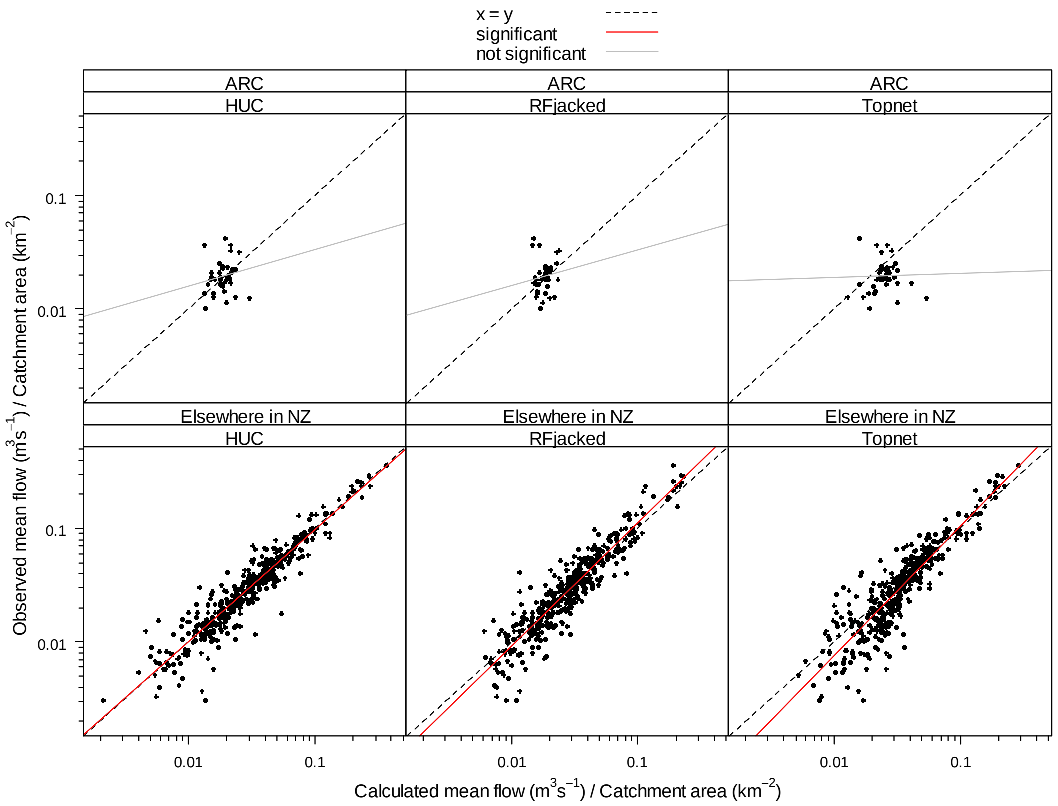

Figure 4-9: Observed versus calculated specific mean flow calculated from three different methods, in the Auckland region (n = 40) and elsewhere in New Zealand (n = 479).

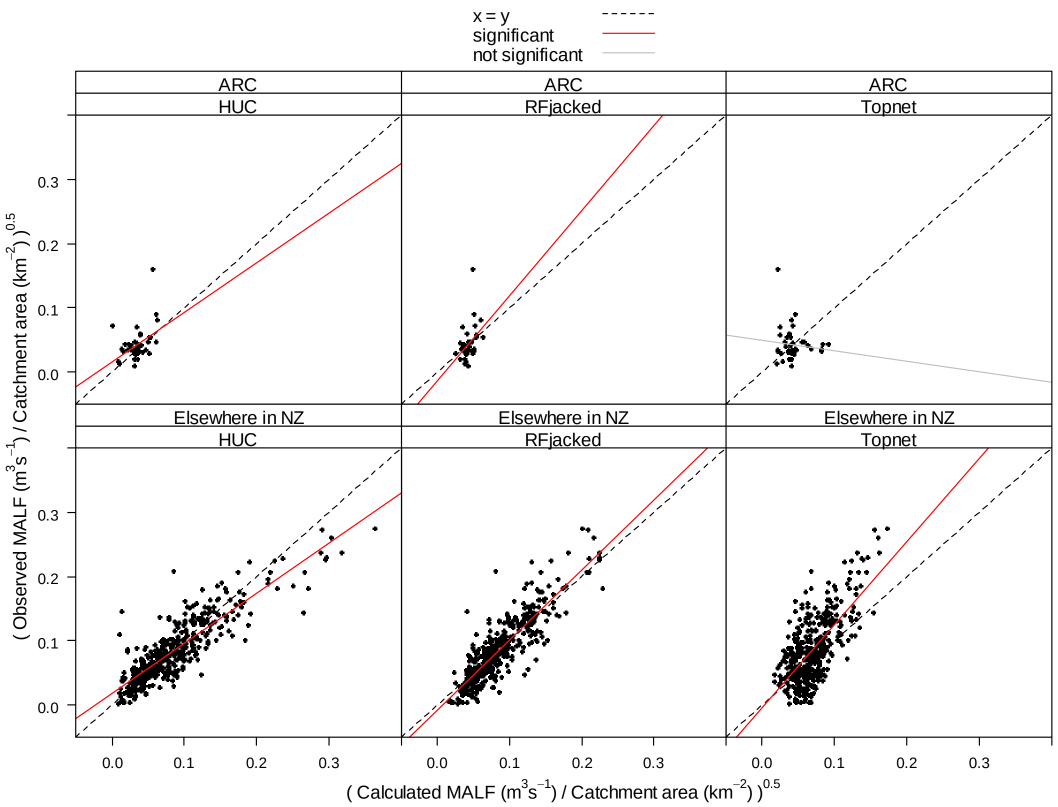

Figure 4-10: Observed versus calculated specific MALF calculated from three different methods, in the Auckland region (n = 40) and elsewhere in New Zealand (n = 479).

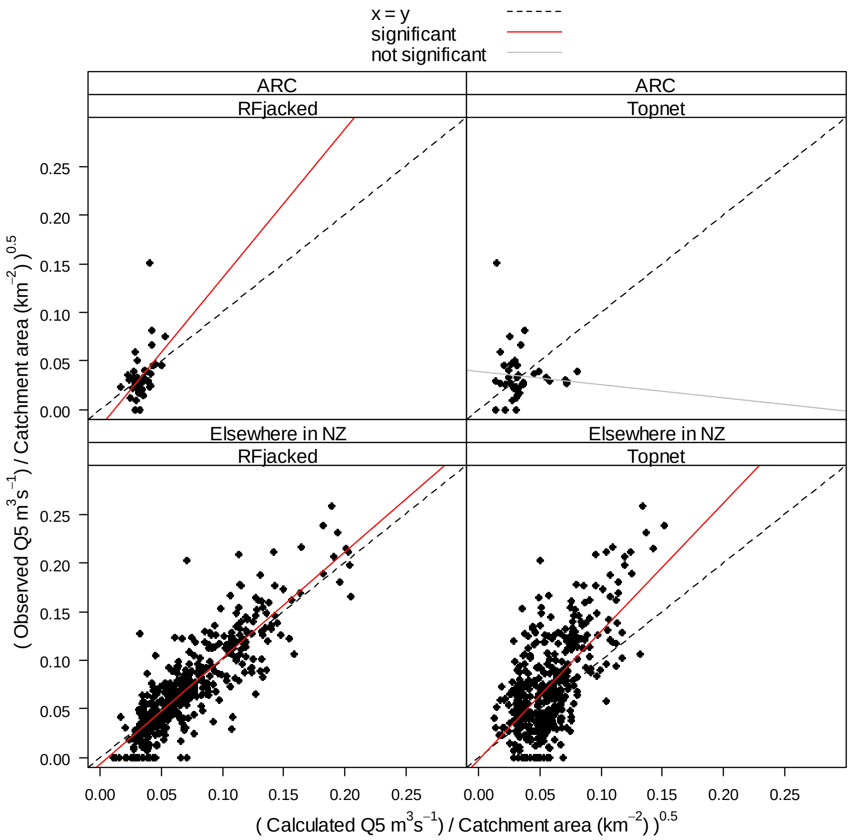

Figure 4-11: Observed versus calculated specific Q_5 calculated from three different methods, in the Auckland region (n = 40) and elsewhere in New Zealand (n = 479).

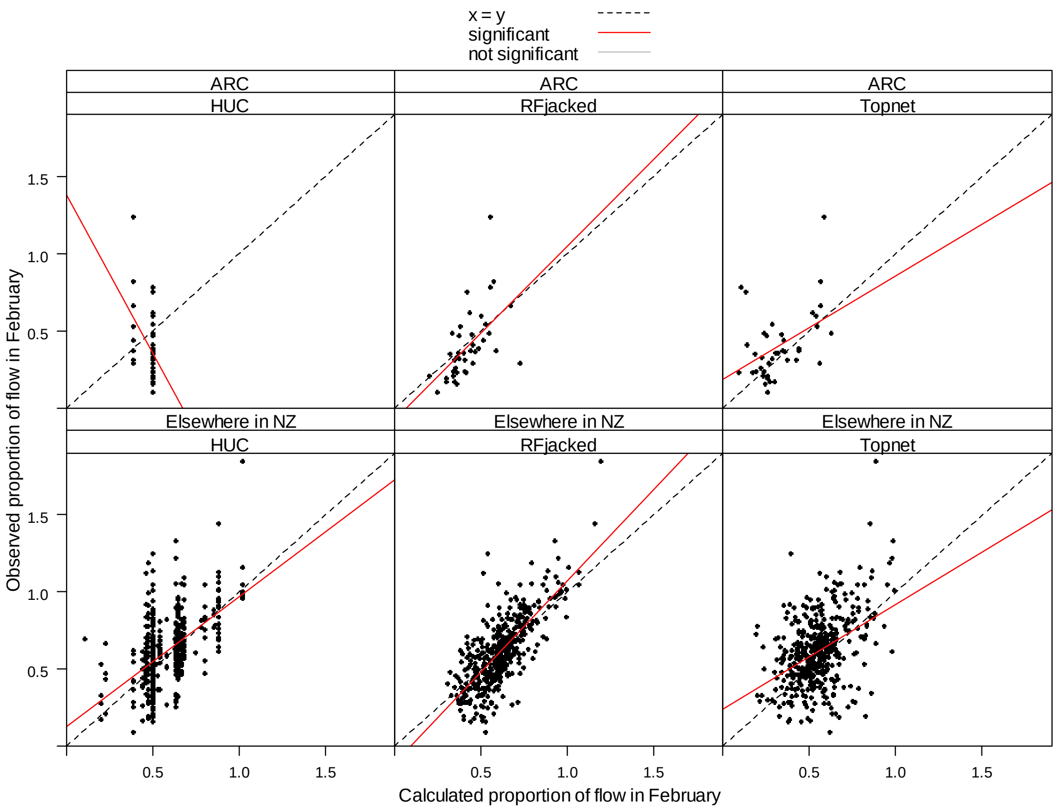

Figure 4-12: Observed versus calculated proportion of flow in February calculated from three different methods, in the Auckland region (n = 40) and elsewhere in New Zealand (n = 479).

RMSD represents average error in transformed space (see Table 3-4 for details of transformations and units) for each method for each hydrological index. Lower RMSD represents more correspondence between observed values and calculated values. On average, specific mean flow in log transformed space was equally well predicted by the Random Forest and HUC methods for observations in the Auckland region (Figure 4-13). In fact, RMSD for the Random Forest method was 1.2% less than that for the HUC method. The HUC method performed better than Random Forest for observed values from the rest of New Zealand. Given this result, and given that the HUC method for calculating mean flow has already been published in the peer-review literature (Woods et al., 2006), we recommend that the HUC method is the best currently available method for calculating mean flow for application to Auckland region.

On average, specific MALF in square root transformed space was better predicted by the Random Forest method than the HUC method in the Auckland region (Figure 4-13). This was the case both for Auckland and elsewhere in New Zealand, therefore, we recommend that the Random Forest method is the best currently available for calculating 7-day MALF for application to the Auckland region.

On average, specific Q_5 in square root transformed space was far better predicted by the Random Forest method than the TopNet method in the Auckland region (Figure 4-13). This was also the case elsewhere in New Zealand. Therefore we recommend that the Random Forest method for calculating 7-day Q_5 is the best currently available method for application to the Auckland region.

On average, the proportion of flow in February was better predicted by the Random Forest method than either the HUC method or the TopNet method in the Auckland region (Figure 4-13). This was also the case elsewhere in New Zealand. Therefore we recommend that the Random Forest method for calculating the proportion of flow in February is the best currently available method for application to the Auckland region. Similar results were also found for other months.

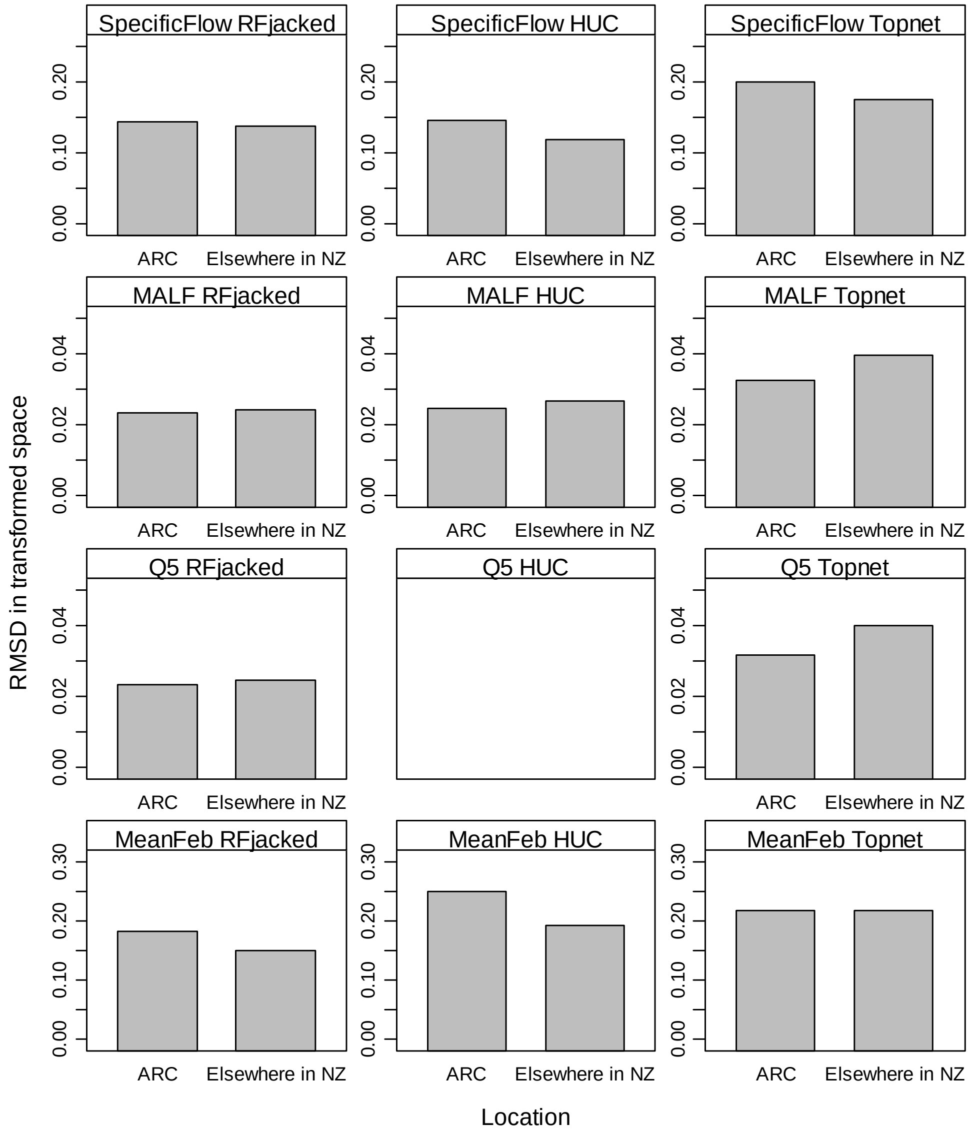

Figure 4-13: Root-mean-square deviance in calculated specific mean flow, MALF, Q_5 and proportion of flow in February calculated from three different methods, in the Auckland region (n = 40) and elsewhere in New Zealand (n = 479).

4.3.2 Flow duration curves

We calculated RMSD for each percentile of many standardised FDCs. RMSD in standardised FDCs was lowest when calculated from for the Random Forest methods for all percentiles and for all months of the year when compared with both the HUC method and the TopNet method (Figure 4-14). The same pattern was also found for the all-time FDC, both in the Auckland region and elsewhere in New Zealand (Figure 4-15). This indicates that the Random Forest method for calculating FDCs over all-time and for each month of the year is the best currently available method for application to the Auckland region. Since these FDCs represent standardised flows, they must be multiplied by mean flow to be transformed into the correct units.

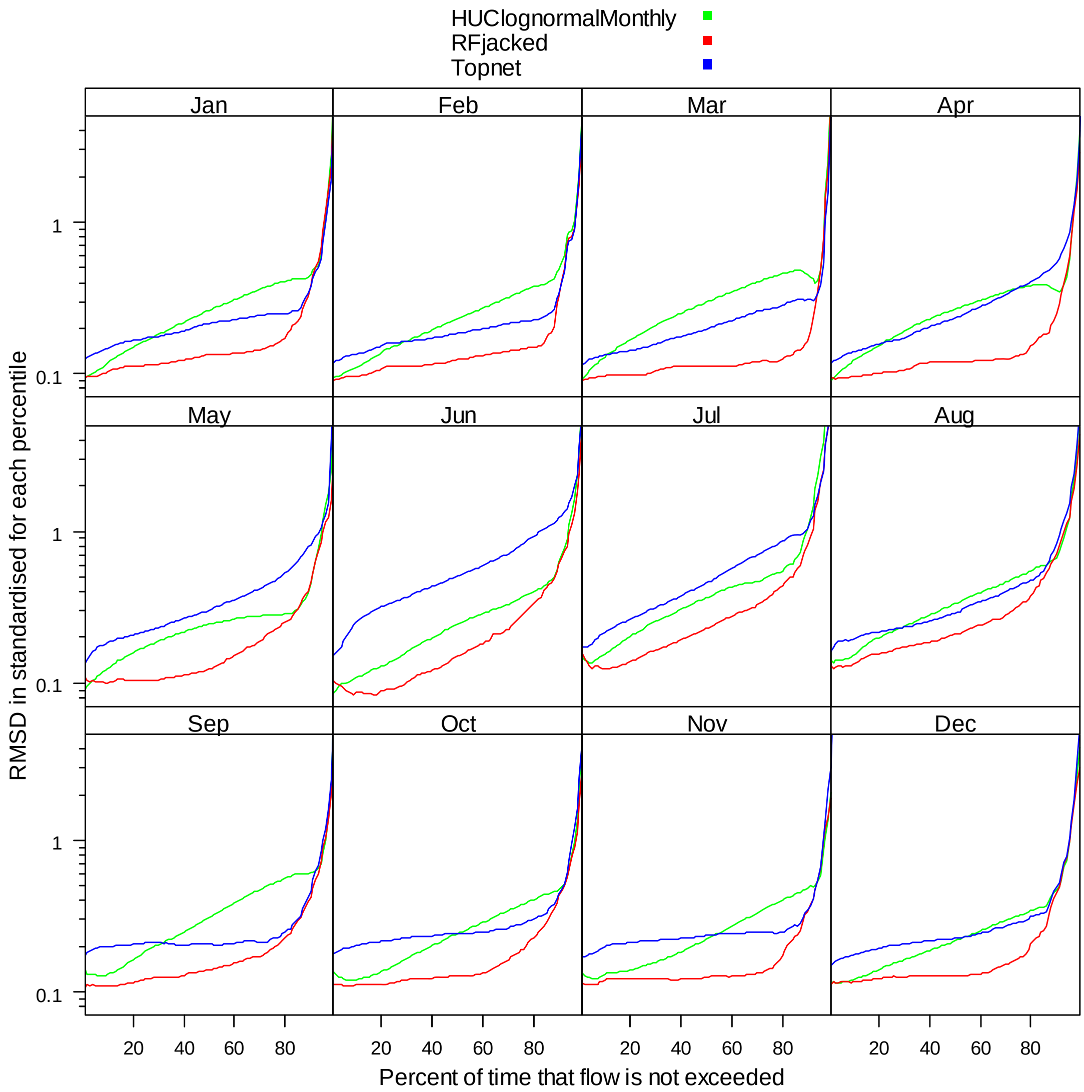

Figure 4-14: For each month, root-mean-square deviance in calculated flow from three different methods, in the Auckland region.

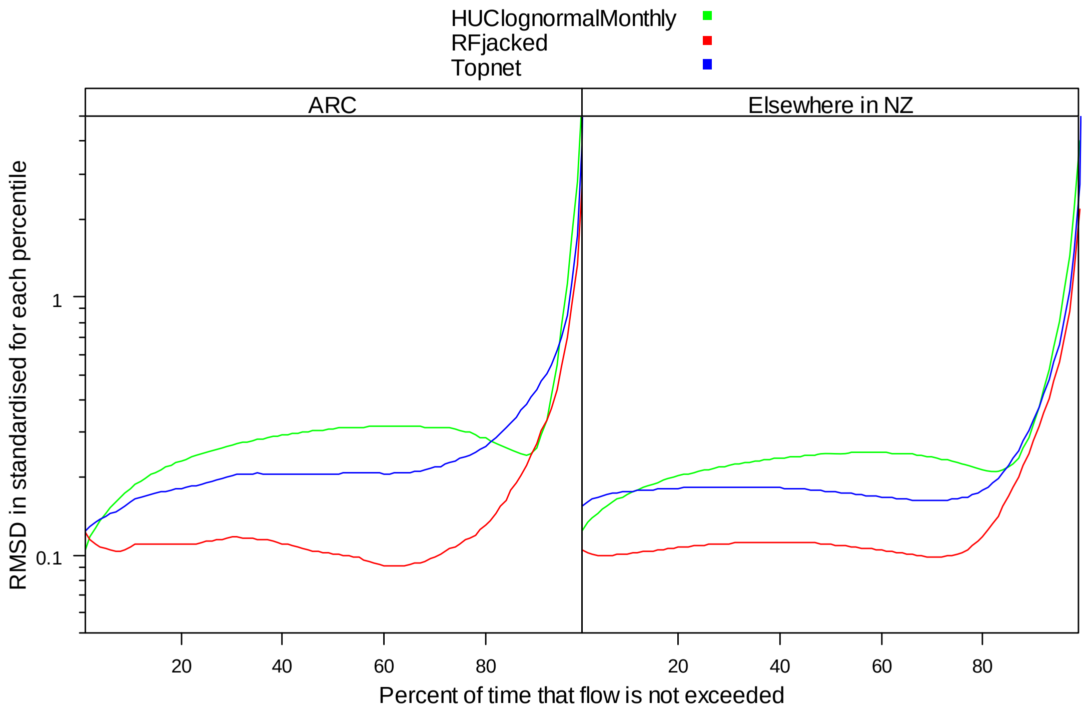

Figure 4-15: For the all-time flow duration curve, root-mean-square deviance in calculated flow from three different methods, in the Auckland region.

4.4 Regional patterns

Figure 4-16 shows the results a random forest model predicting the position of MALF on the February FDC. This represents the percentage of time in February for which flow is lower than MALF. This is equivalent to the percentage of time in February for which total restriction would apply if the minimum flow were set to be MALF at each location. We suggest that this type of information can be applied when managing water resources and in particular setting default minimum flows and total allocations at a regional level. Some patterns can be seen in Figure 4-16. For example, flow is lower than MALF in February for a relatively short percentage of the time in particular locations. In contrast, flow is lower than MALF in February for a longer percentage of the time in other locations. These variations mostly relate to the geological conditions that exist across the Auckland region. This is a good example of a spatially varying outcome (different levels of restriction) that has been generated from a spatially uniform rule (minimum flow is set to MALF). See Snelder et al., (2011) for more details of this phenomenon.

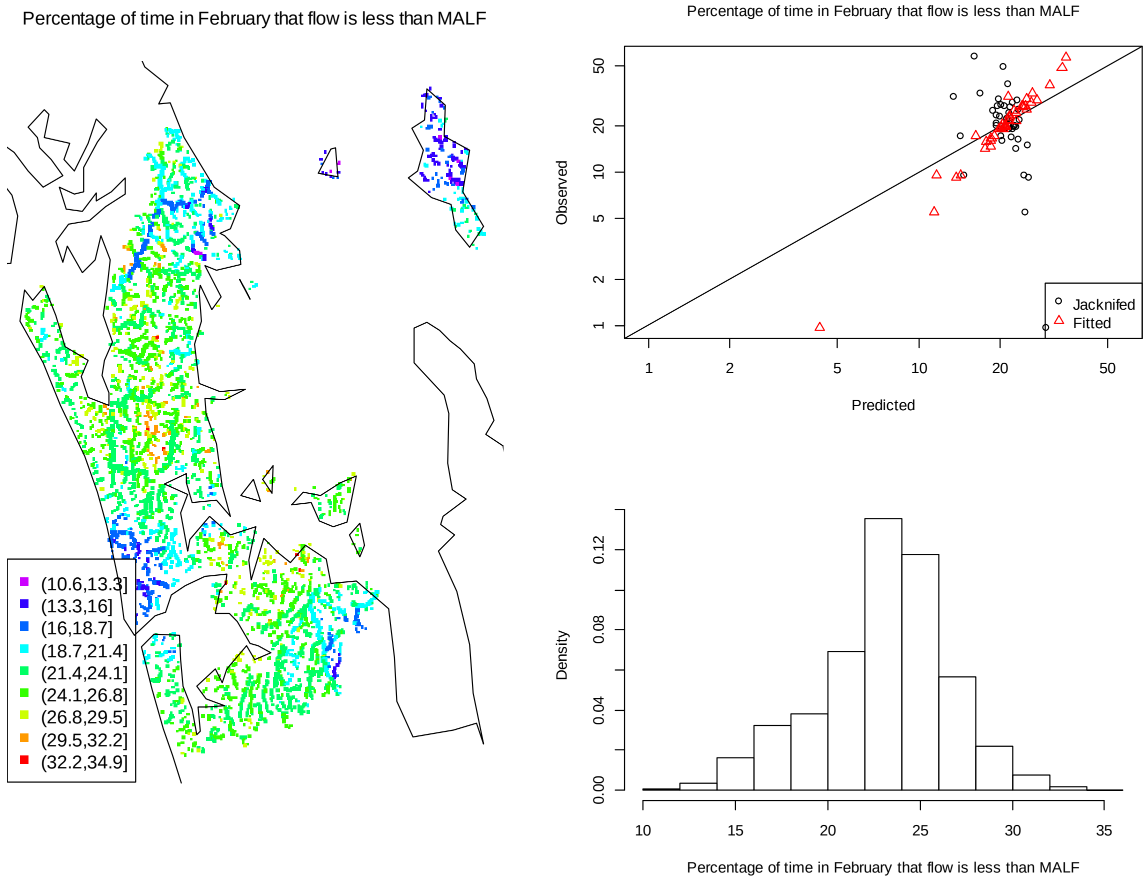

Figure 4-16: Map, histogram and observed against calculated percentage of time in February that flow is less than MALF for rivers of second order and higher in the Auckland region.

5.0 Discussion

We compared the ability of various methods for calculating several hydrological indices across New Zealand, and specifically for the Auckland. We found that no one method out-performed the other methods for all indices in all regions of New Zealand. For example, the HUC method produced the best correspondence between observed and calculated values of mean discharge, whereas the Random Forest method produced best correspondence between observed and calculated values for MALF in the most, but not all regions.

We applied various methods for calculating a suite of hydrological indices. We found differences in the correspondence between observed and calculated values between the various methods. We compared particular implementations of random forests and TopNet. Different sets of estimates could have been produced if these methods had been deployed in a different way. For example, random forest could have been fitted using a different set of independent variables or a different data set, which would have changed the calculated values produced by this method. Improved estimates would be expected for random forests methods had more data been available. Improved performance by the TopNet method would also be expected with improvements in parameter calibration. We used the national application of TopNet to provide calculated values for this method. This application of TopNet is uncalibrated. Although the performance of the Topnet model was not as good as the other two methods for most cases, we note that: (i) the model was uncalibrated (ii) it is capable of providing continuous hydrographs for ungauged catchments (iii) it is capable of providing estimates of the potential impacts of climate change and land use change (see e.g. Poyck et al, 2011, Woods et al. 2010). Development of an improved national TopNet model, including improvements to parameter estimation, is taking place at the same time as this project, and a new set of national estimates is expected to be available in August 2012.

Discrepancies between observed and calculated values may have been caused by a combination of errors in both observations and calculations. We aimed to calculate and test hydrological indices that represented reasonably natural hydrological conditions. We therefore removed any hydrological records that were either heavily abstracted or affected by large engineering projects such as dams or flow diversions from our analysis. We assumed that all the remaining flow records could be considered to be reasonably natural, and therefore they were included in our test data set. Many of the flow records that we used will have been modified to some degree. For example, changes in land cover are known to affect hydrological patterns. However, if we had only included flow records draining completely natural catchments, then only a very limited, and heavily biased, data set would have been available for testing. Furthermore, naturalisation (adding known flow alterations to observed flow records) is a notoriously difficult and data hungry process. We also assumed that all observed flow records could be considered to represent actual flows. However, during data quality checking we found several errors in the observed data. For example, gaps in the records that had been recorded as constant flows. We corrected these errors prior to analysis. Another uncertainty in the observed data is related to catchment area. This is particularly the case for small catchments where it may be impossible to quantify the true catchment area. Incorrect estimates of catchment area, rather than prediction error, may be one explanation for the discrepancies between observed and calculated values in Figure 4-9 for very small catchments.

We performed comparisons between observed and calculated values in standardised and transformed space. This was necessary in order to provide an unbiased assessment of the calculated hydrological indices. This was appropriate for this study because we aimed to assess the relative performance of each method to calculate each index, but applying this method meant that it is difficult to interpret the units of RMSD to assess the absolute accuracy of the calculated values. We therefore back-transformed RMSD and displayed the mean error in the original units for each hydrological index (Figure 5-1 and Figure 5-2).

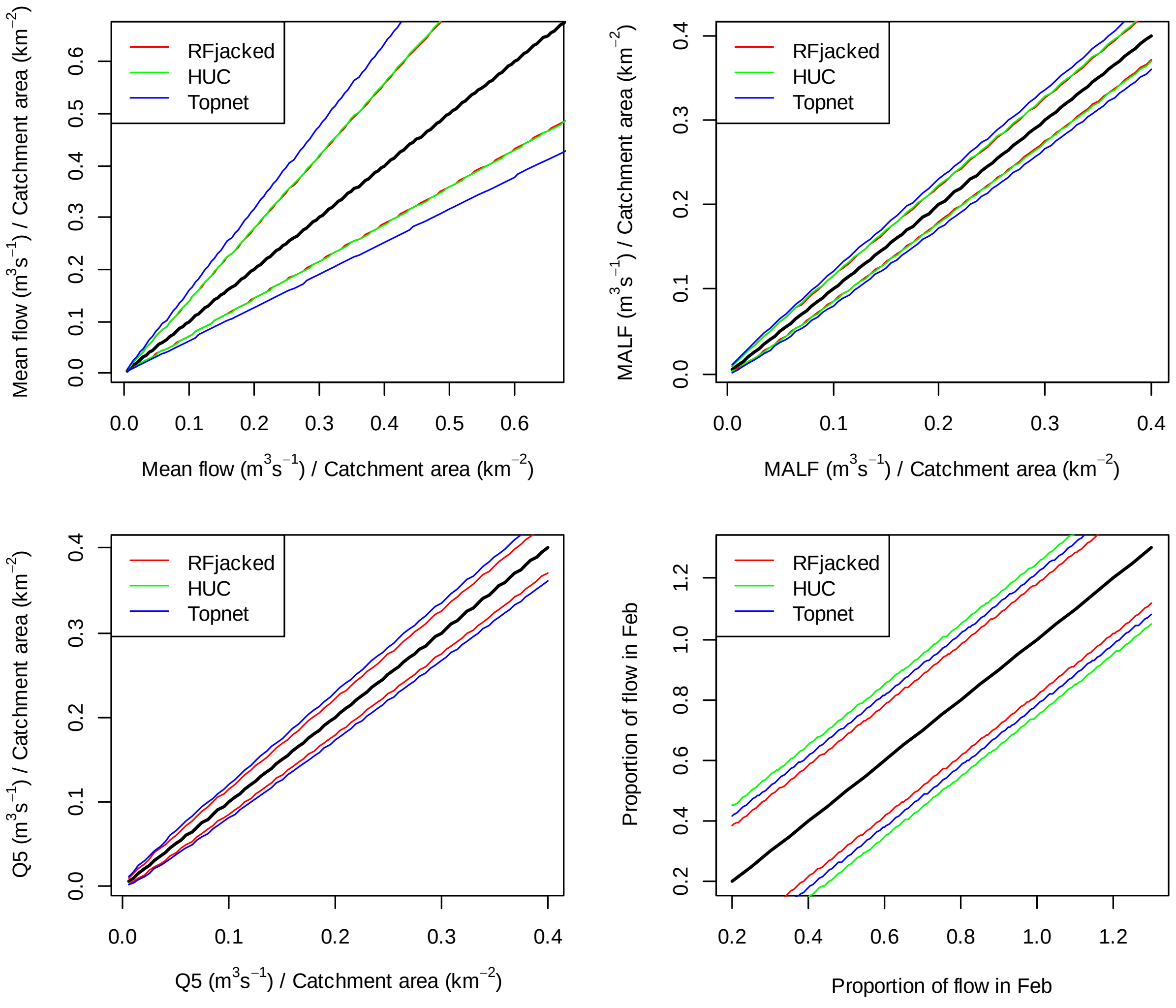

Figure 5-1: Mean errors for each of four hydrological indices across a range of values in non-logged space, in the Auckland region.

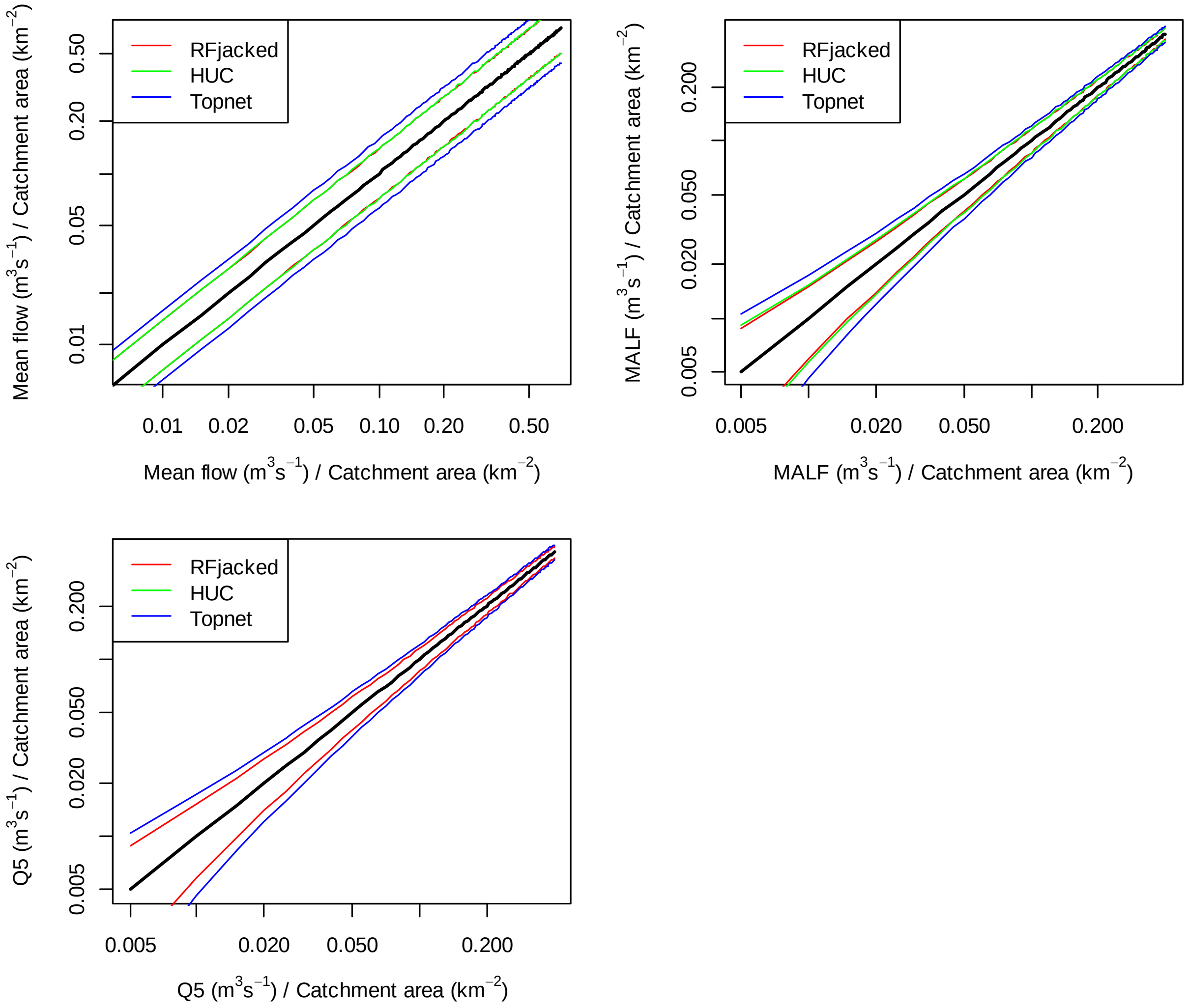

Figure 5-2: Mean errors for each of four hydrological indices across a range of values in logged space, in the Auckland region.

6.0 Conclusions

For this project 485 flow records containing at least five years of mean daily flow data were assembled. These records were used to create regression (random forest) models to calculate several hydrological indices. Calculated values of the same hydrological indices were also extracted from NIWA's national TopNet model and databases available from the previously completed Hydrology of Ungauged Catchment (HUC) projects. Calculated values for each method were then compared with observed values using scatterplots and by calculating root-mean-square deviance. Results indicated that:

- the HUC method is the best currently available method for calculating mean flow for application to Auckland region;
- the Random Forest method is the best currently available for calculating 7-day mean annual low flow (MALF) for application to the Auckland region;
- the Random Forest method for calculating 7-day one-in-five low flow (Q_5) is the best currently available method for application to the Auckland region;
- the Random Forest method for calculating the proportion of flow in February is the best currently available method for application to the Auckland region.
- the Random Forest method for calculating FDCs over all-time and for each month of the year is the best currently available method for application to the Auckland region.

These data were used to demonstrate how calculated hydrological values at all rivers in a region can be used to inform river management decisions. For example, maps were used to illustrate that the proportion of time in February that is lower than the 7-day MALF varies across a region. This has implications for both reliability of supply to water users and for ecological effects when setting minimum flow and total allocations as a proportion of 7-day MALF.

7.0 Deliverables

Tables containing estimates of MALF, Q_5 and Q_{bar} and parameters describing FDCs for all reaches of the NZ river network (as defined by the REC) in the Auckland region along with definitions, units and instructions on FDC generation are provided as supplementary appendices to this report[1].

[1] Note: In the meantime, tables containing these estimates are available for all reaches of the New Zealand river network as part of the Ministry for the Environment's data service:
https://data.mfe.govt.nz/table/2536-natural-river-flow-statistics-predicted-for-all-river-reaches/data/
(last accessed 15 August 2016)

8.0 Acknowledgements

We thank Gillian Crowcroft and Clive Coleman for their assistance in providing flow data and information of the catchments above gauging stations in Northland. We thank Kathy Walter and Jani Diettrich with help collating and extracting flow data. We also thank Roddy Henderson and Paul Franklin, who provided advice on various aspects of the work.

9.0 References

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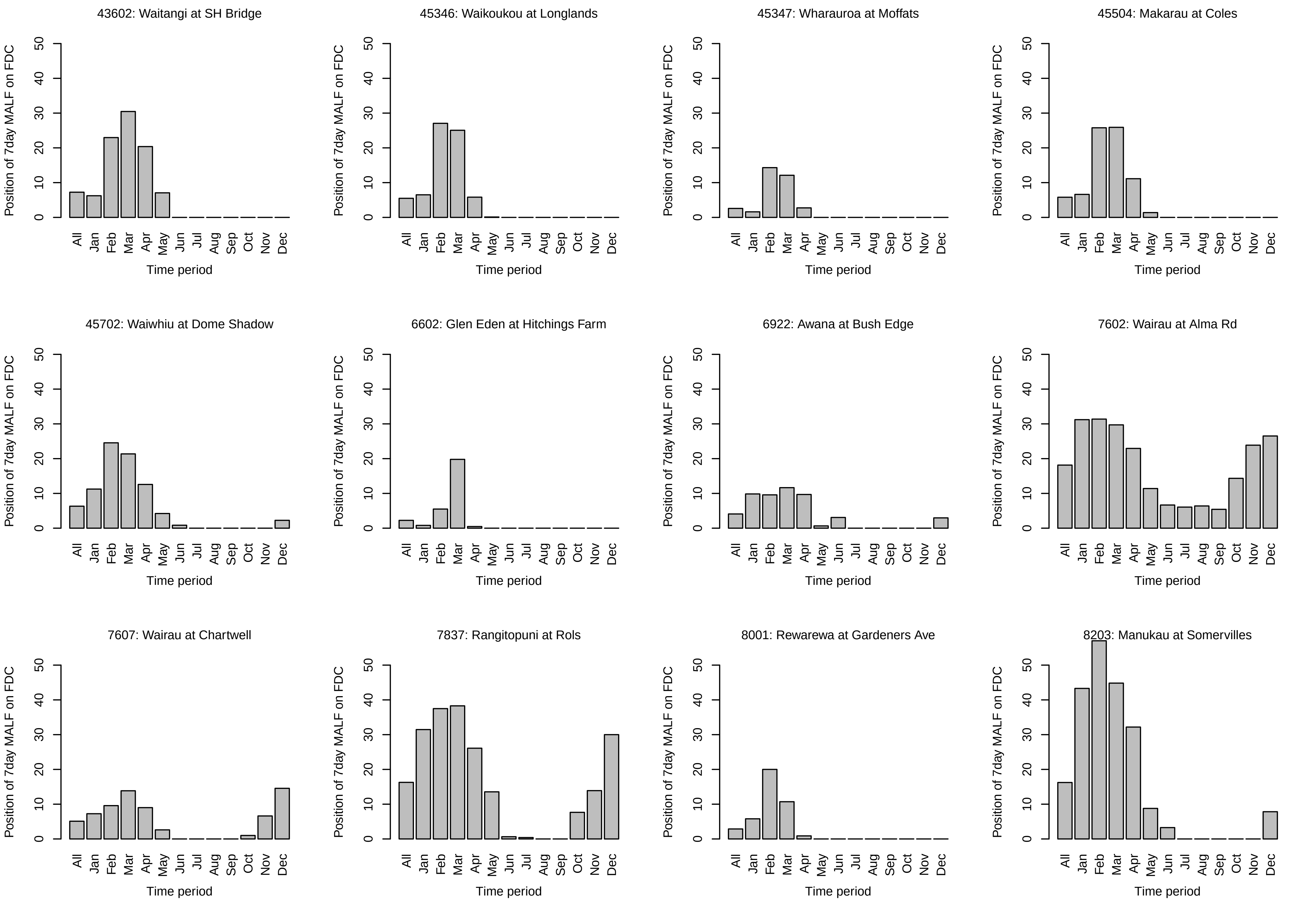
Appendix A Position of 7day MALF on the flow duration curve


43602: Waitangi at SH Bridge
45346: Waikoukou at Longlands
45347: Wharauroa at Moffats
45504: Makarau at Coles
45702: Waiwhiu at Dome Shadow
6602: Glen Eden at Hitchings Farm
6922: Awana at Bush Edge
7602: Wairau at Alma Rd
7607: Wairau at Chartwell
7837: Rangitopuni at Rols
8001: Rewarewa at Gardeners Ave
8203: Manukau at Somervilles
Position of 7day MALF on FDC
0
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All
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May
Jun
Jul
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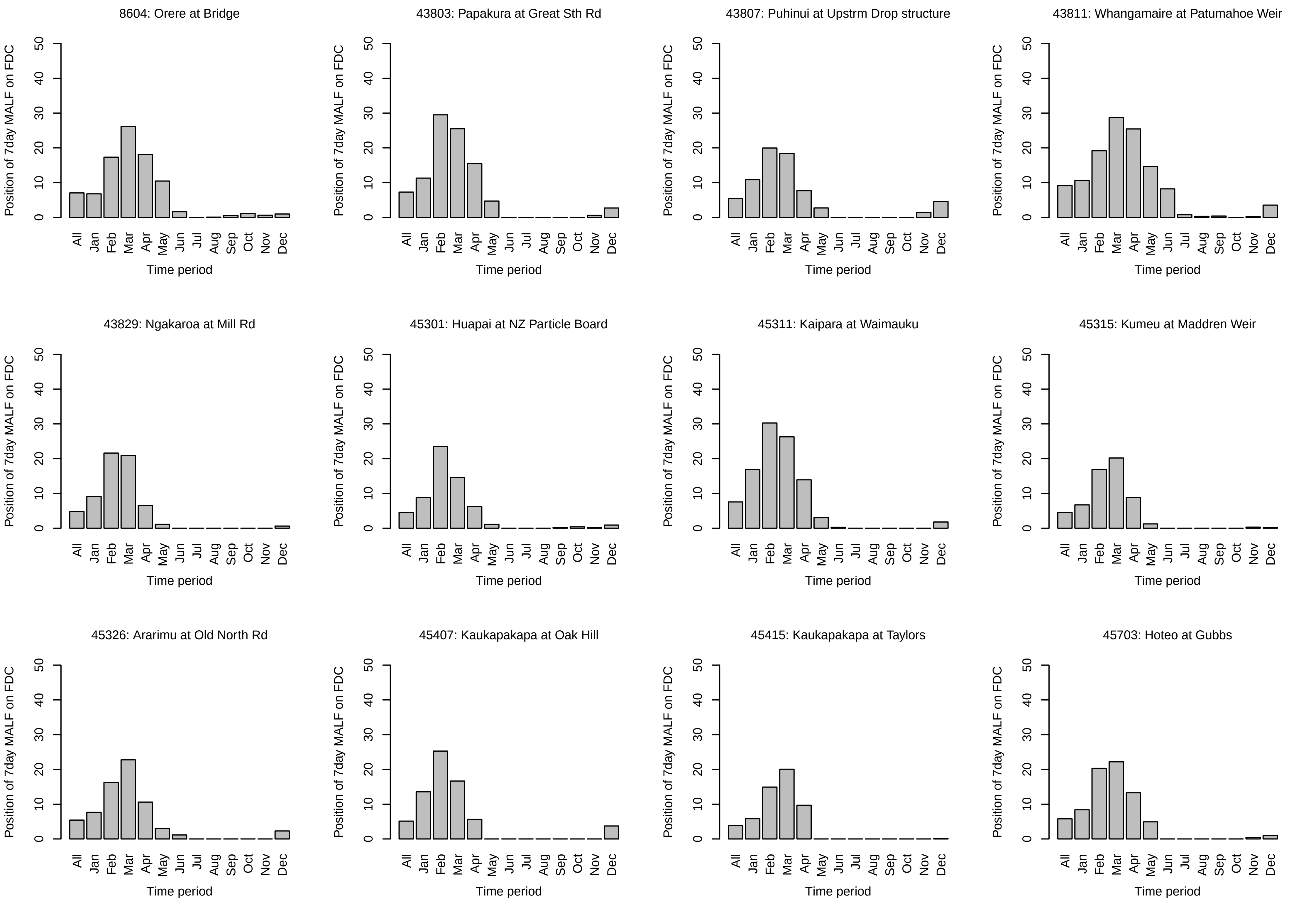
Oct
Nov
Dec
Time period


8604: Orere at Bridge
43803: Papakura at Great Sth Rd
43807: Puhinui at Upstrm Drop structure
43811: Whangamaire at Patumahoe Weir
43829: Ngakaroa at Mill Rd
45301: Huapai at NZ Particle Board
45311: Kaipara at Waimauku
45315: Kumeu at Maddren Weir
45326: Ararimu at Old North Rd
45407: Kaukapakapa at Oak Hill
45415: Kaukapakapa at Taylors
45703: Hoteo at Gubbs
Position of 7day MALF on FDC
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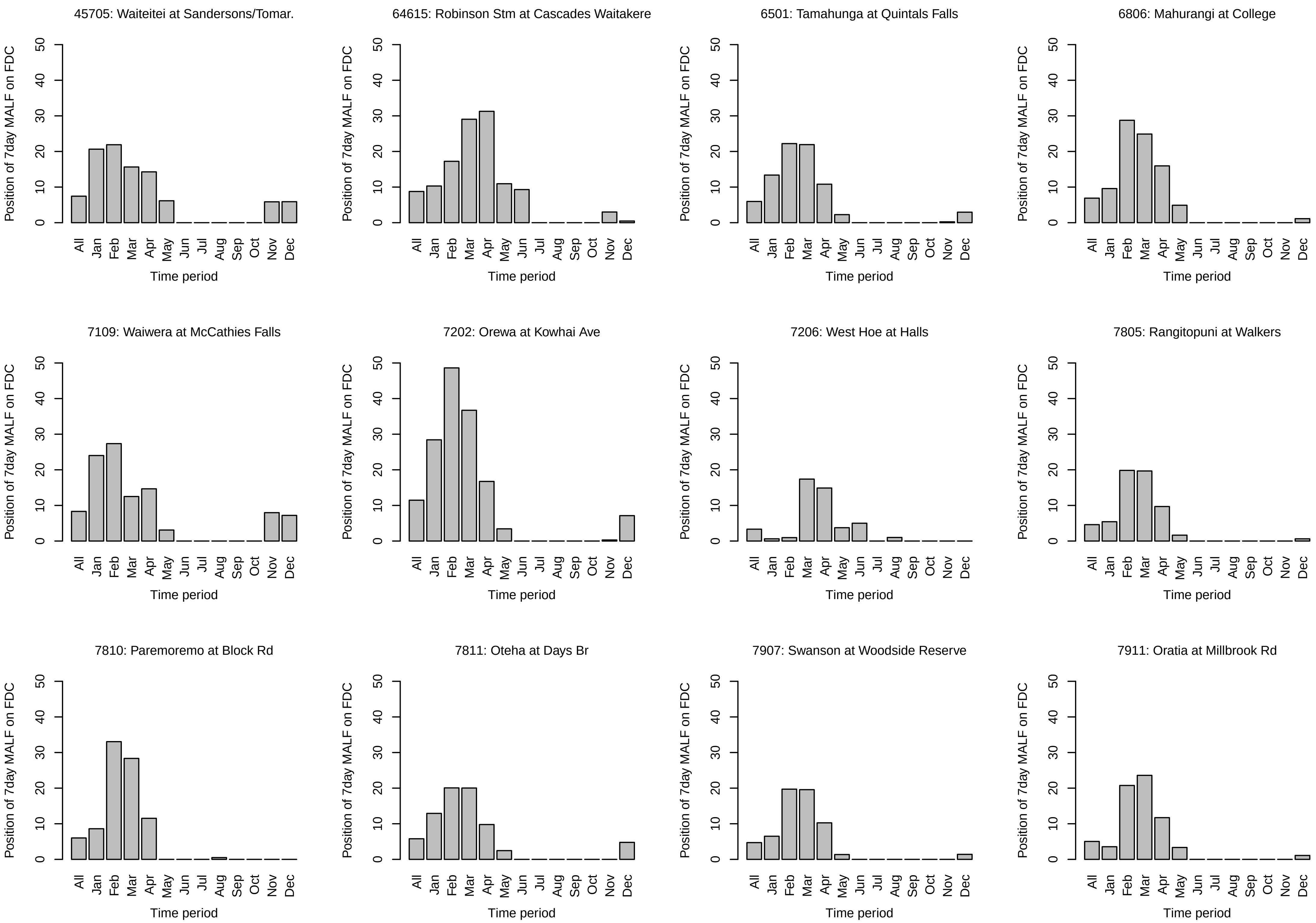
Time period


45705: Waiteitei at Sandersons/Tomar.
64615: Robinson Stm at Cascades Waitakere
6501: Tamahunga at Quintals Falls
6806: Mahurangi at College
7109: Waiwera at McCathies Falls
7202: Orewa at Kowhai Ave
7206: West Hoe at Halls
7805: Rangitopuni at Walkers
7810: Paremoremo at Block Rd
7811: Oteha at Days Br
7907: Swanson at Woodside Reserve
7911: Oratia at Millbrook Rd
Position of 7day MALF on FDC
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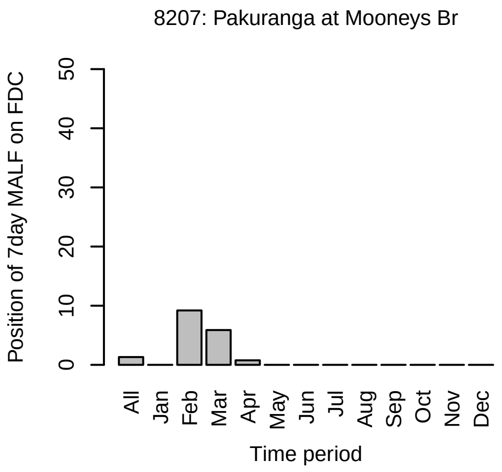
8207: Pakuranga at Mooneys Br
Position of 7day MALF on FDC
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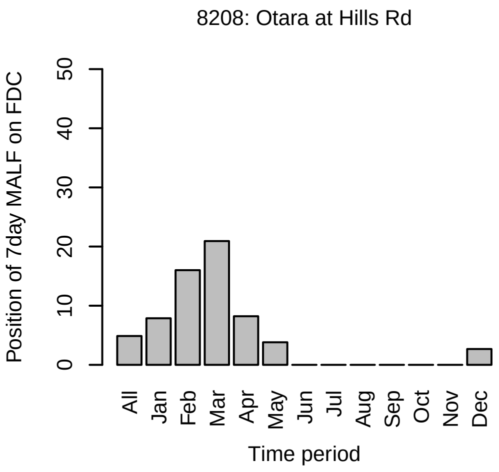
Time period


8208: Otara at Hills Rd
Position of 7day MALF on FDC
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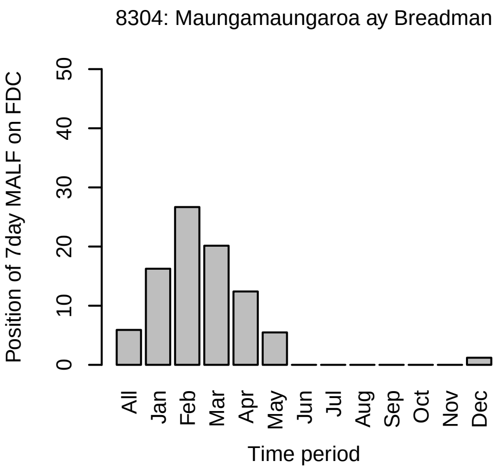
Time period


8304: Maungamaungaroa ay Breadman
Position of 7day MALF on FDC
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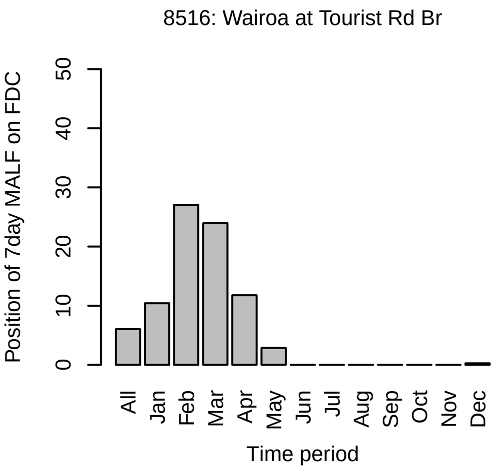
Time period


8516: Wairoa at Tourist Rd Br
Position of 7day MALF on FDC
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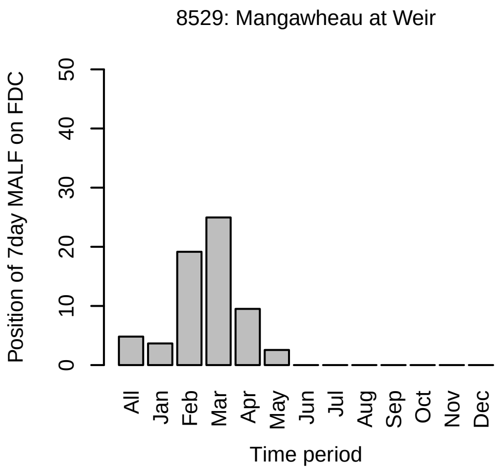
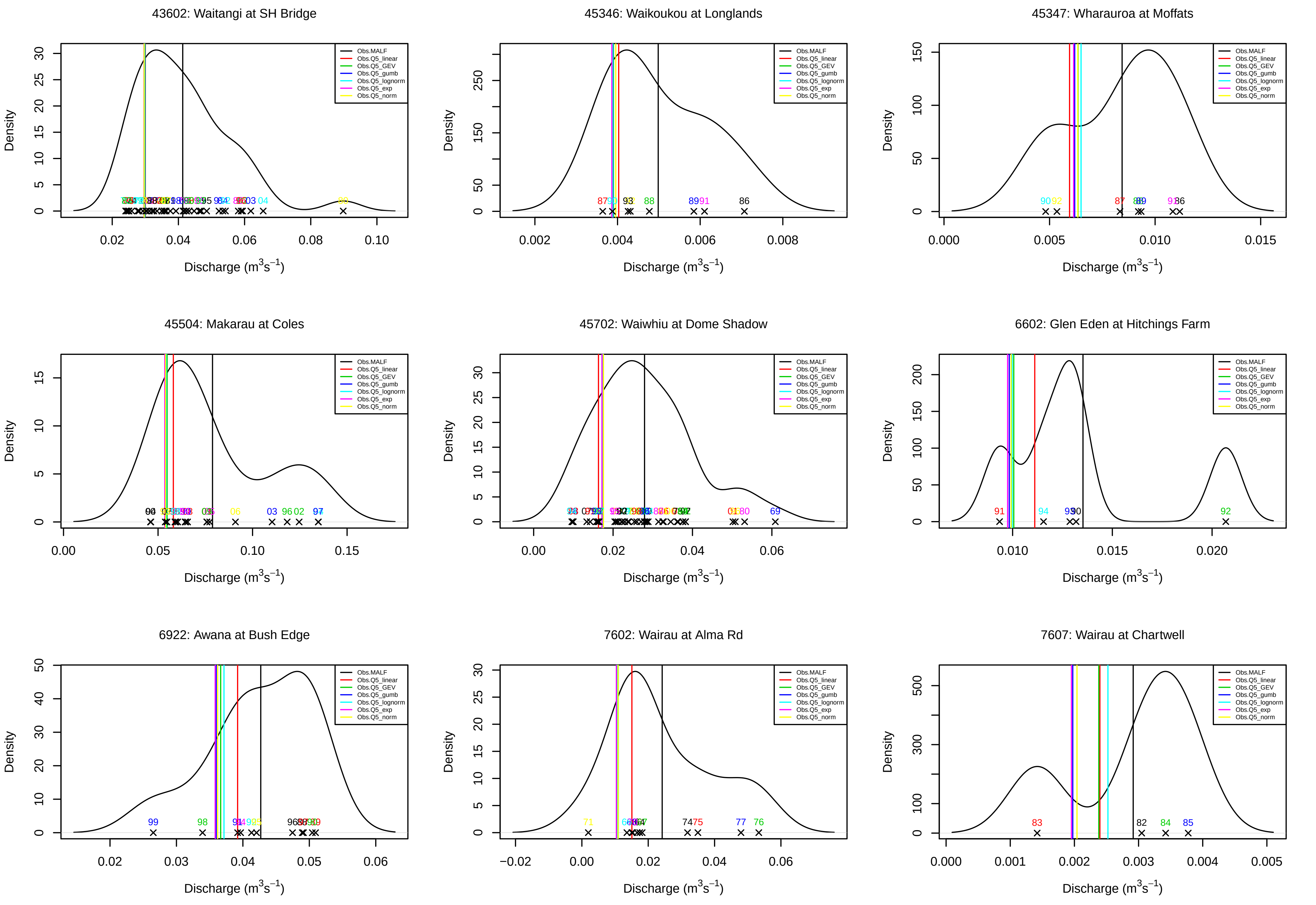
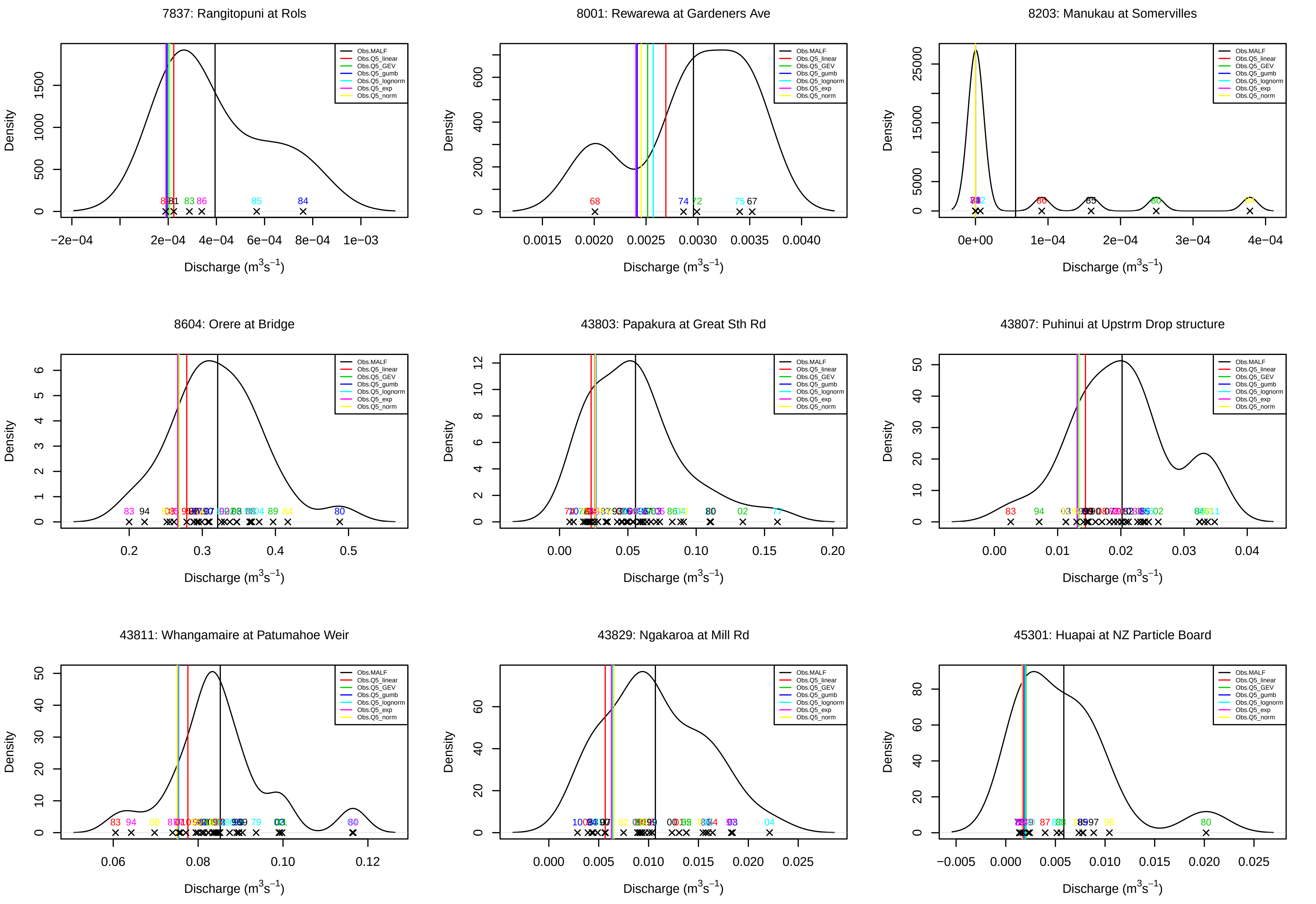
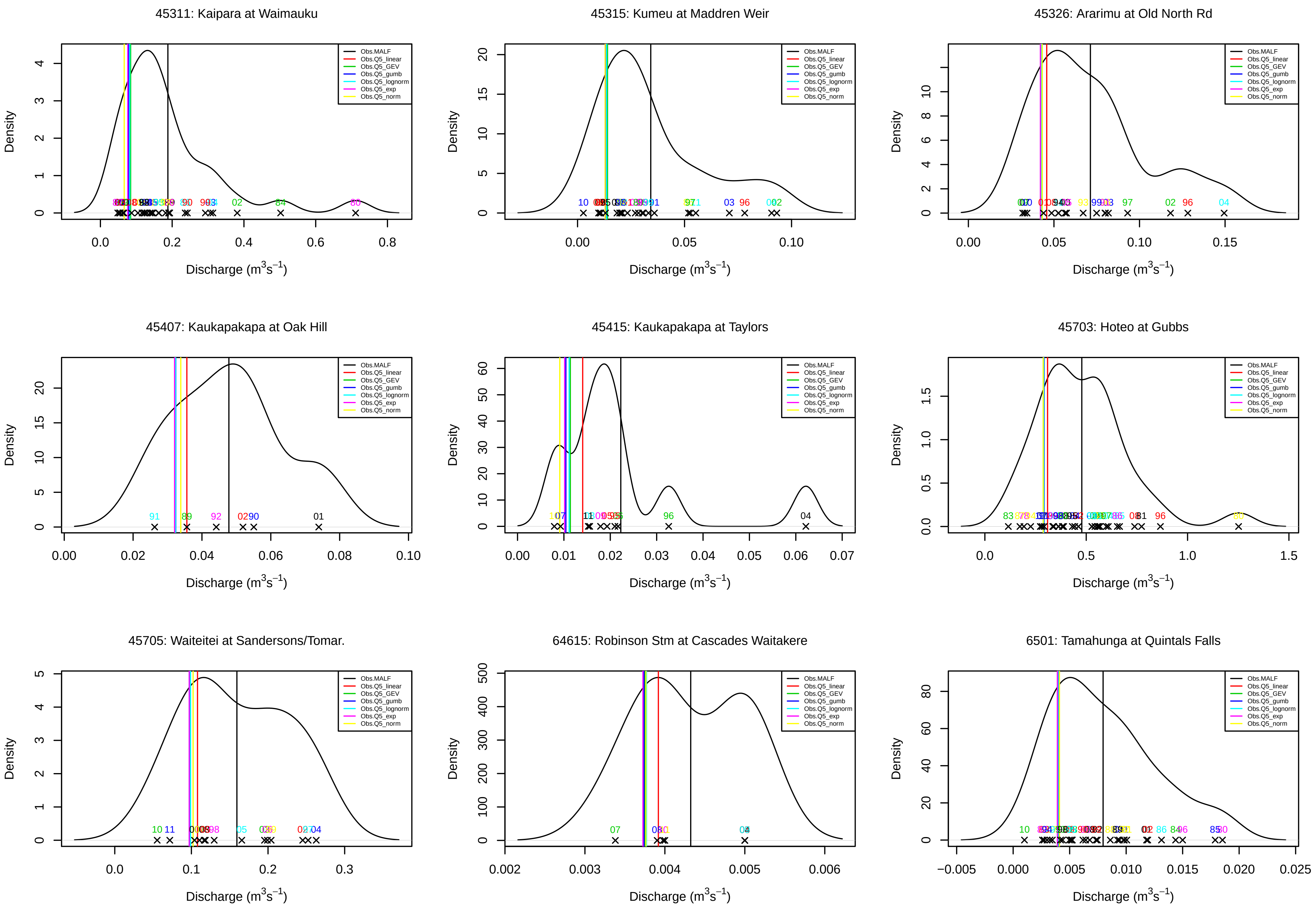
Jul
Aug
Sep
Oct
Nov
Dec
Time period

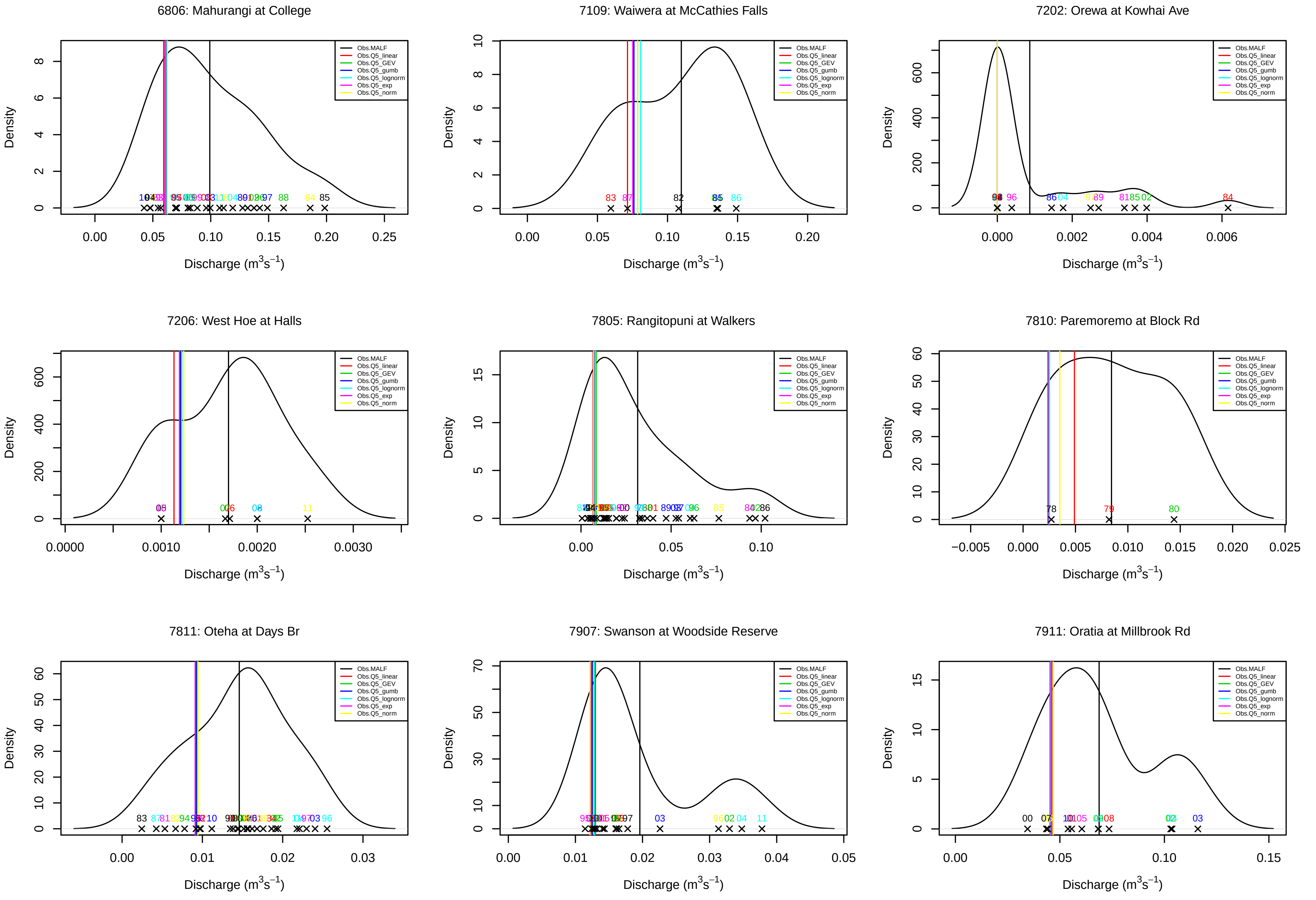

8529: Mangawheau at Weir
Position of 7day MALF on FDC
0
10
20
30
40
50
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Time period

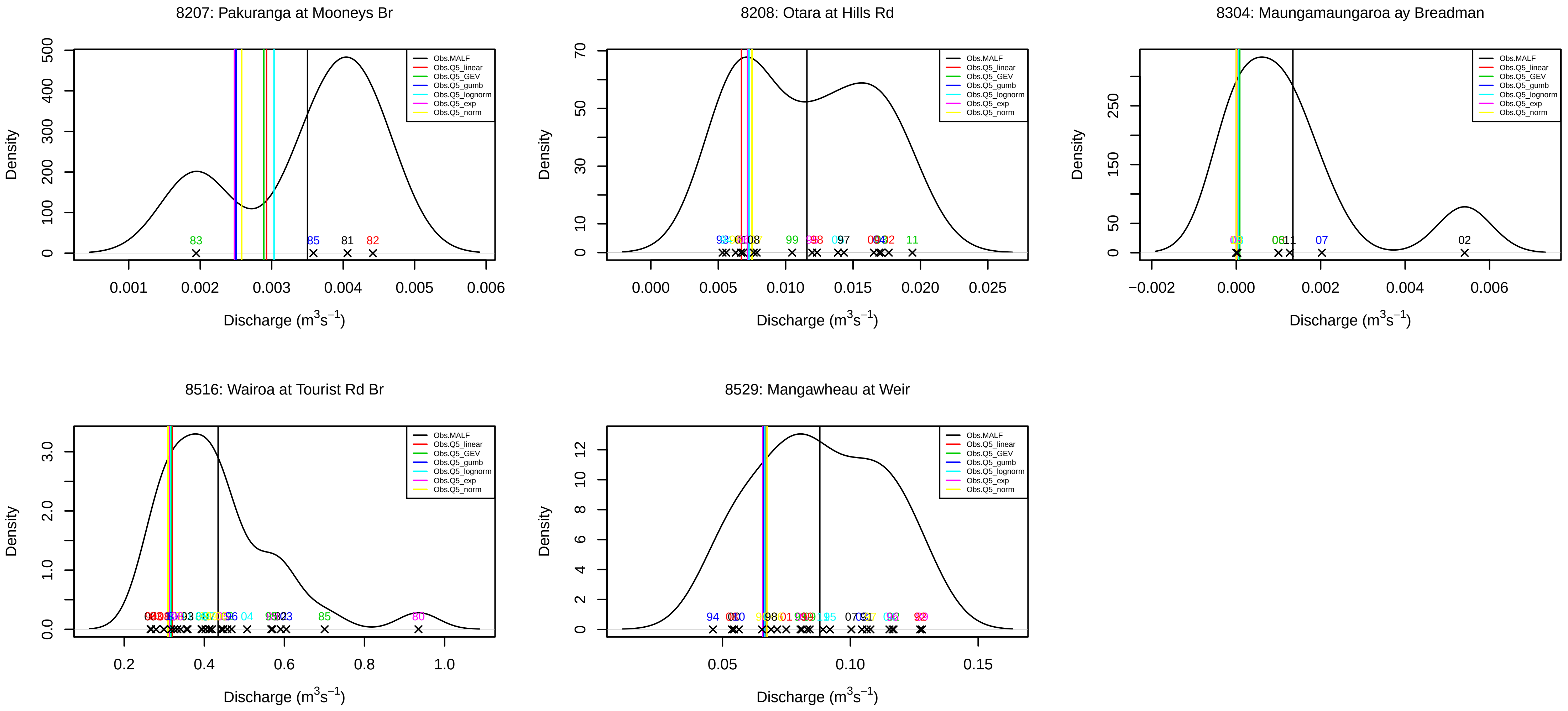
Appendix B Low flow distribution


43602: Waitangi at SH Bridge
45346: Waikoukou at Longlands
45347: Wharauroa at Moffats
45504: Makarau at Coles
45702: Waiwhiu at Dome Shadow
6602: Glen Eden at Hitchings Farm
6922: Awana at Bush Edge
7602: Wairau at Alma Rd
7607: Wairau at Chartwell
Density
Discharge (m3s−1)
Obs.MALF
Obs.Q5_linear
Obs.Q5_GEV
Obs.Q5_gumb
Obs.Q5_lognorm
Obs.Q5_exp
Obs.Q5_norm


7837: Rangitopuni at Rols
8001: Rewarewa at Gardeners Ave
8203: Manukau at Somervilles
8604: Orere at Bridge
43803: Papakura at Great Sth Rd
43807: Puhinui at Upstrm Drop structure
43811: Whangamaire at Patumahoe Weir
43829: Ngakaroa at Mill Rd
45301: Huapai at NZ Particle Board
Density
Discharge (m^3s^{-1})
Obs.MALF
Obs.Q5_linear
Obs.Q5_GEV
Obs.Q5_gumb
Obs.Q5_lognorm
Obs.Q5_exp
Obs.Q5_norm

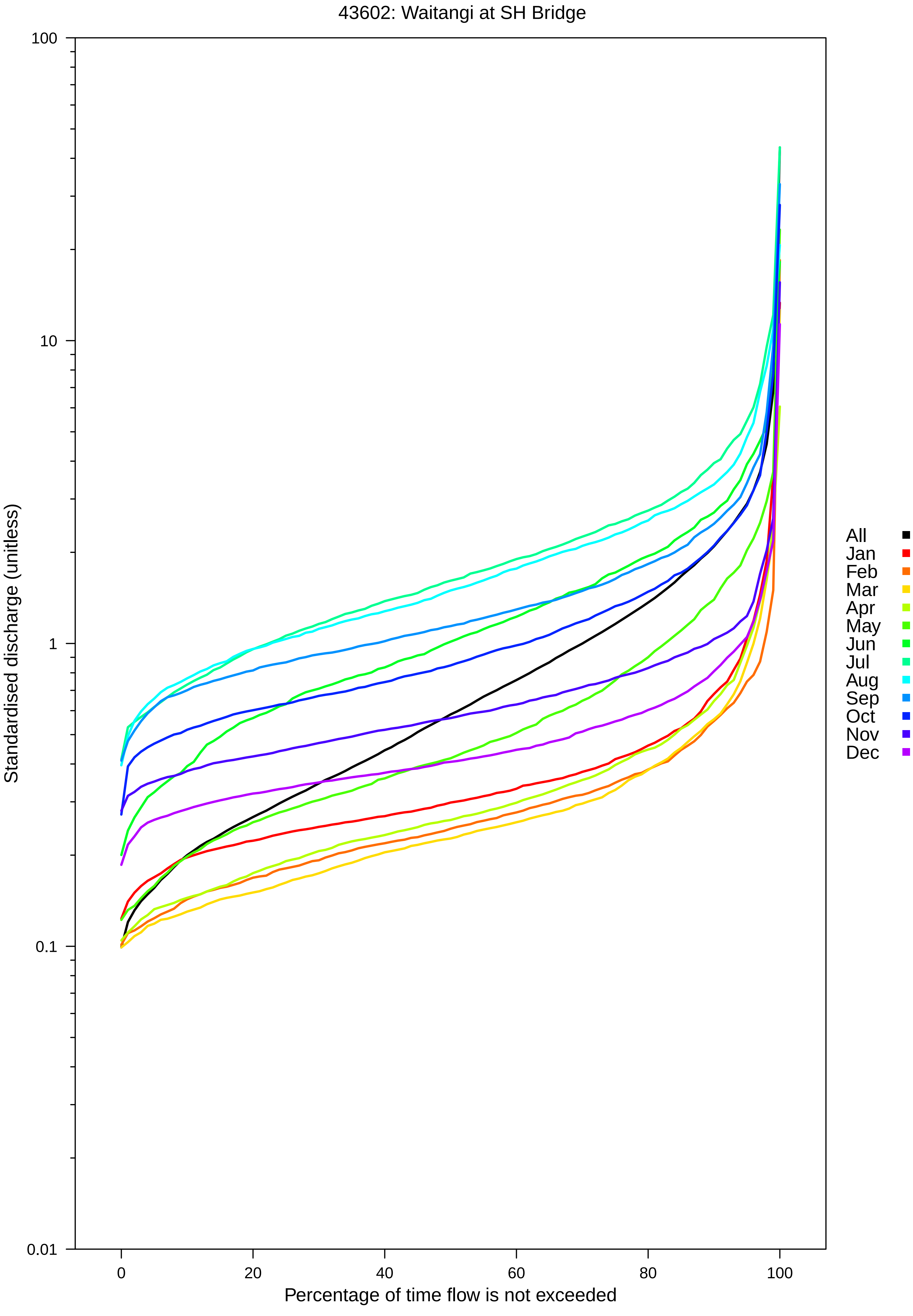

45311: Kaipara at Waimauku
45315: Kumeu at Maddren Weir
45326: Ararimu at Old North Rd
45407: Kaukapakapa at Oak Hill
45415: Kaukapakapa at Taylors
45703: Hoteo at Gubbs
45705: Waiteitei at Sandersons/Tomar.
64615: Robinson Stm at Cascades Waitakere
6501: Tamahunga at Quintals Falls
Density
Discharge (m^{3}s^{-1})
Obs.MALF
Obs.Q5_linear
Obs.Q5_GEV
Obs.Q5_gumb
Obs.Q5_lognorm
Obs.Q5_exp
Obs.Q5_norm


6806: Mahurangi at College
7109: Waiwera at McCathies Falls
7202: Orewa at Kowhai Ave
7206: West Hoe at Halls
7805: Rangitopuni at Walkers
7810: Paremoremo at Block Rd
7811: Oteha at Days Br
7907: Swanson at Woodside Reserve
7911: Oratia at Millbrook Rd
Density
Discharge (m^{3}s^{-1})
Obs.MALF
Obs.Q5_linear
Obs.Q5_GEV
Obs.Q5_gumb
Obs.Q5_lognorm
Obs.Q5_exp
Obs.Q5_norm

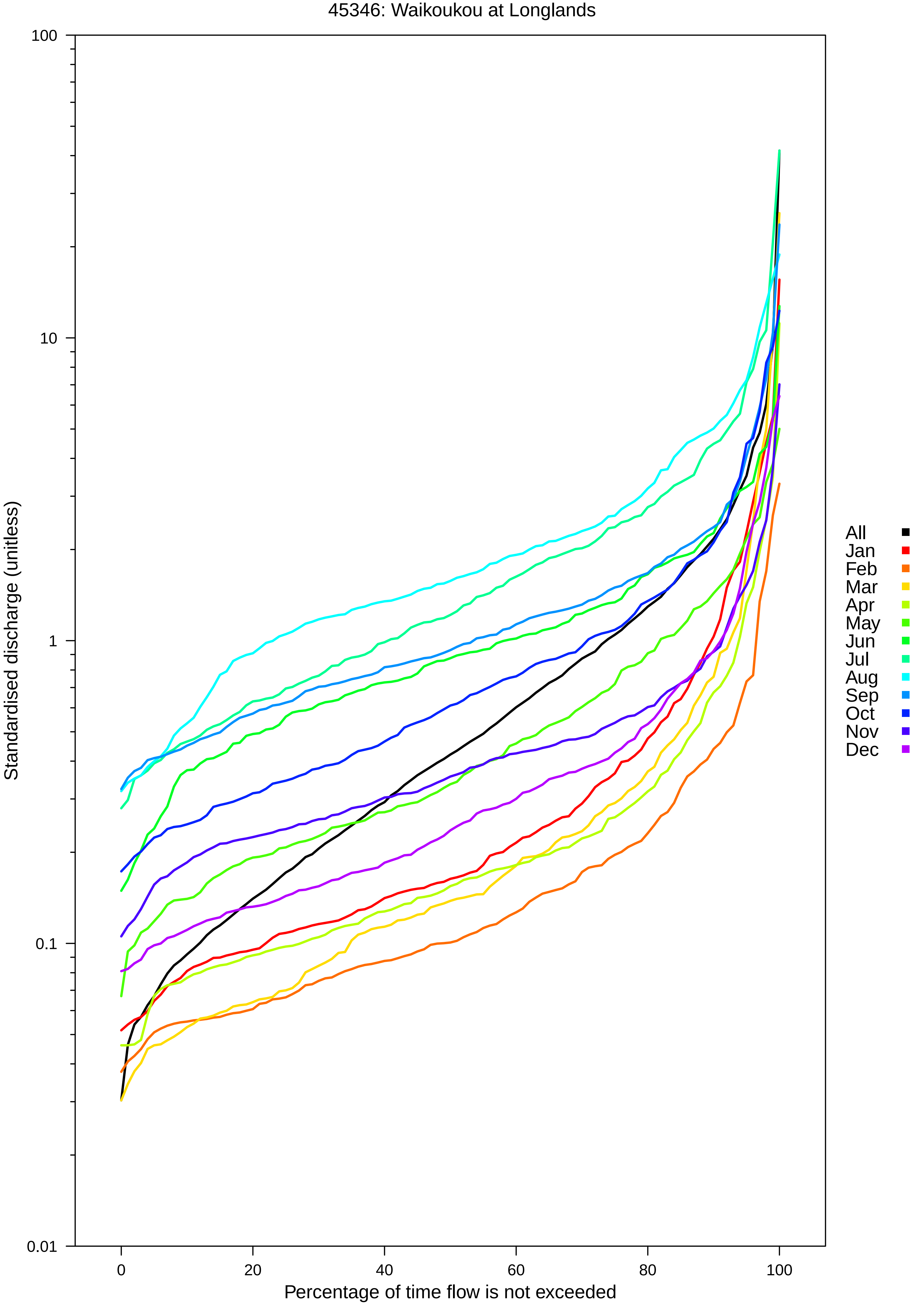


8207: Pakuranga at Mooneys Br
8208: Otara at Hills Rd
8304: Maungamaungaroa ay Breadman
8516: Wairoa at Tourist Rd Br
8529: Mangawheau at Weir
Density
Discharge (m^3s^{-1})
Obs.MALF
Obs.Q5_linear
Obs.Q5_GEV
Obs.Q5_gumb
Obs.Q5_lognorm
Obs.Q5_exp
Obs.Q5_norm

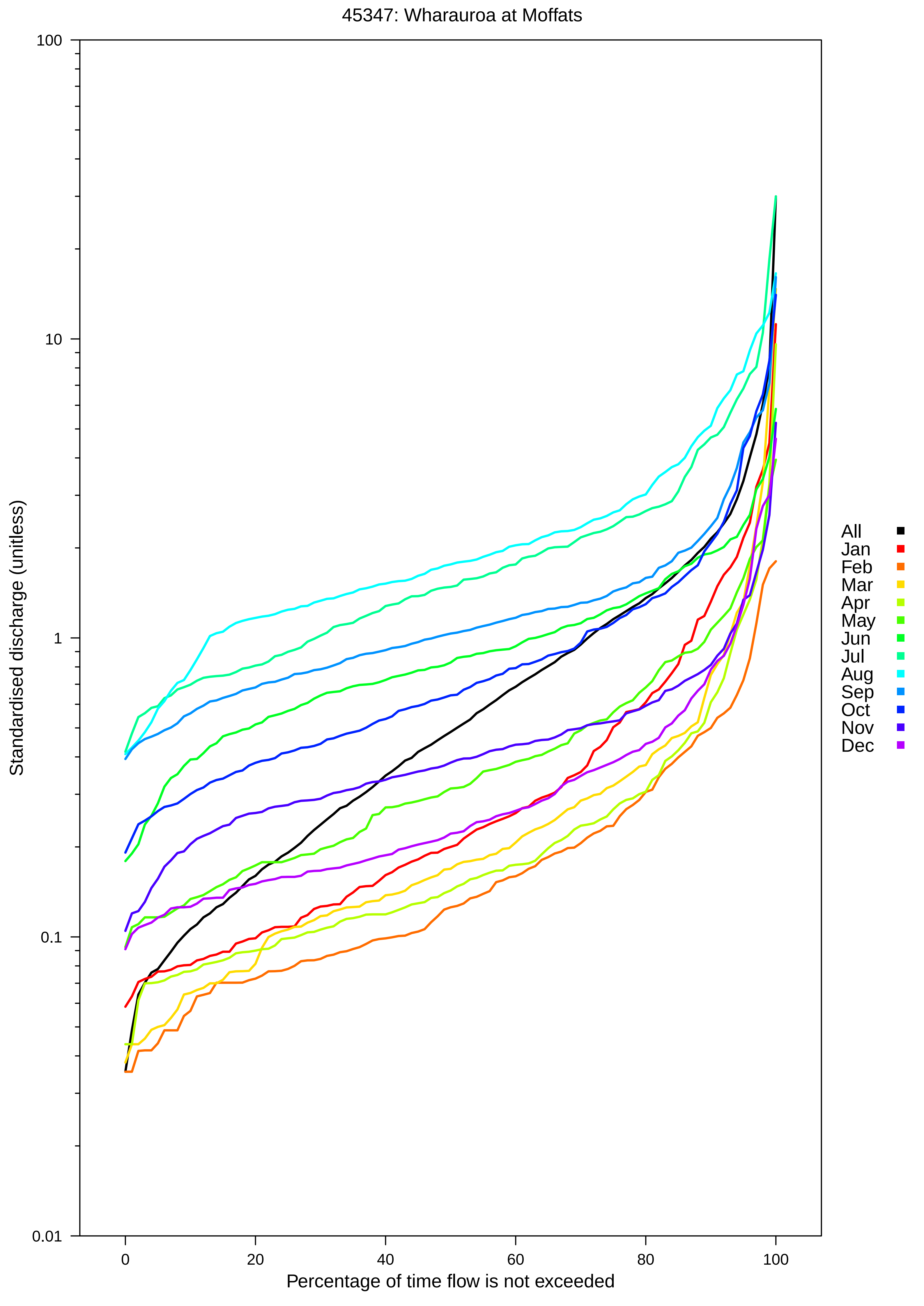
Appendix C Observed flow duration curves for Auckland



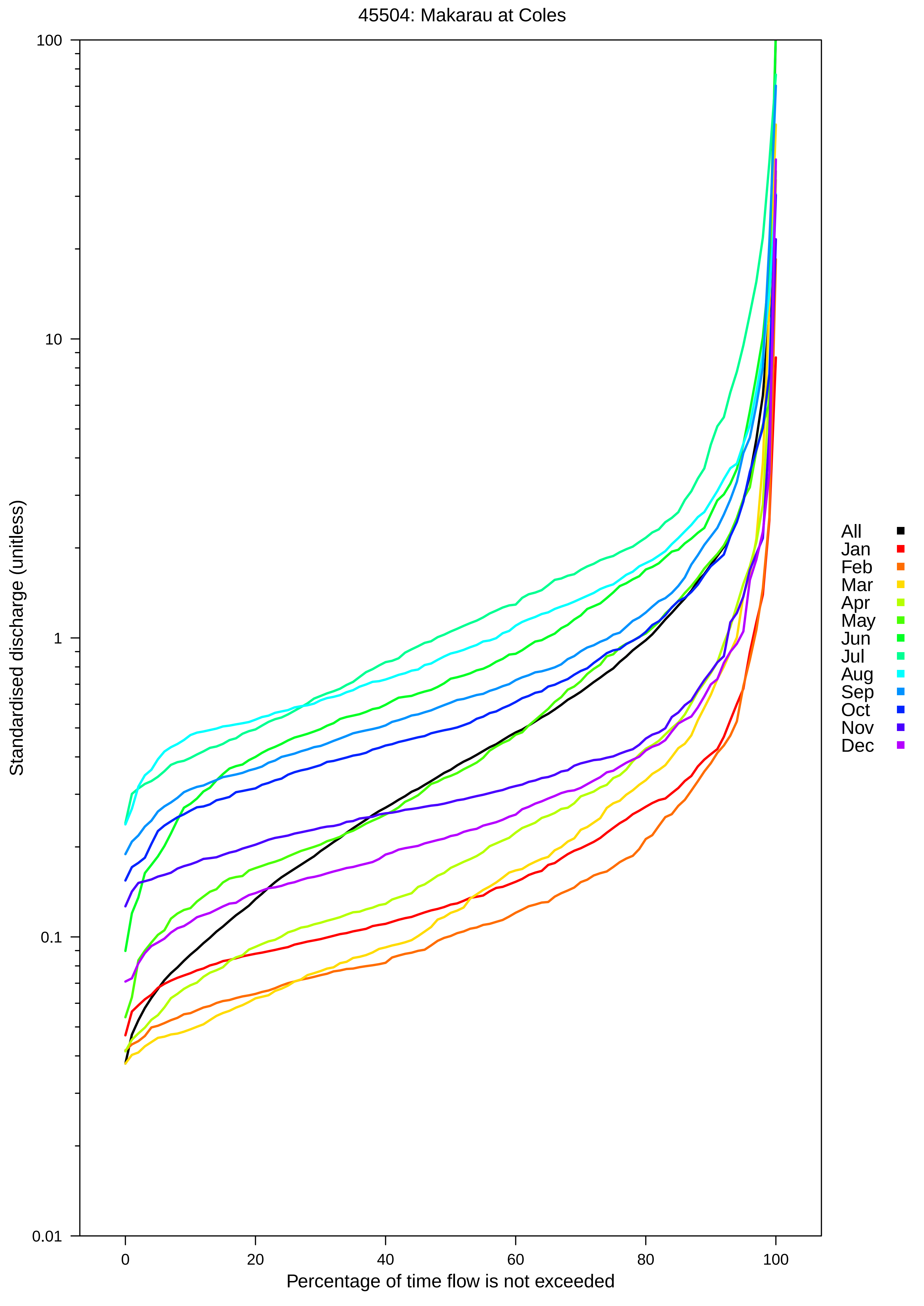
43602: Waitangi at SH Bridge
Standardised discharge (unitless)
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

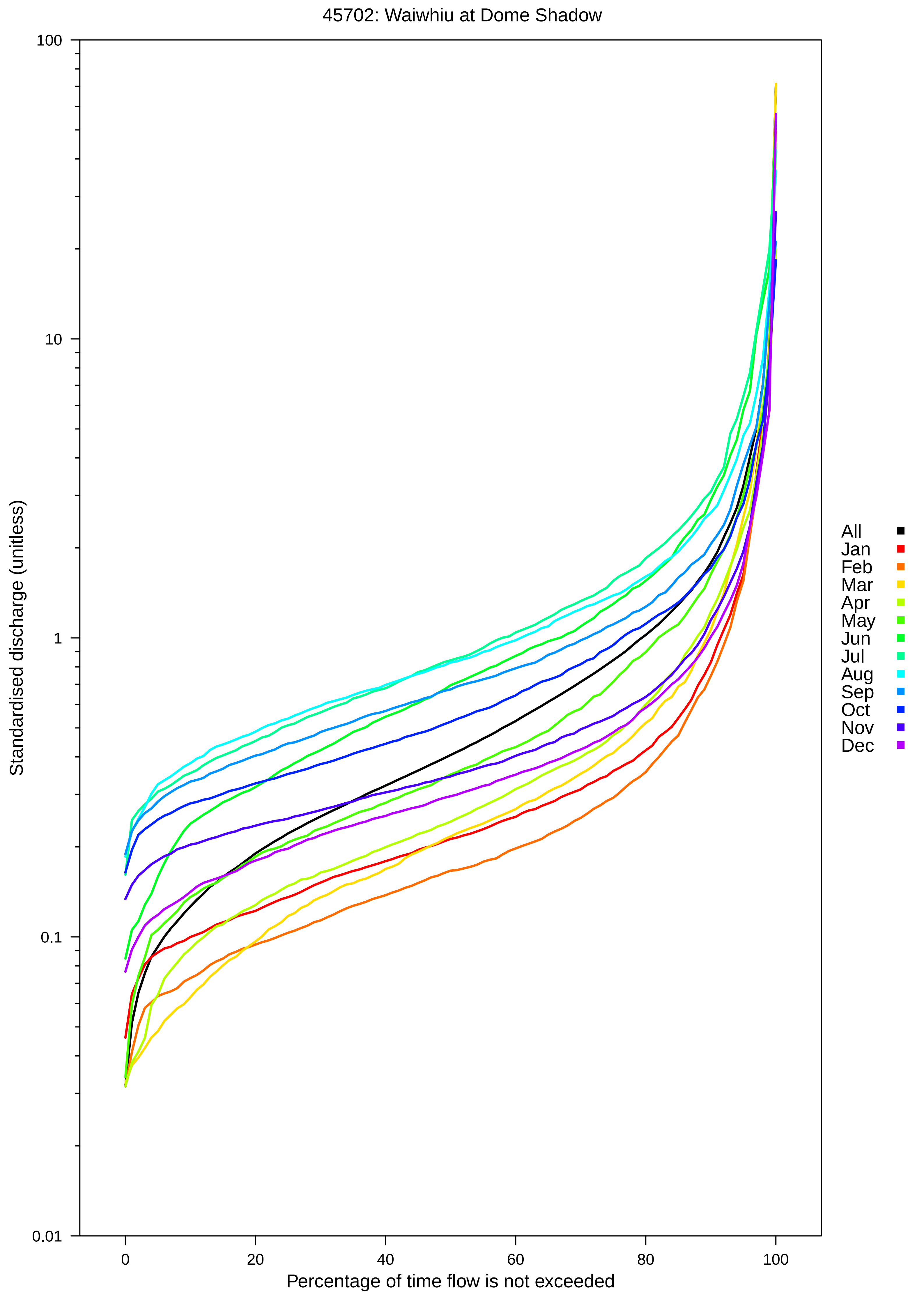


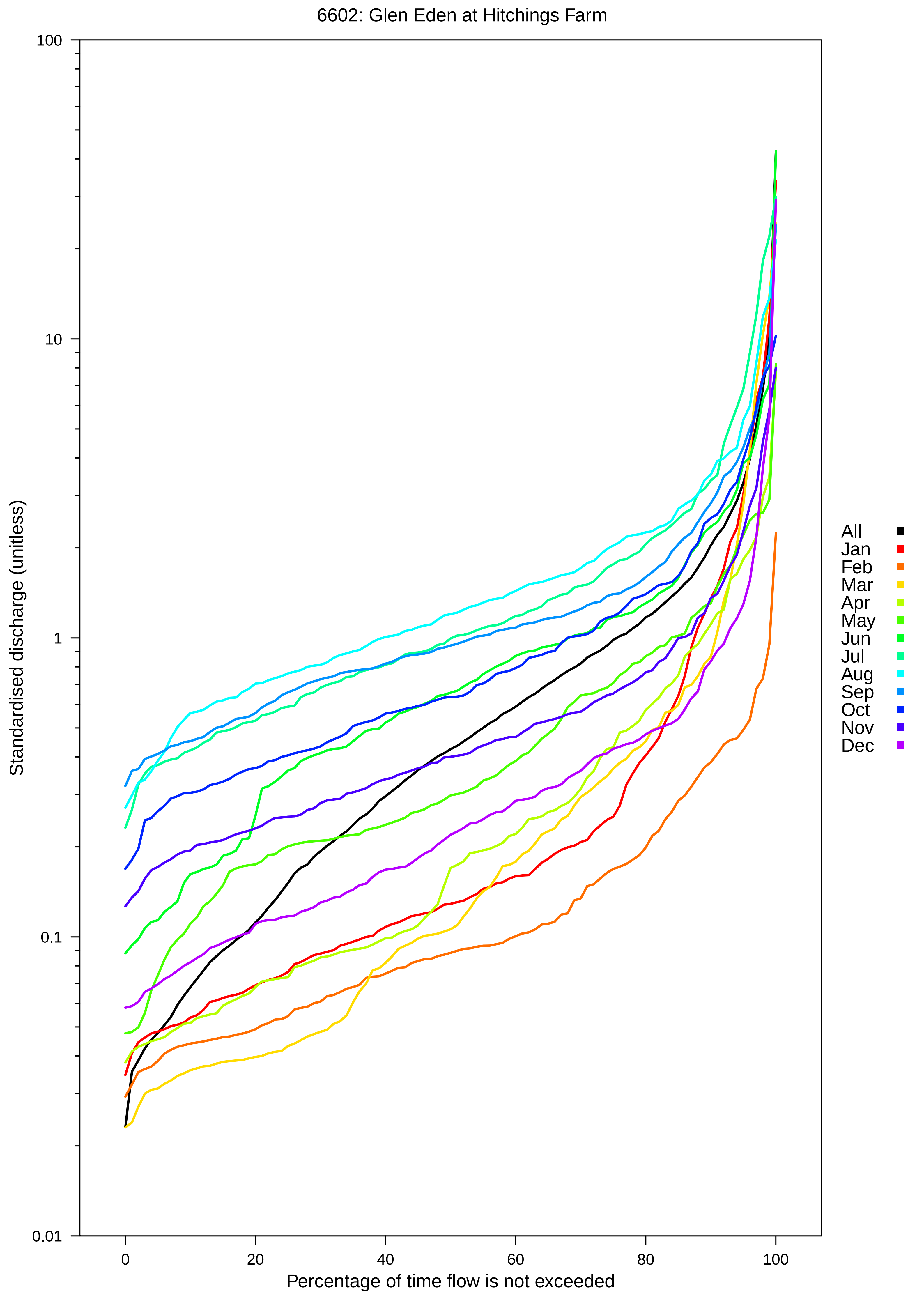
45346: Waikoukou at Longlands
Standardised discharge (unitless)
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec



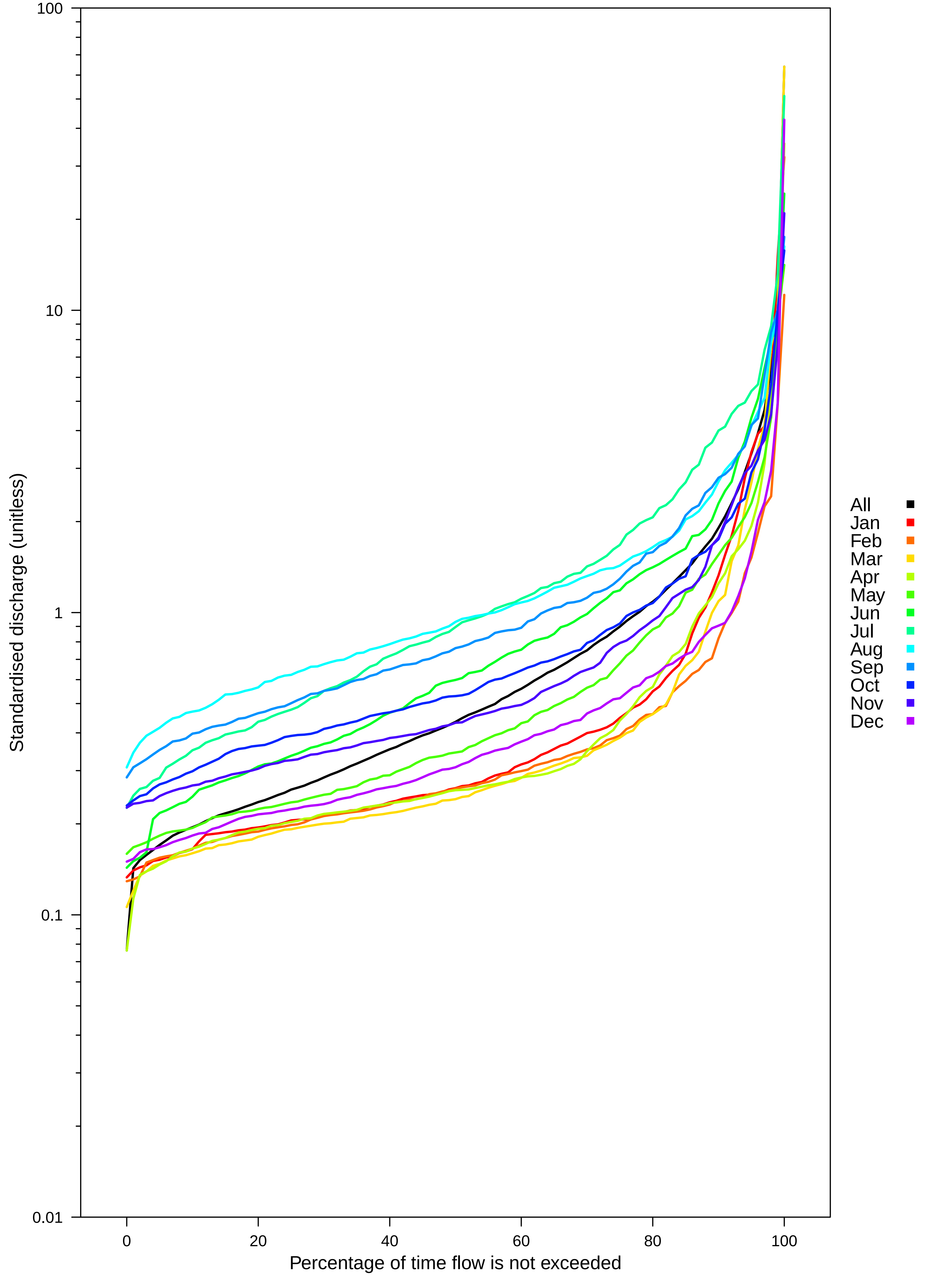
45347: Wharauroa at Moffats
100
10
1
0.1
0.01
Standardised discharge (unitless)
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

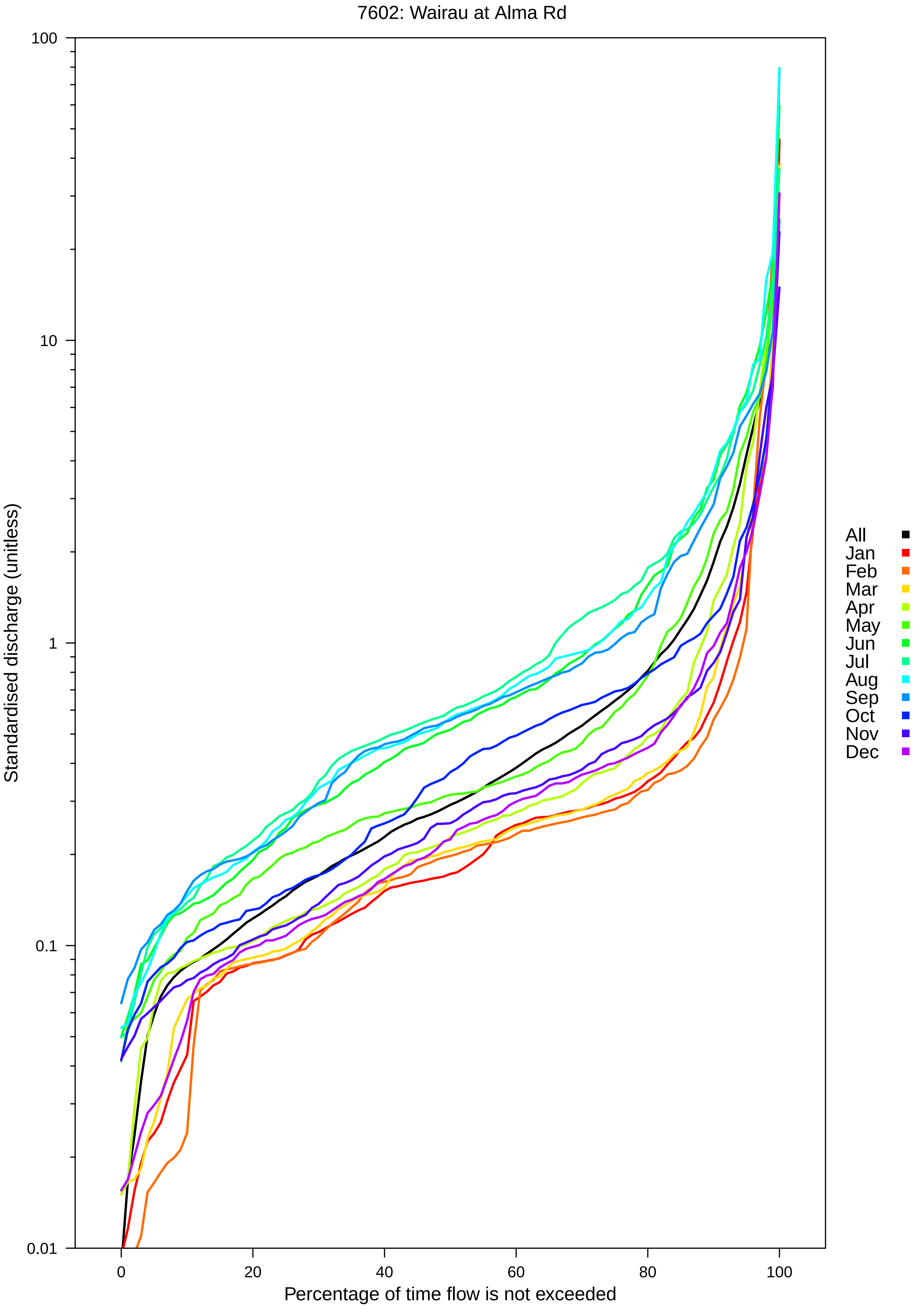

45504: Makarau at Coles
100
10
1
0.1
0.01
Standardised discharge (unitless)
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


45702: Waiwhiu at Dome Shadow
Standardised discharge (unitless)
Percentage of time flow is not exceeded
100
10
1
0.1
0.01
0
20
40
60
80
100
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

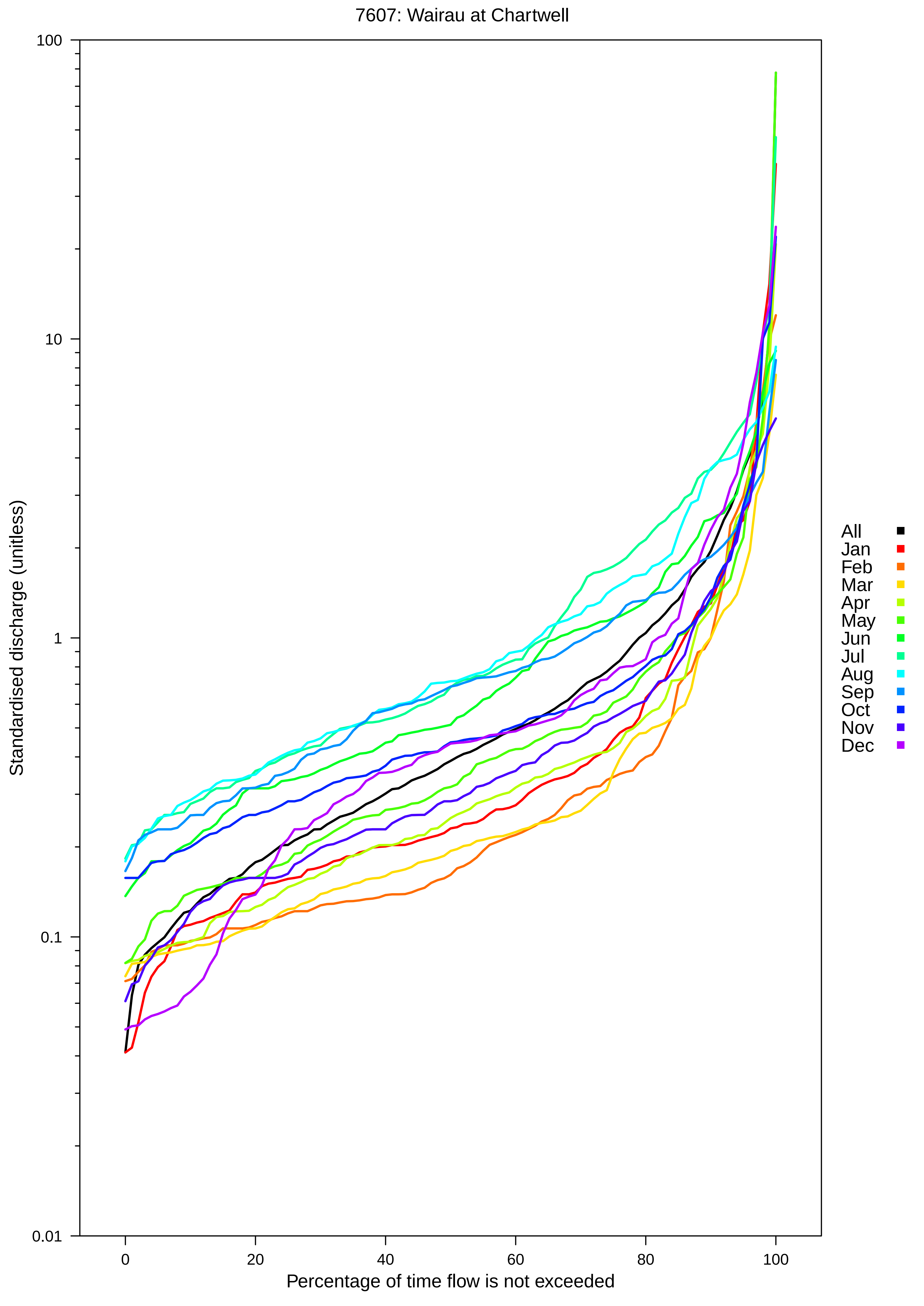

6602: Glen Eden at Hitchings Farm
100
10
1
0.1
0.01
Standardised discharge (unitless)
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

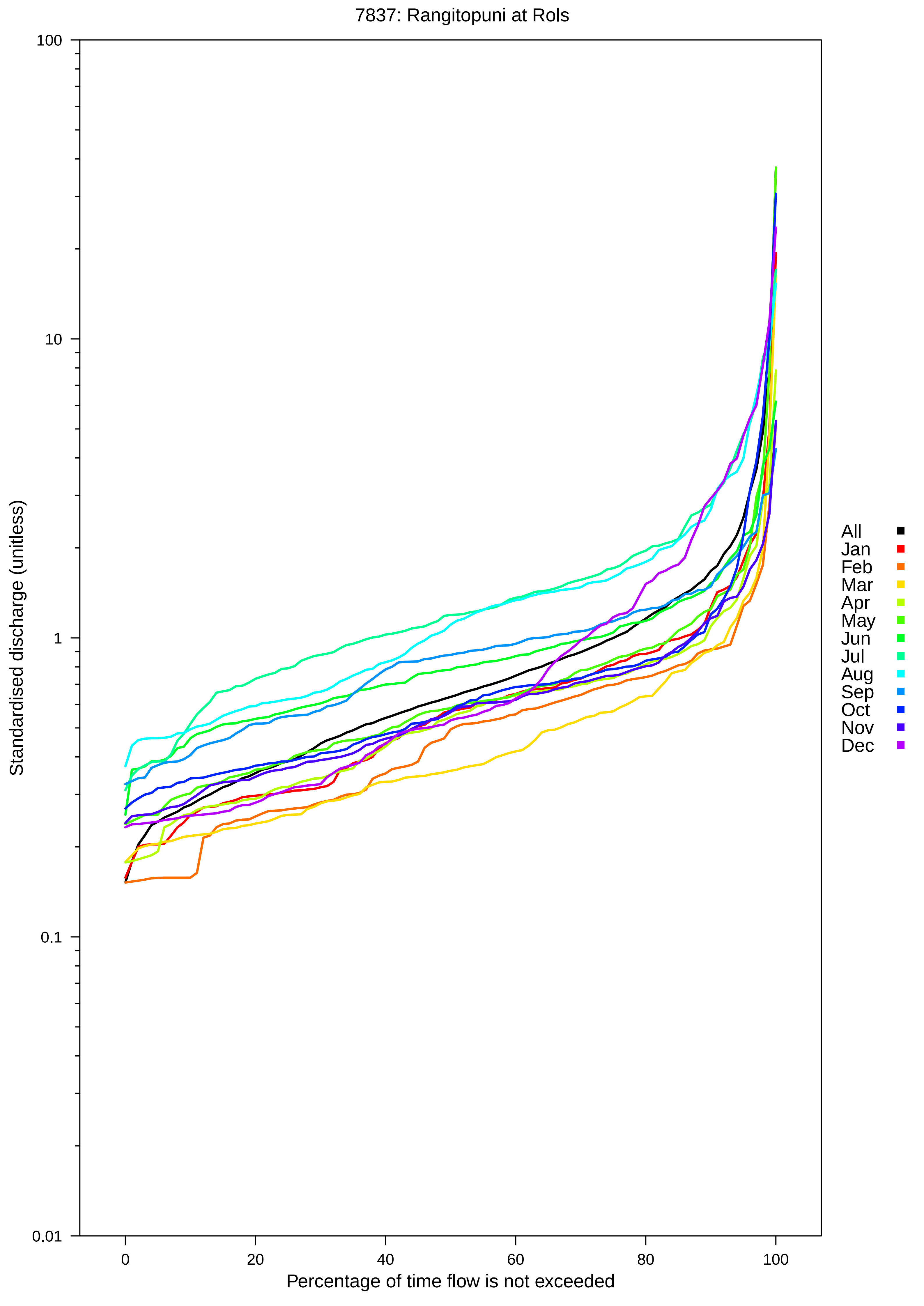
6922: Awana at Bush Edge



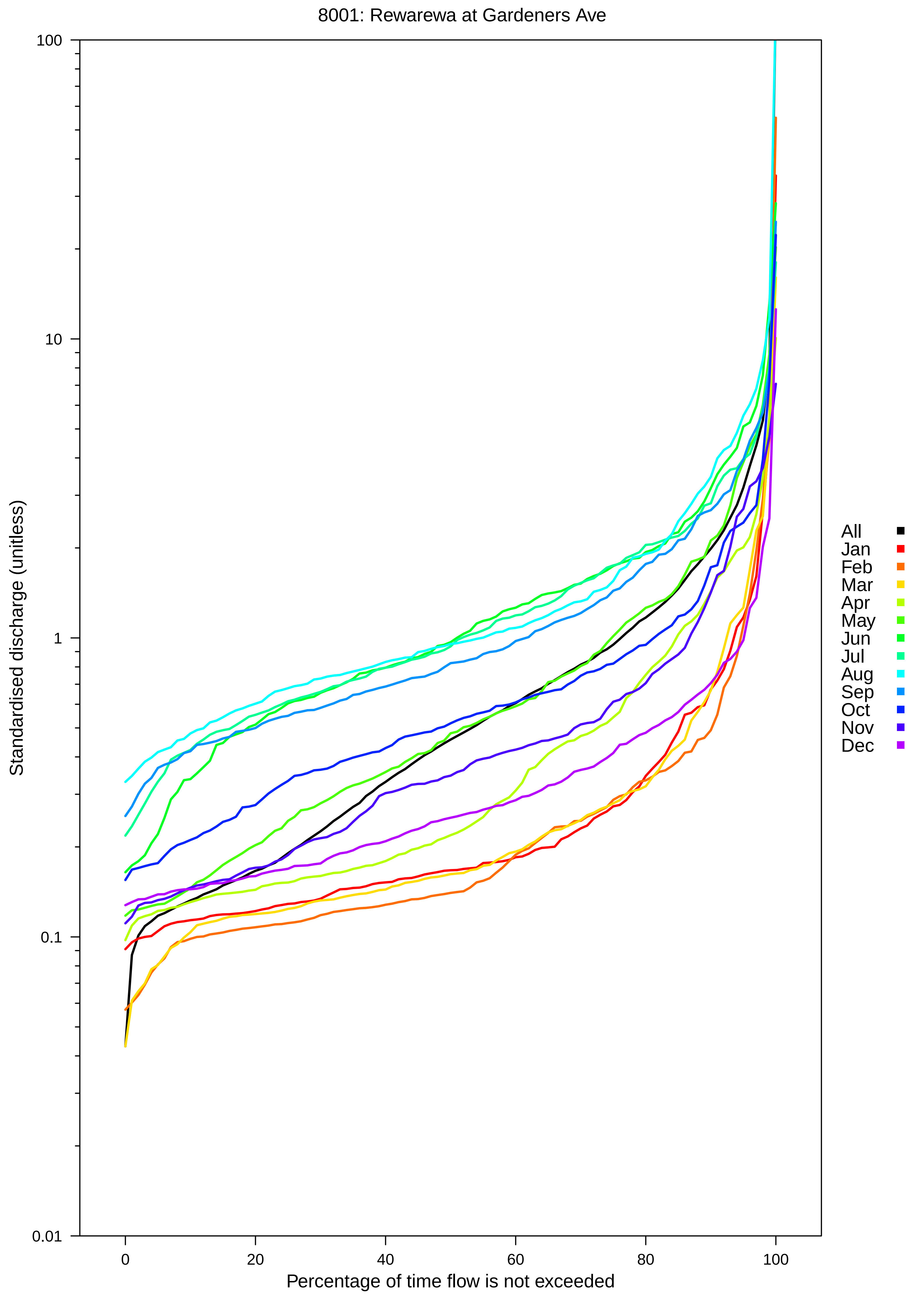


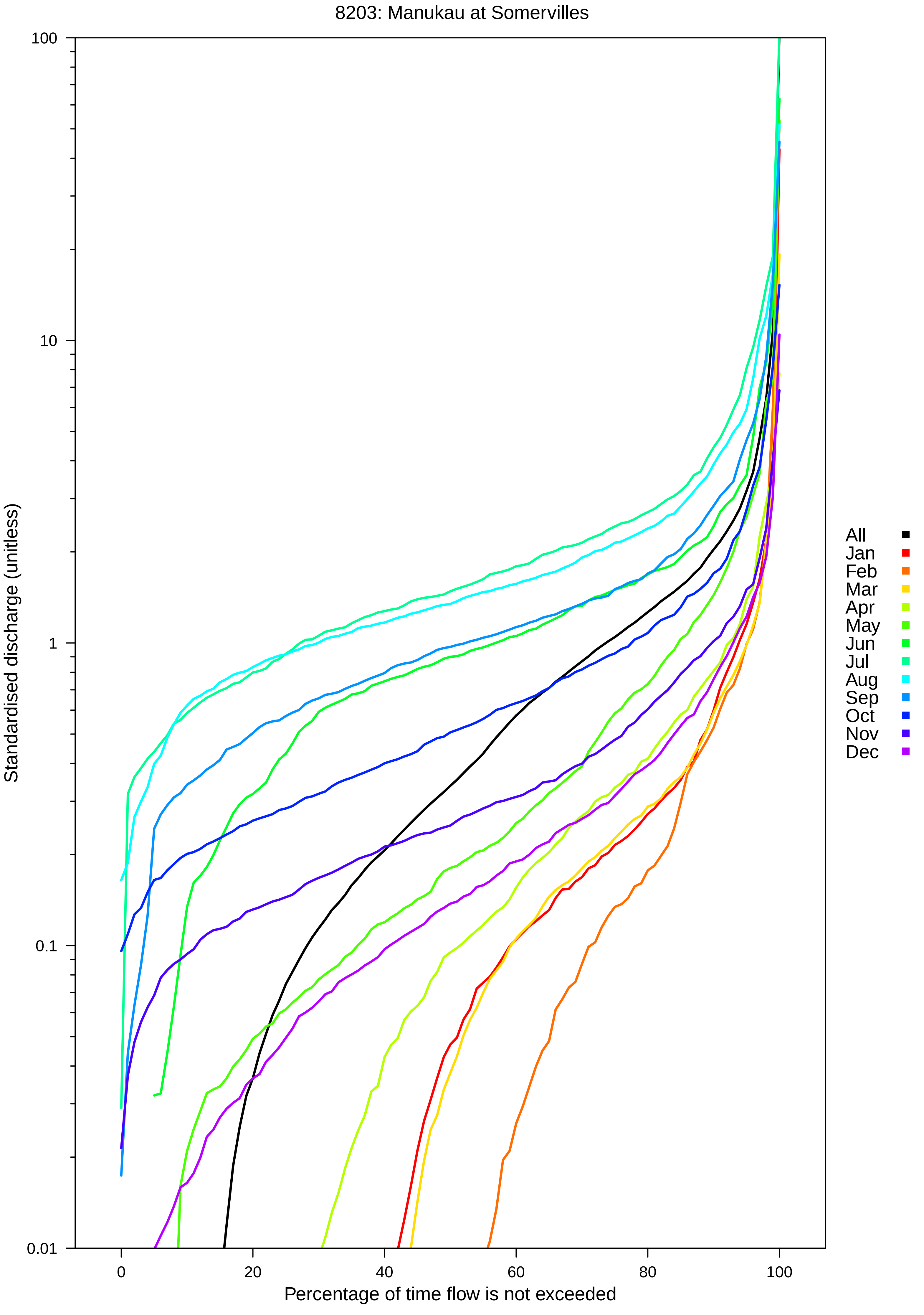
7602: Wairau at Alma Rd
Standardised discharge (unitless)
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

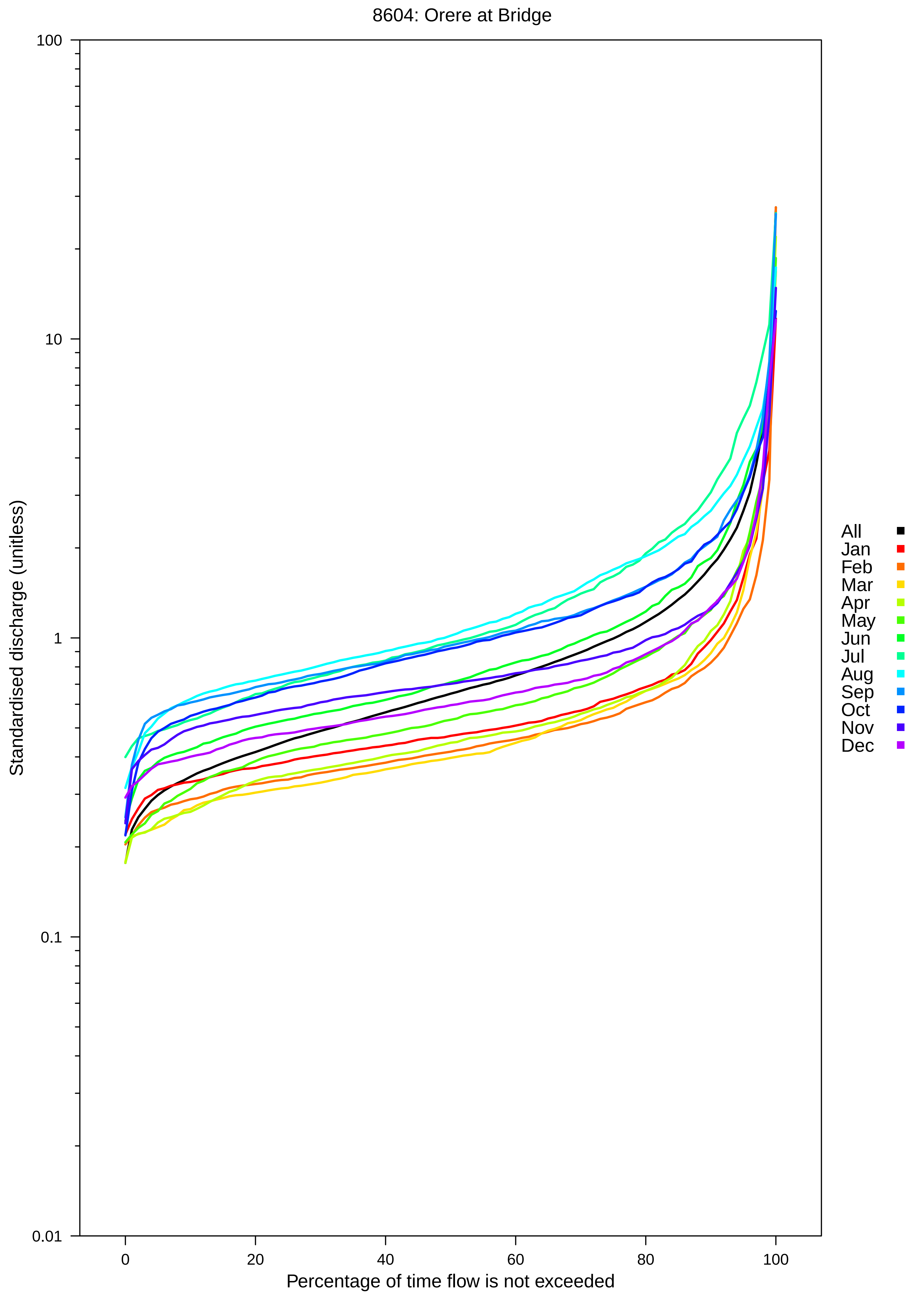

7607: Wairau at Chartwell
Standardised discharge (unitless)
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

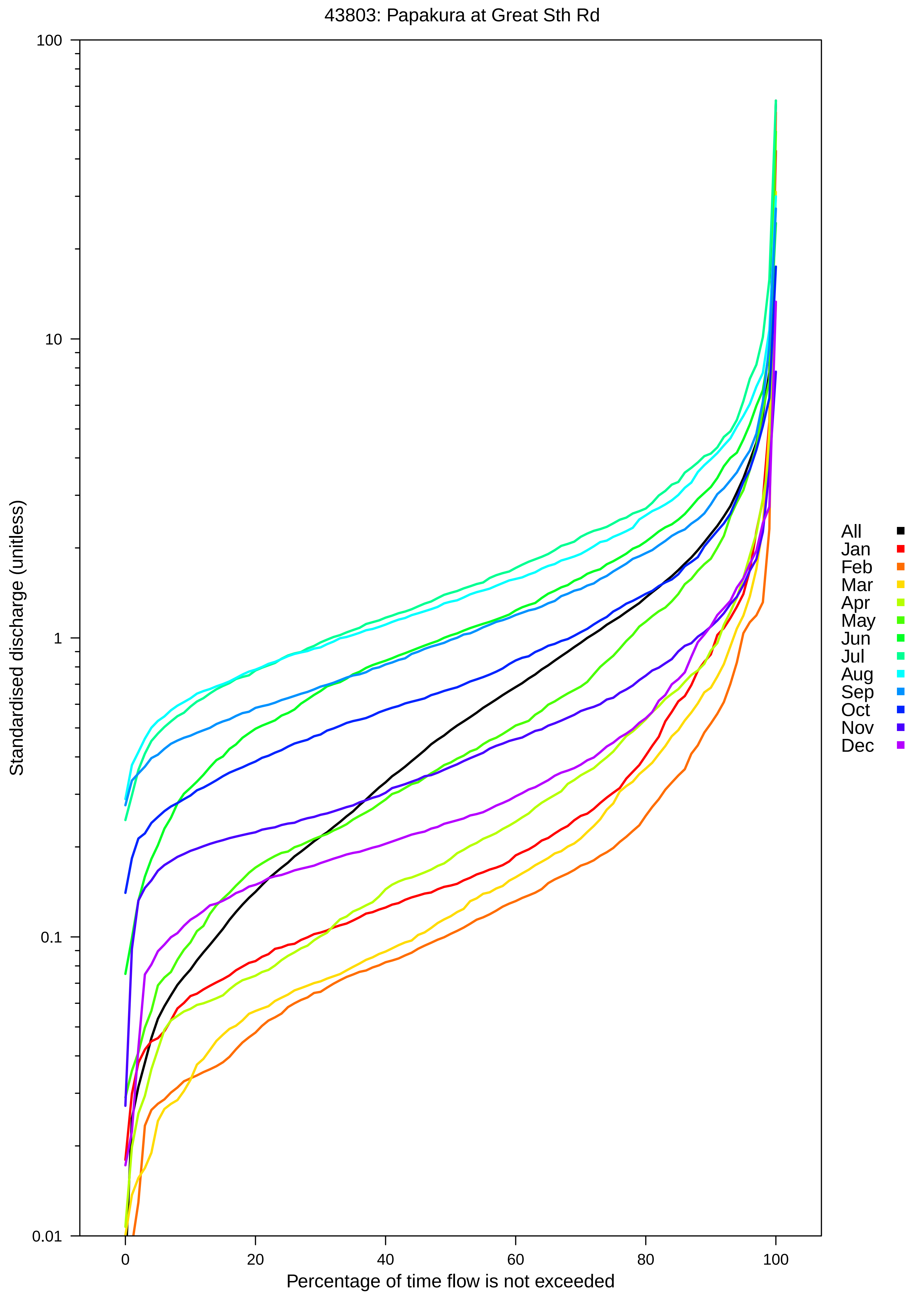


7837: Rangitopuni at Rols
Standardised discharge (unitless)
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

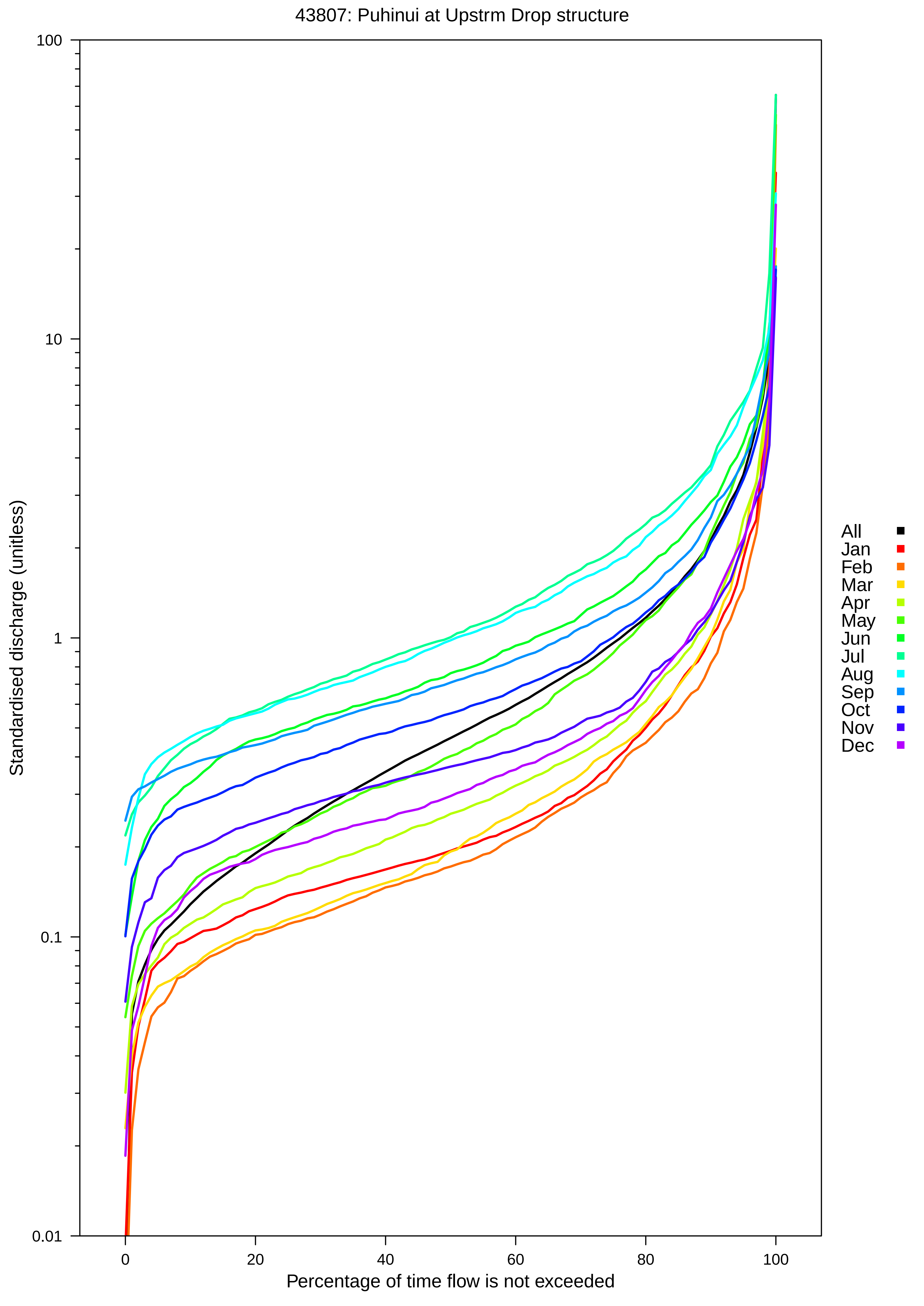

8001: Rewarewa at Gardeners Ave
Standardised discharge (unitless)
Percentage of time flow is not exceeded
100
10
1
0.1
0.01
0
20
40
60
80
100
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


8203: Manukau at Somervilles
Standardised discharge (unitless)
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

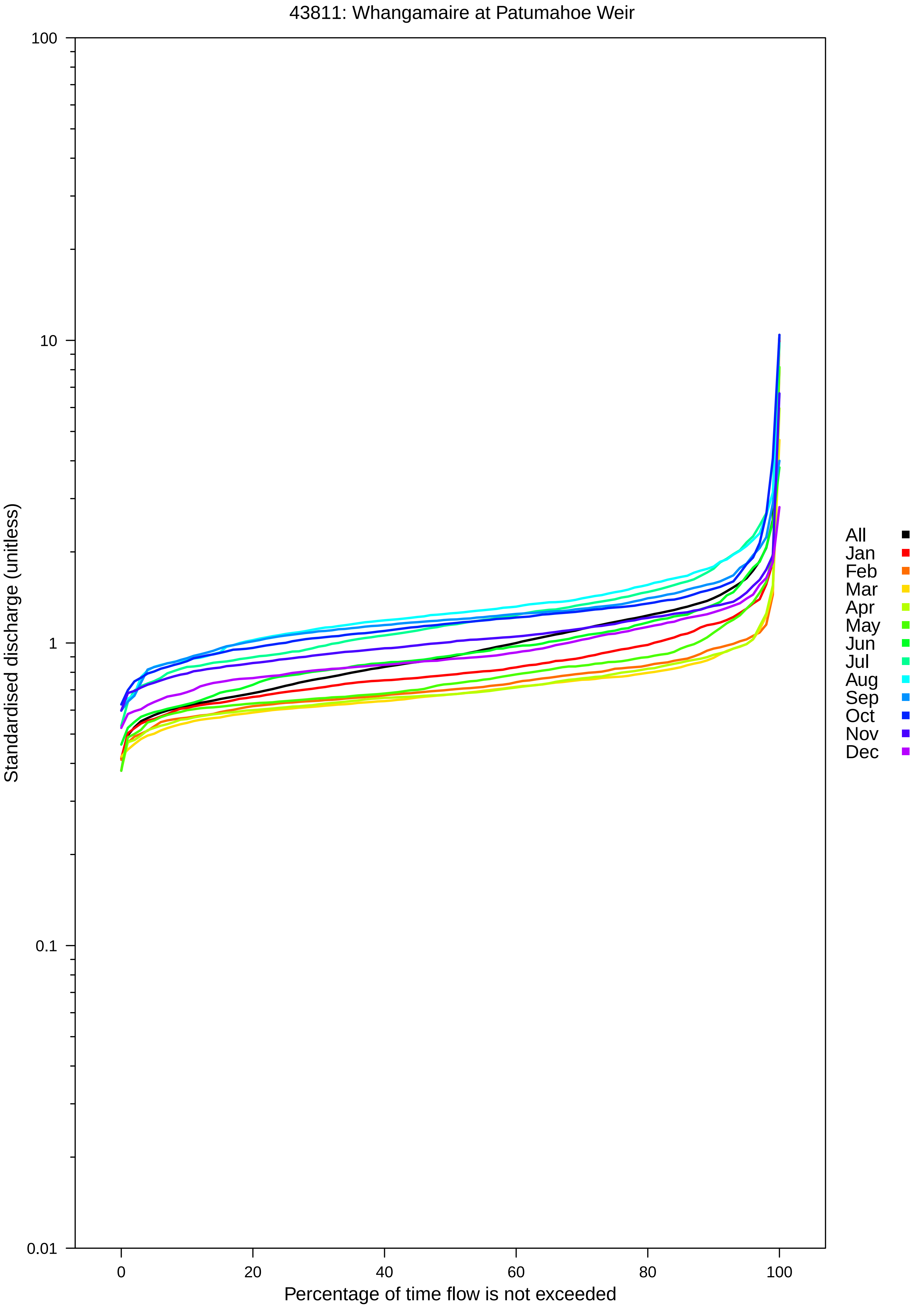

8604: Orere at Bridge
100
10
1
0.1
0.01
Standardised discharge (unitless)
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

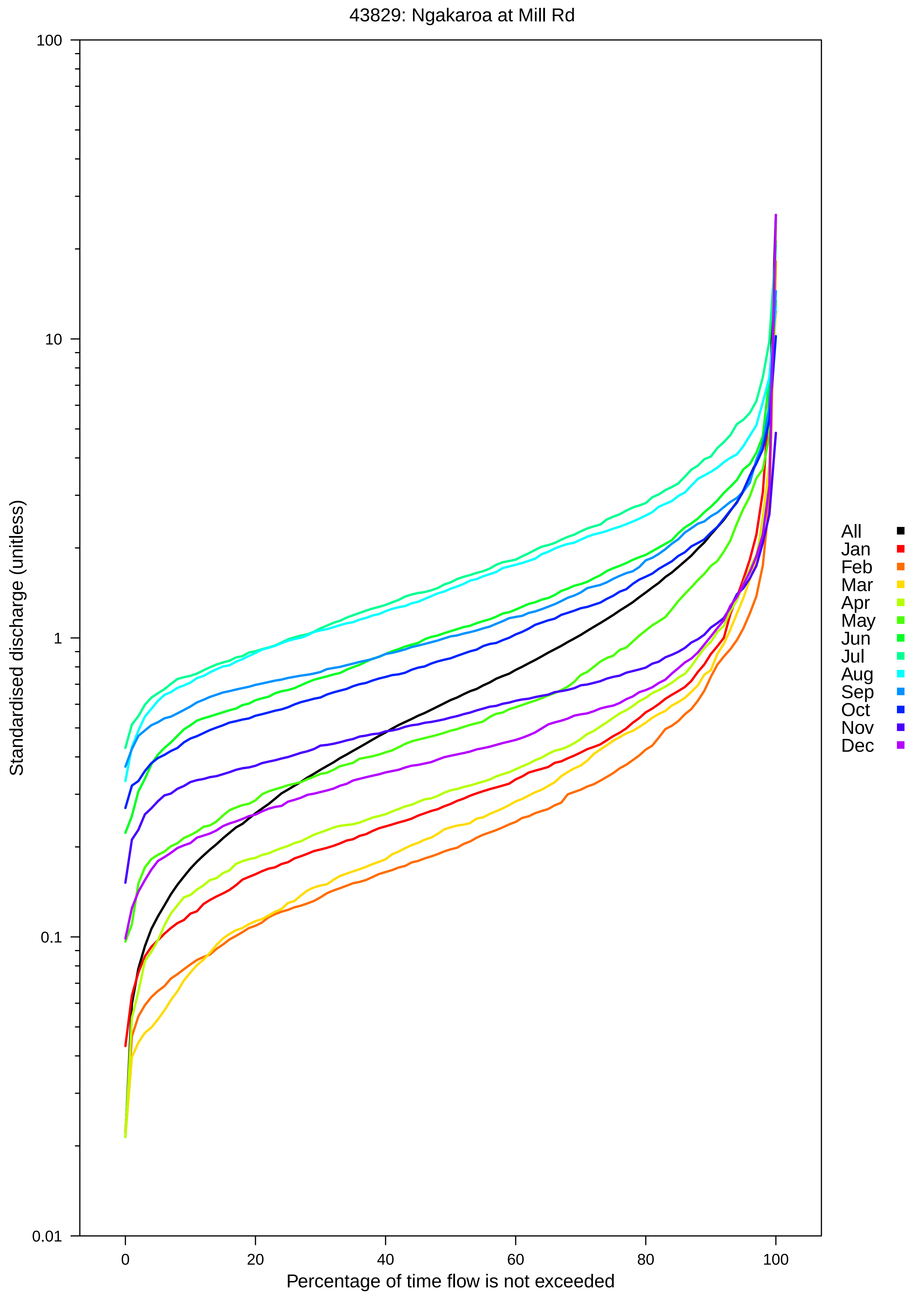


43803: Papakura at Great Sth Rd
100
10
1
0.1
0.01
Standardised discharge (unitless)
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

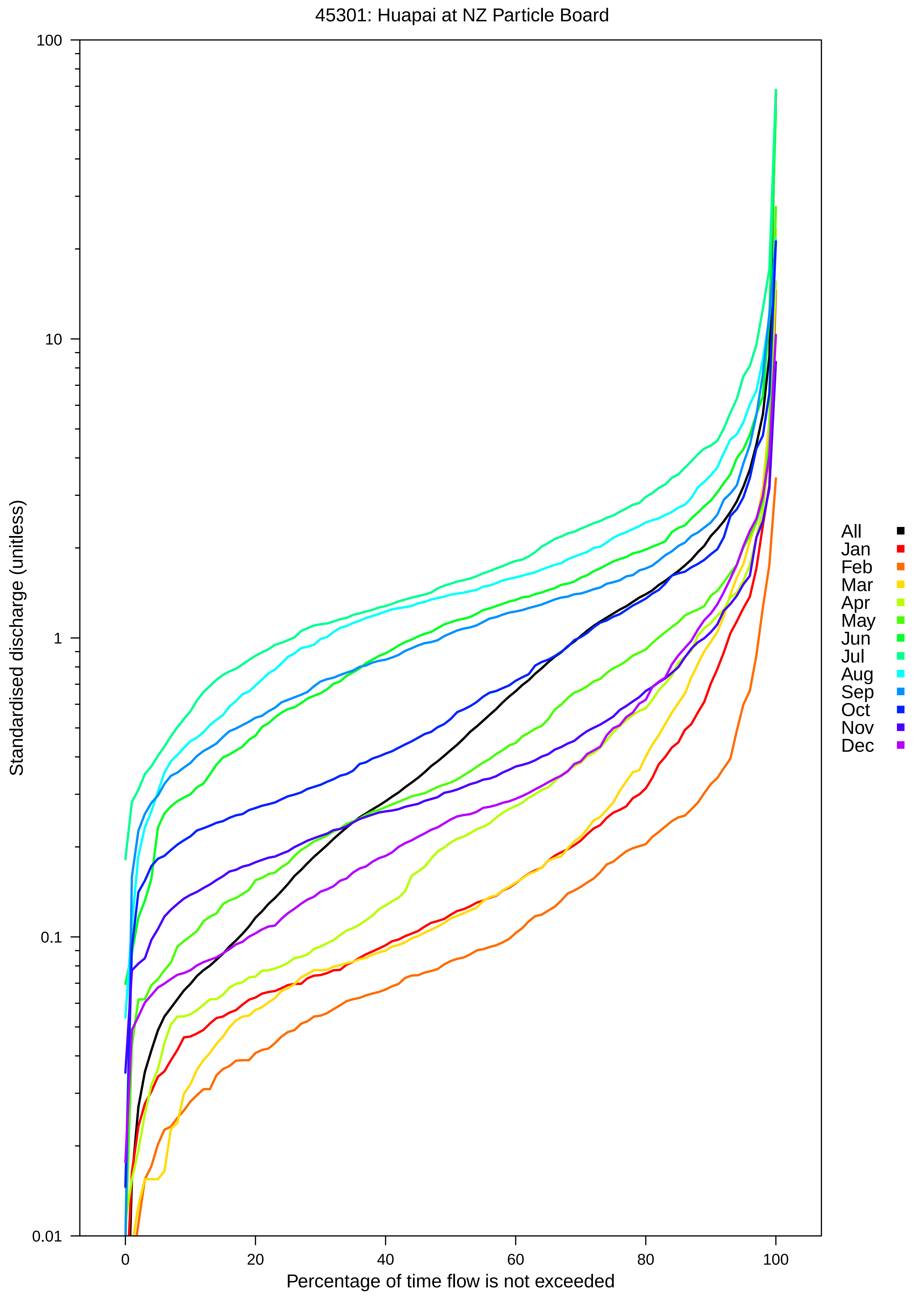


43807: Puhinui at Upstrm Drop structure
100
10
1
0.1
0.01
Standardised discharge (unitless)
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

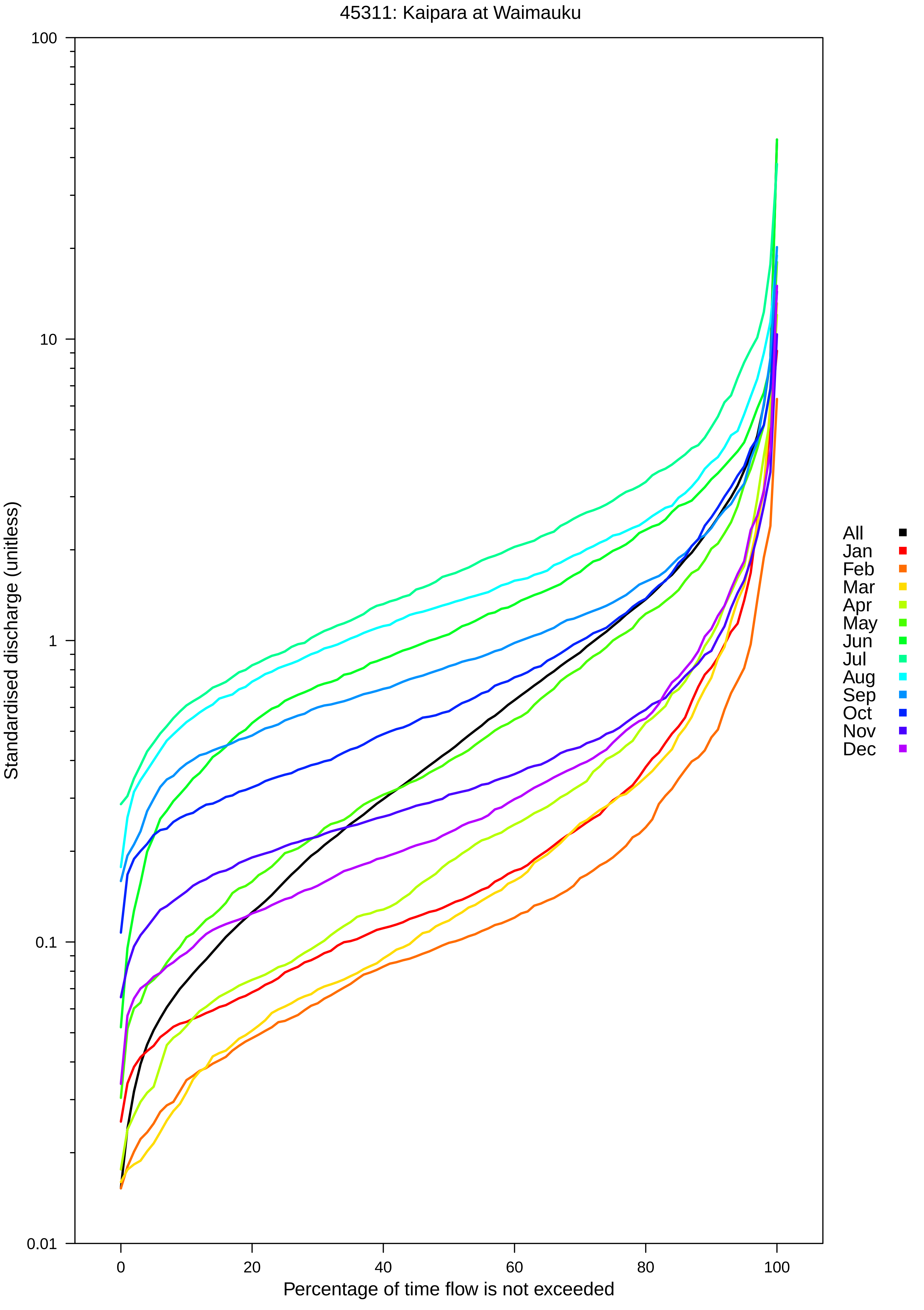

43811: Whangamaire at Patumahoe Weir
100
10
1
0.1
0.01
Standardised discharge (unitless)
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec



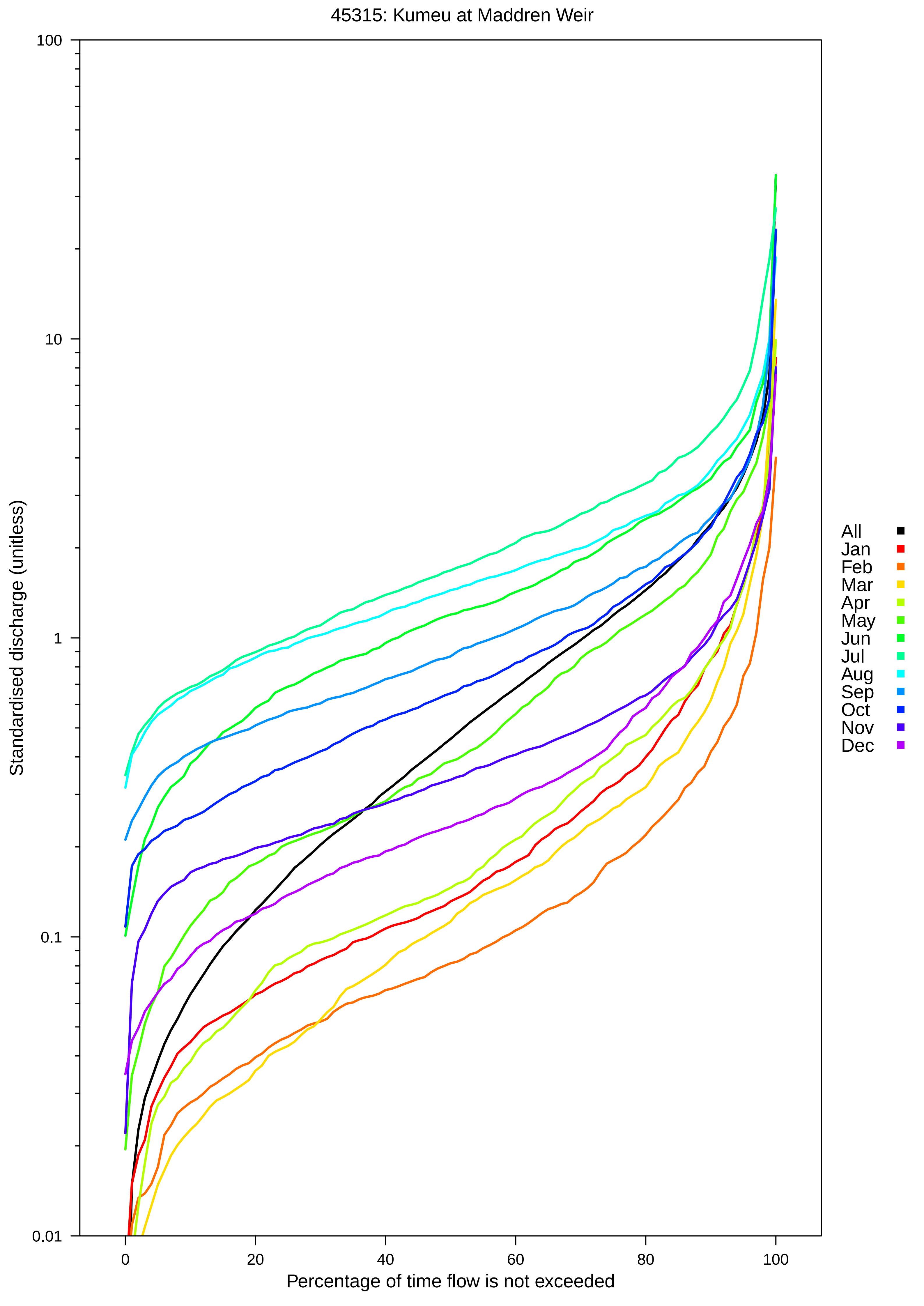
43829: Ngakaroa at Mill Rd
100
10
1
0.1
0.01
Standardised discharge (unitless)
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec



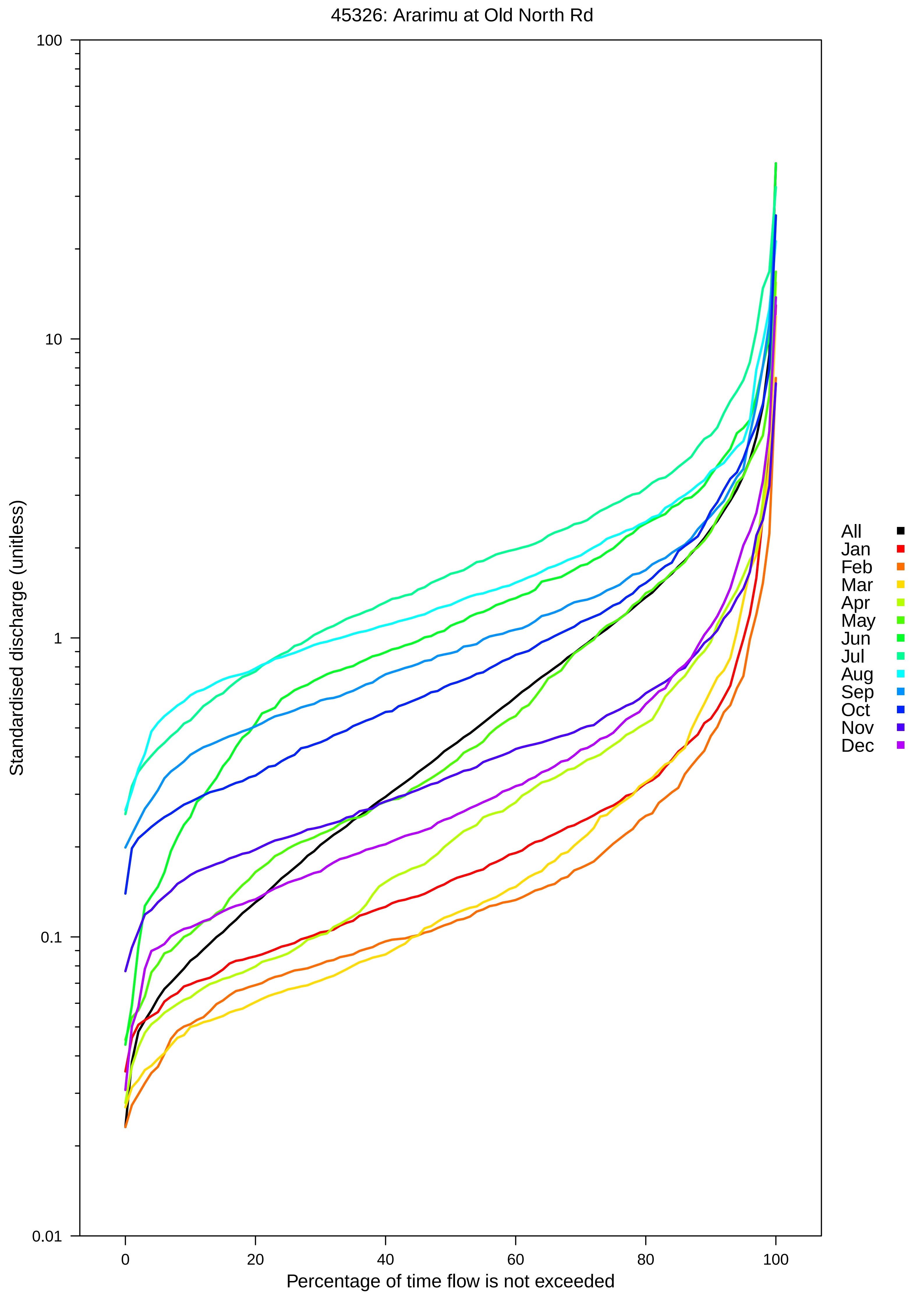
45301: Huapai at NZ Particle Board
Standardised discharge (unitless)
Percentage of time flow is not exceeded
100
10
1
0.1
0.01
0
20
40
60
80
100
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

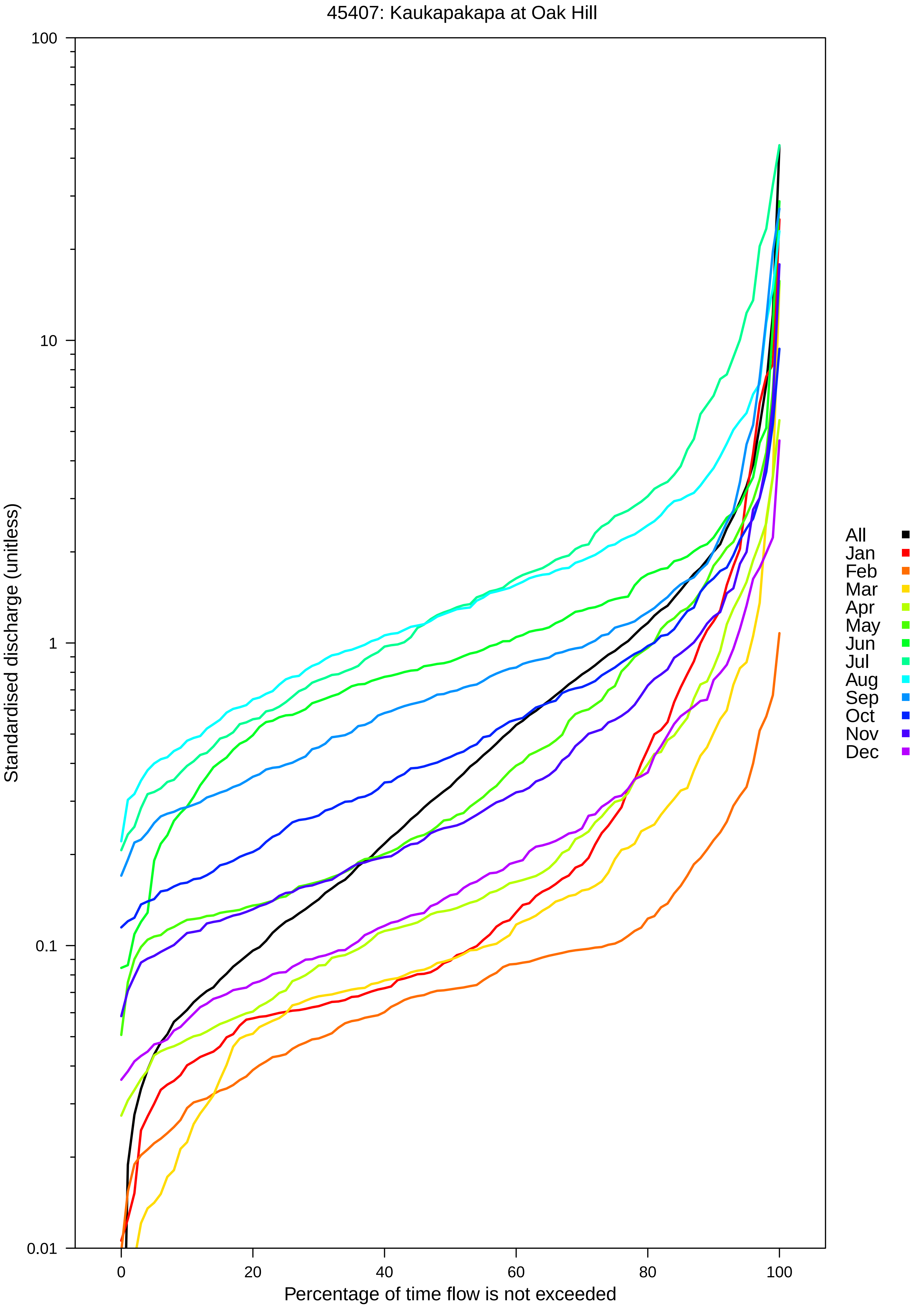


45311: Kaipara at Waimauku
100
10
1
0.1
0.01
Standardised discharge (unitless)
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

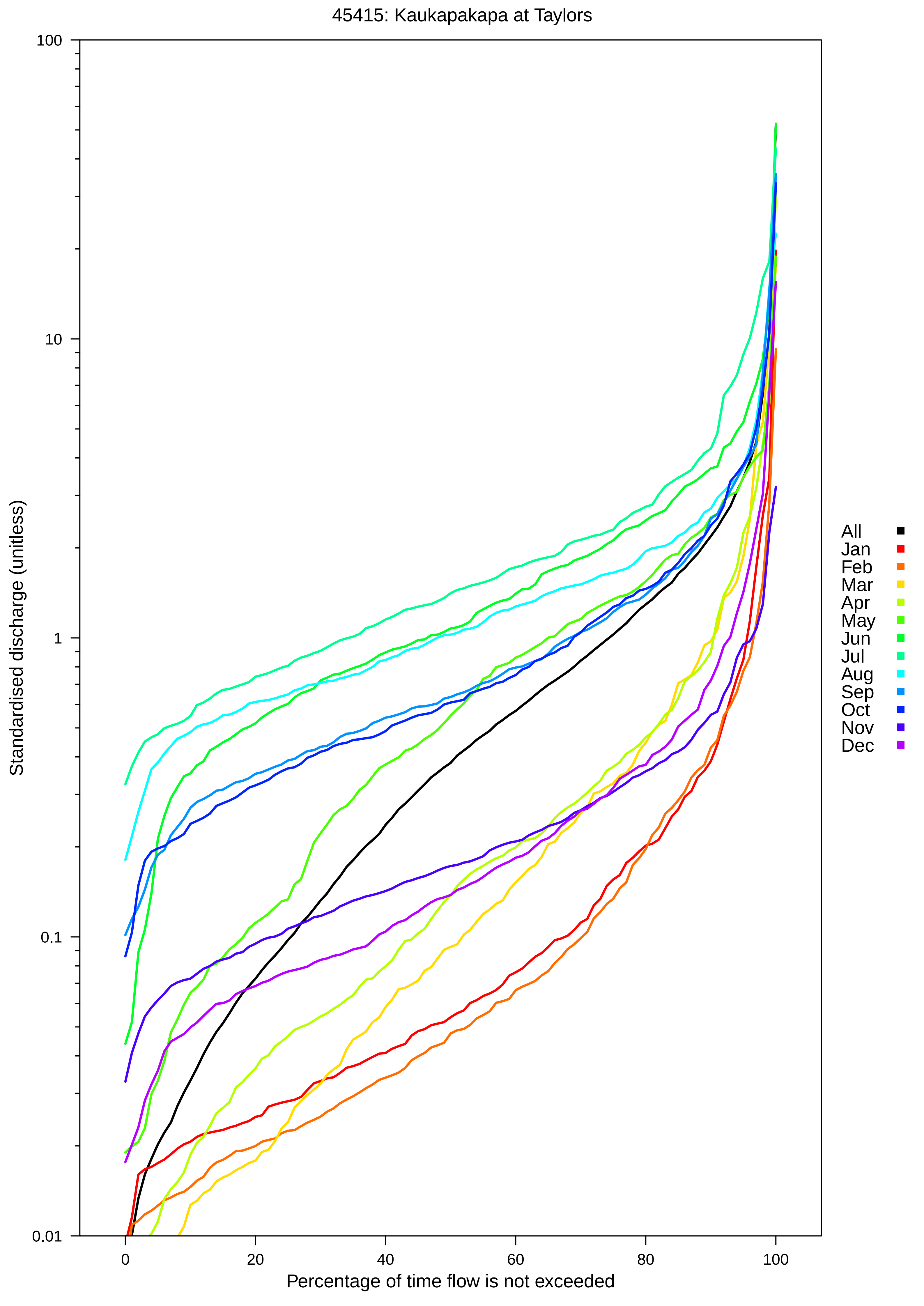


45315: Kumeu at Maddren Weir
Standardised discharge (unitless)
Percentage of time flow is not exceeded
100
10
1
0.1
0.01
0
20
40
60
80
100
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

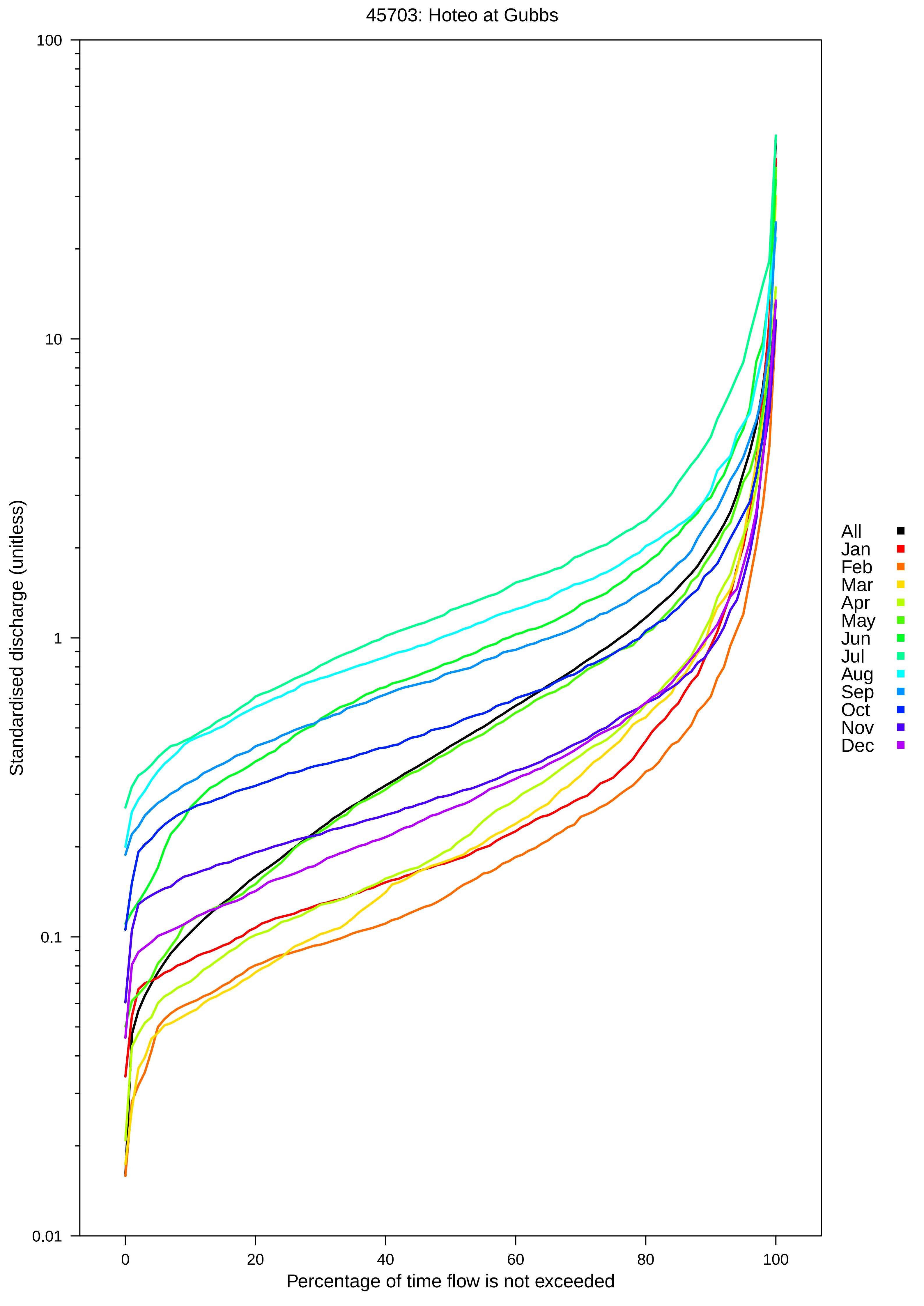

45326: Ararimu at Old North Rd
Standardised discharge (unitless)
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec



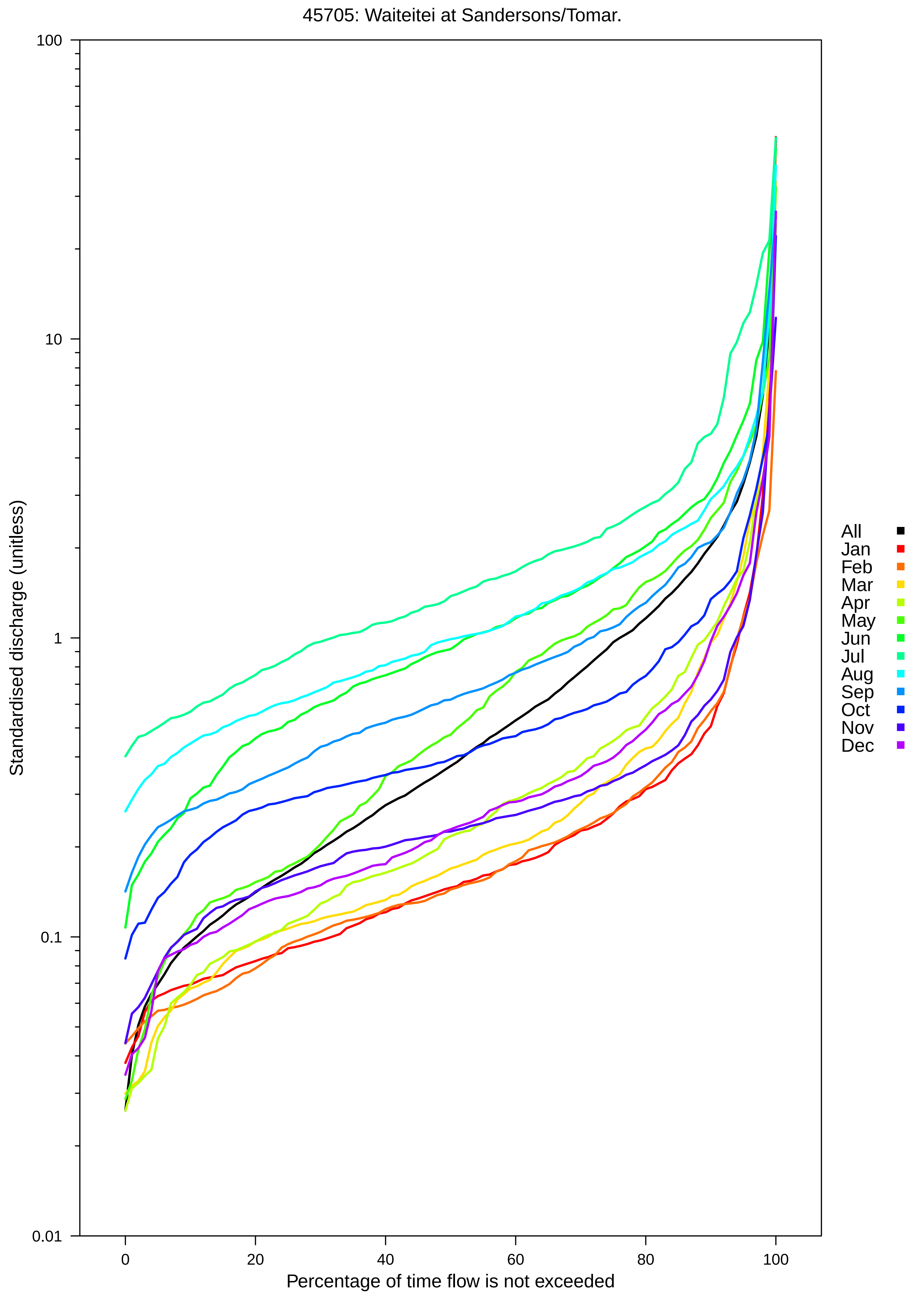
45407: Kaukapakapa at Oak Hill
Standardised discharge (unitless)
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec



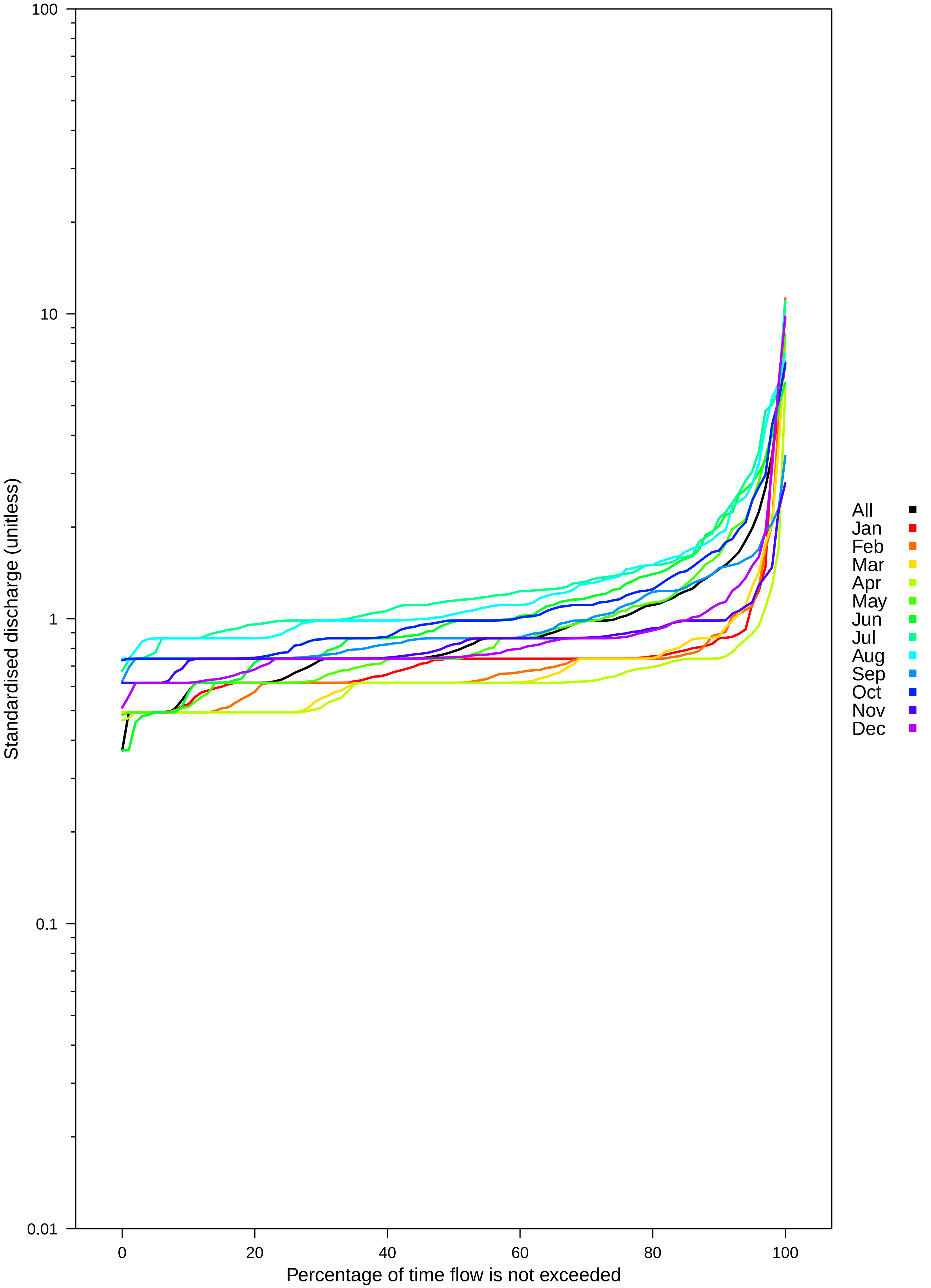
45415: Kaukapakapa at Taylors
100
10
1
0.1
0.01
Standardised discharge (unitless)
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

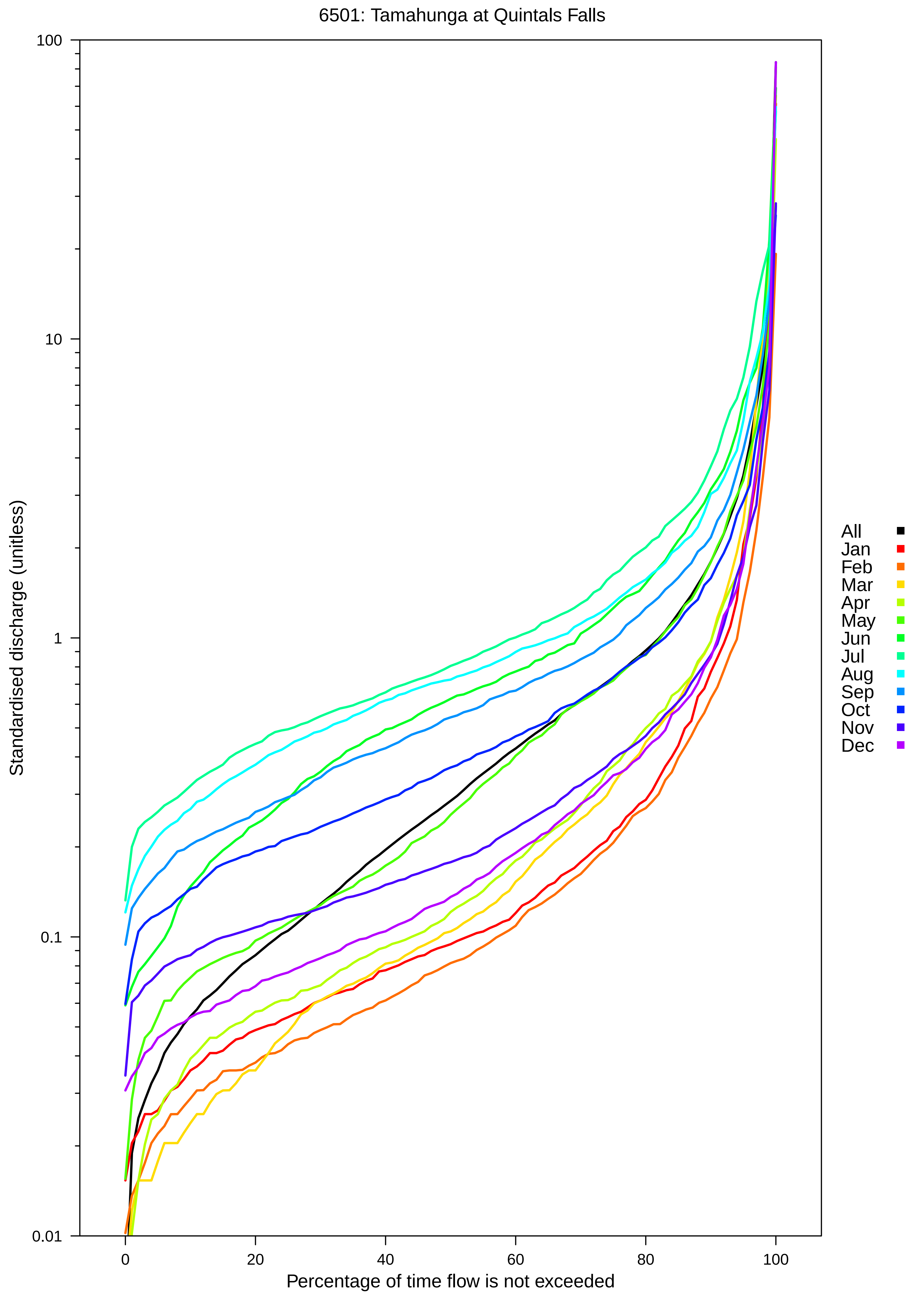


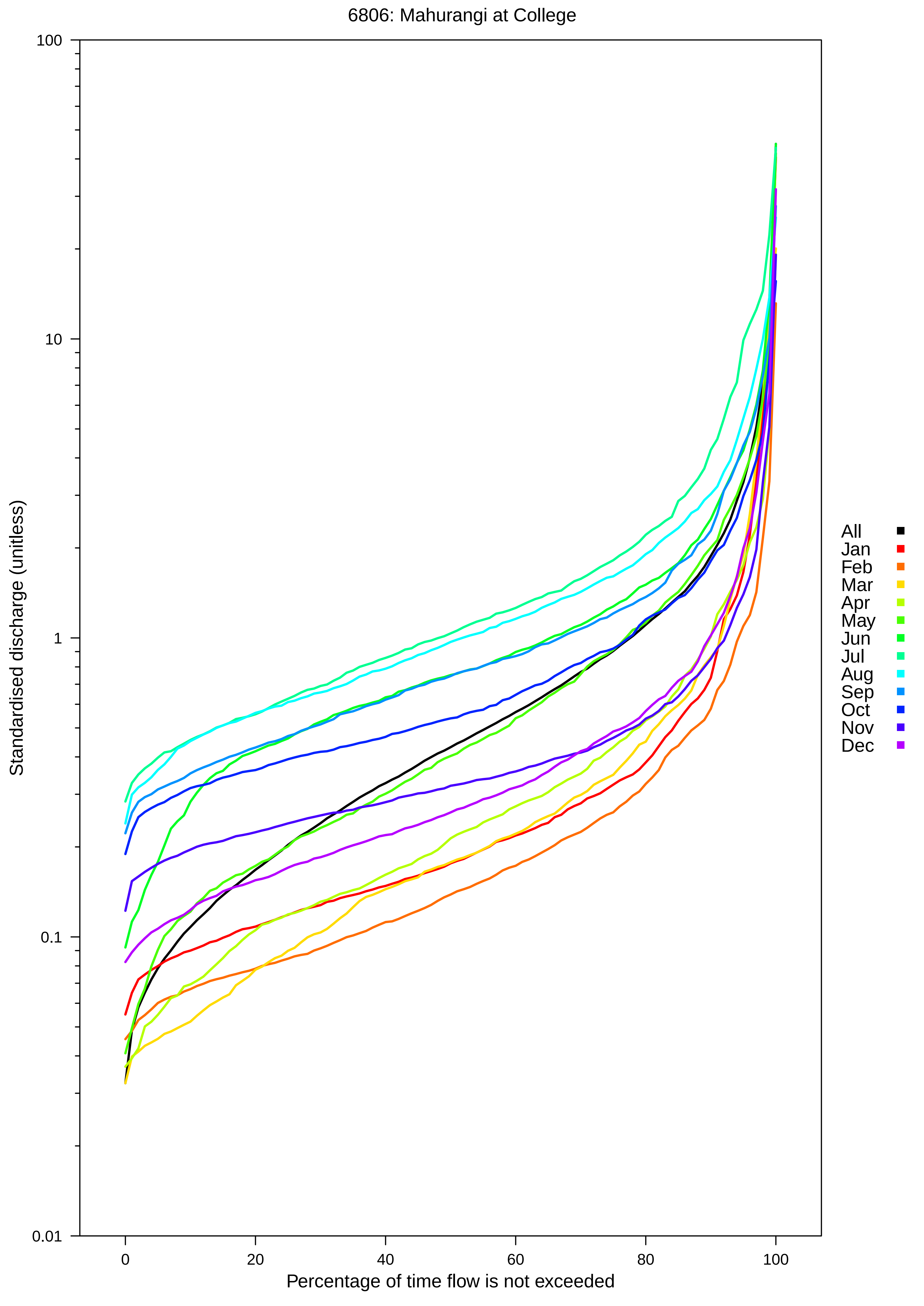
45703: Hoteo at Gubbs
100
10
1
0.1
0.01
Standardised discharge (unitless)
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


45705: Waiteitei at Sandersons/Tomar.
100
10
1
0.1
0.01
Standardised discharge (unitless)
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

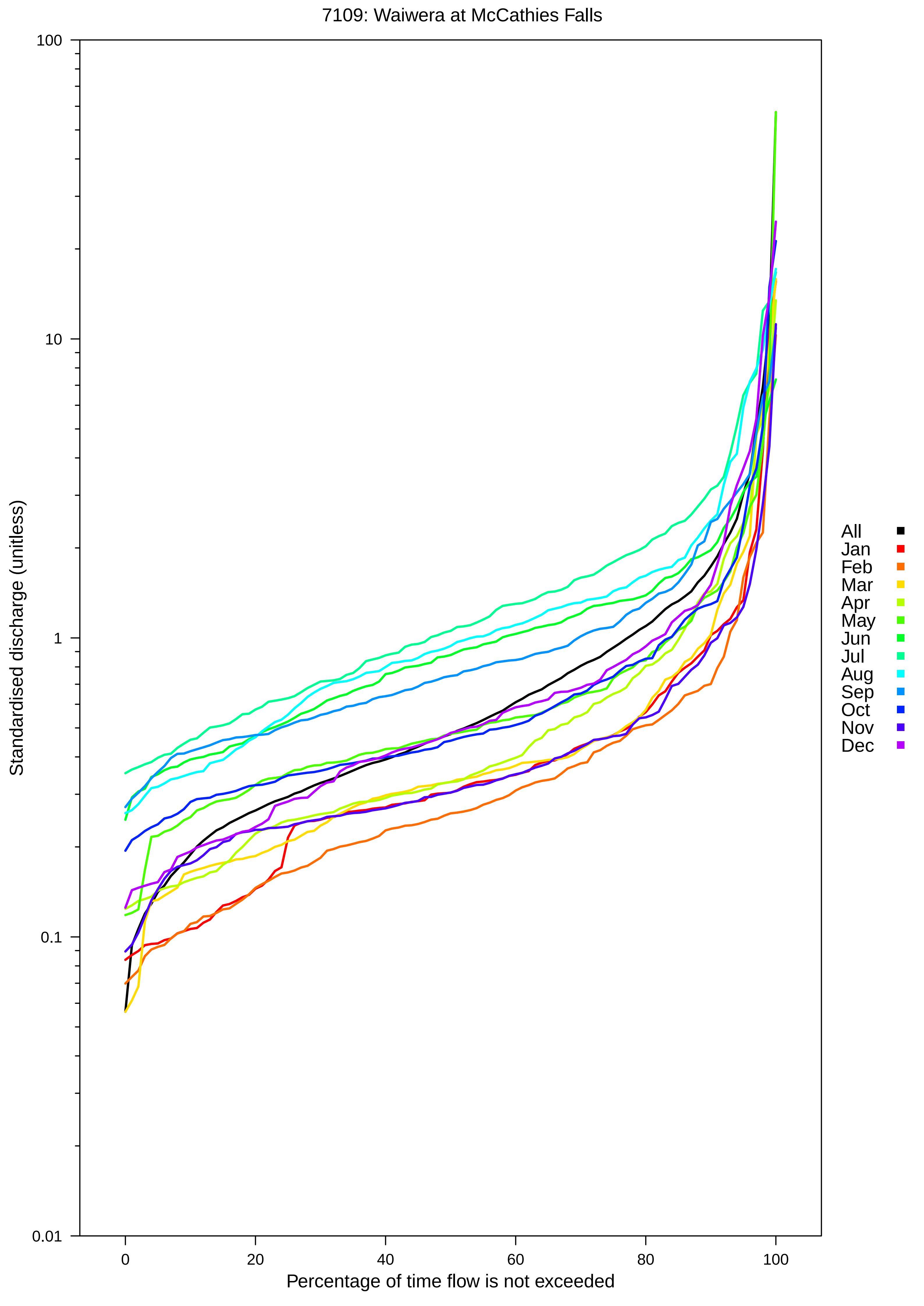
64615: Robinson Stm at Cascades Waitakere



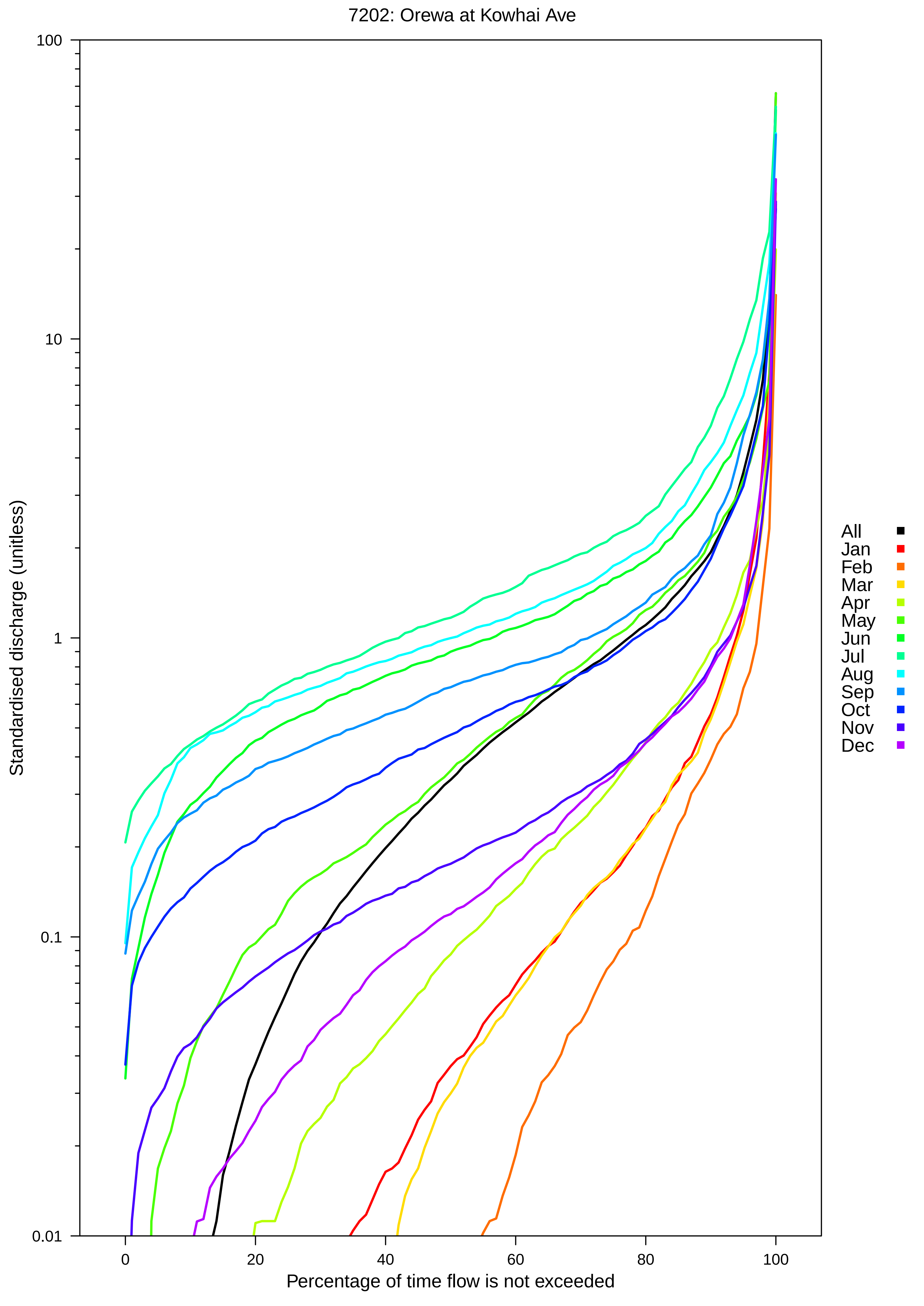

6501: Tamahunga at Quintals Falls
Standardised discharge (unitless)
Percentage of time flow is not exceeded
100
10
1
0.1
0.01
0
20
40
60
80
100
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec



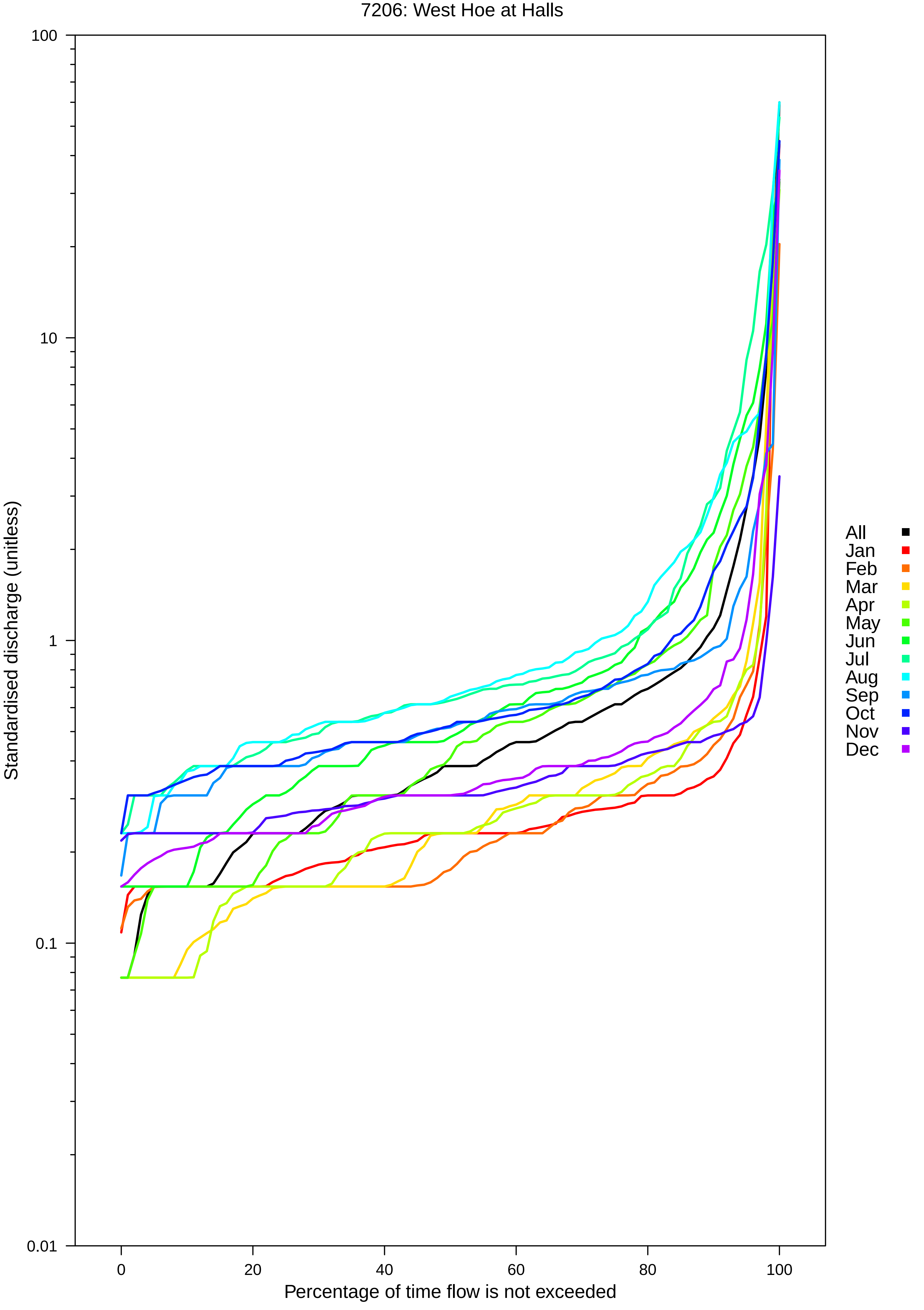
6806: Mahurangi at College
100
10
1
0.1
0.01
Standardised discharge (unitless)
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

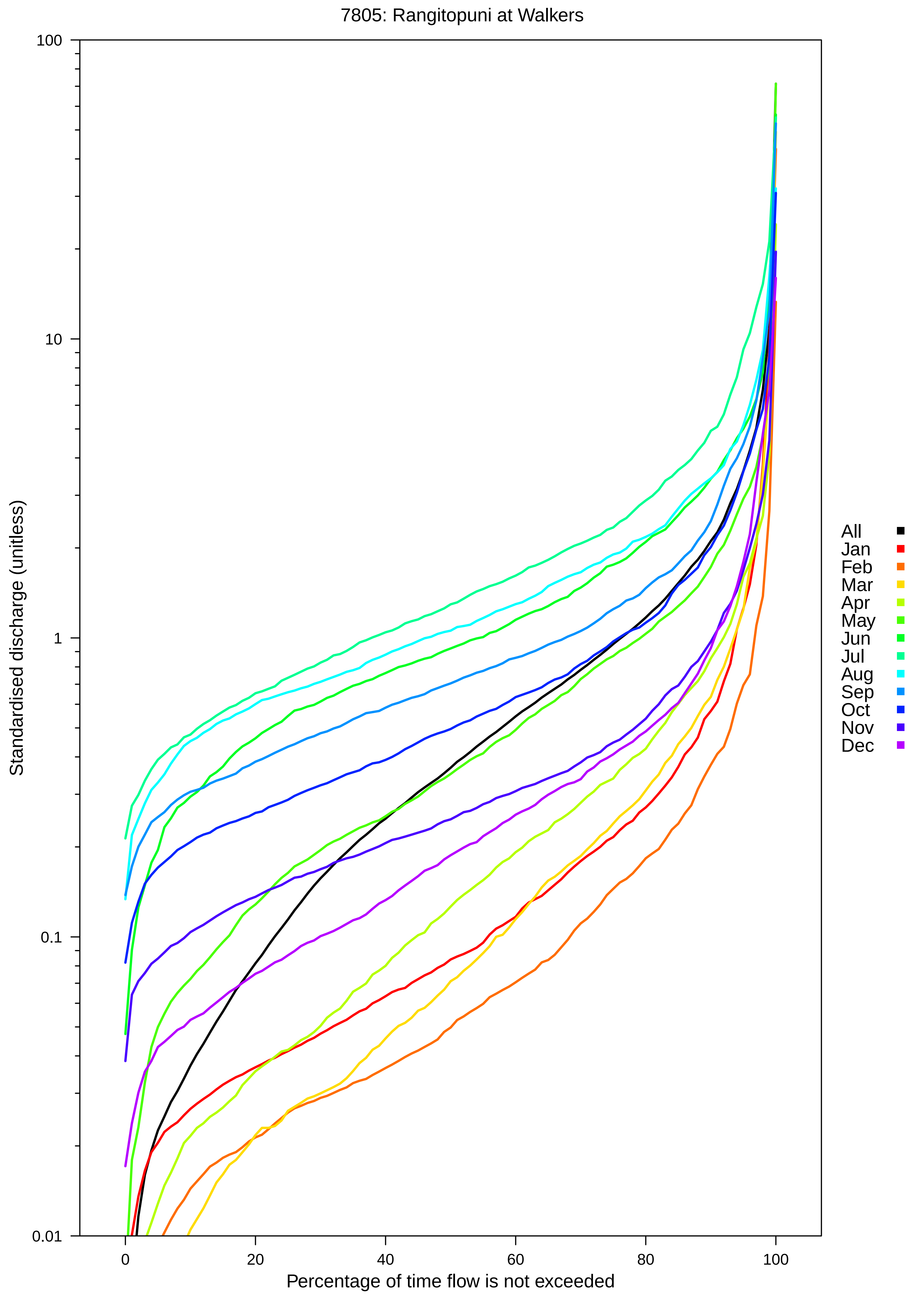


7109: Waiwera at McCathies Falls
100
10
1
0.1
0.01
Standardised discharge (unitless)
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

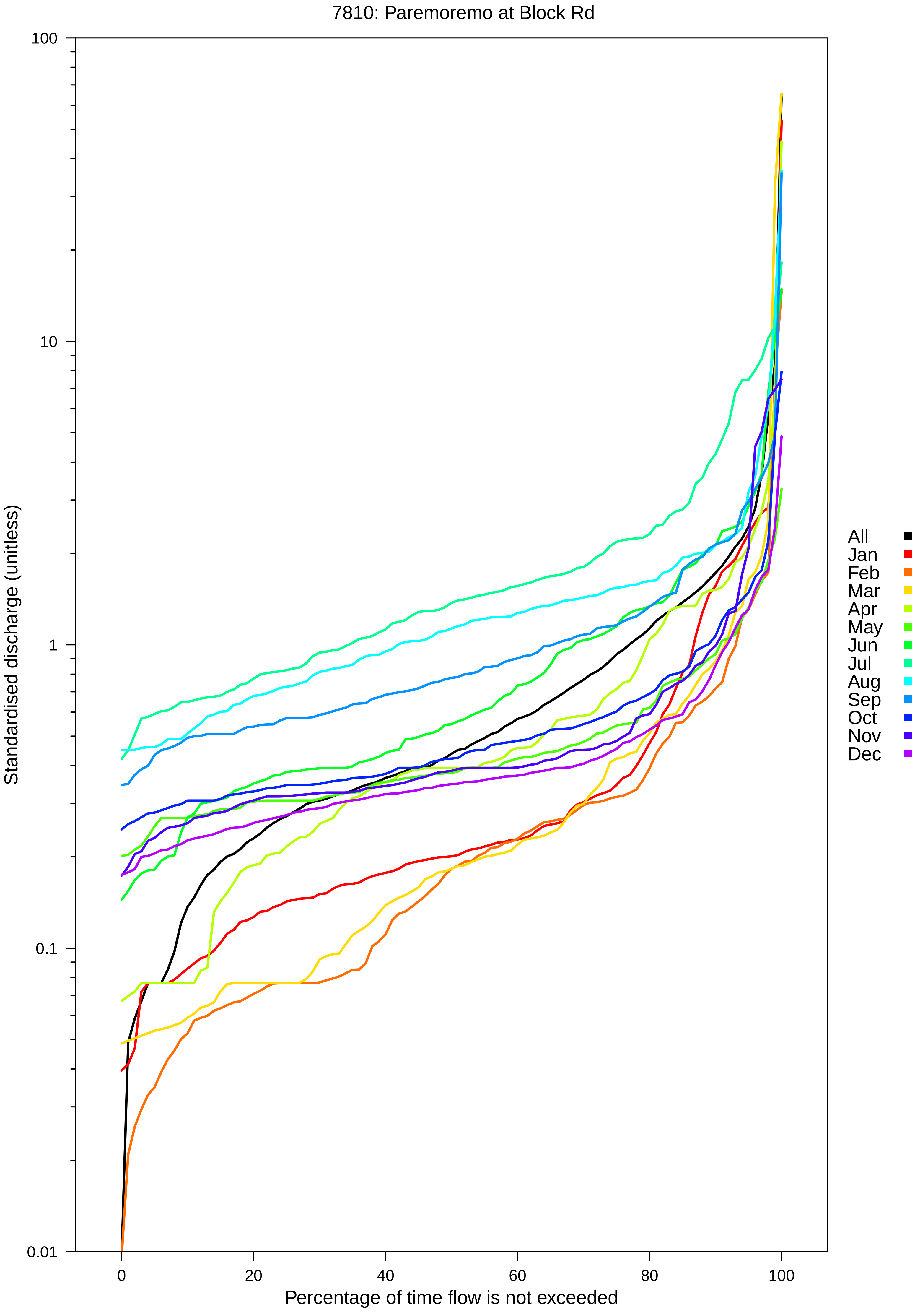


7202: Orewa at Kowhai Ave
Standardised discharge (unitless)
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

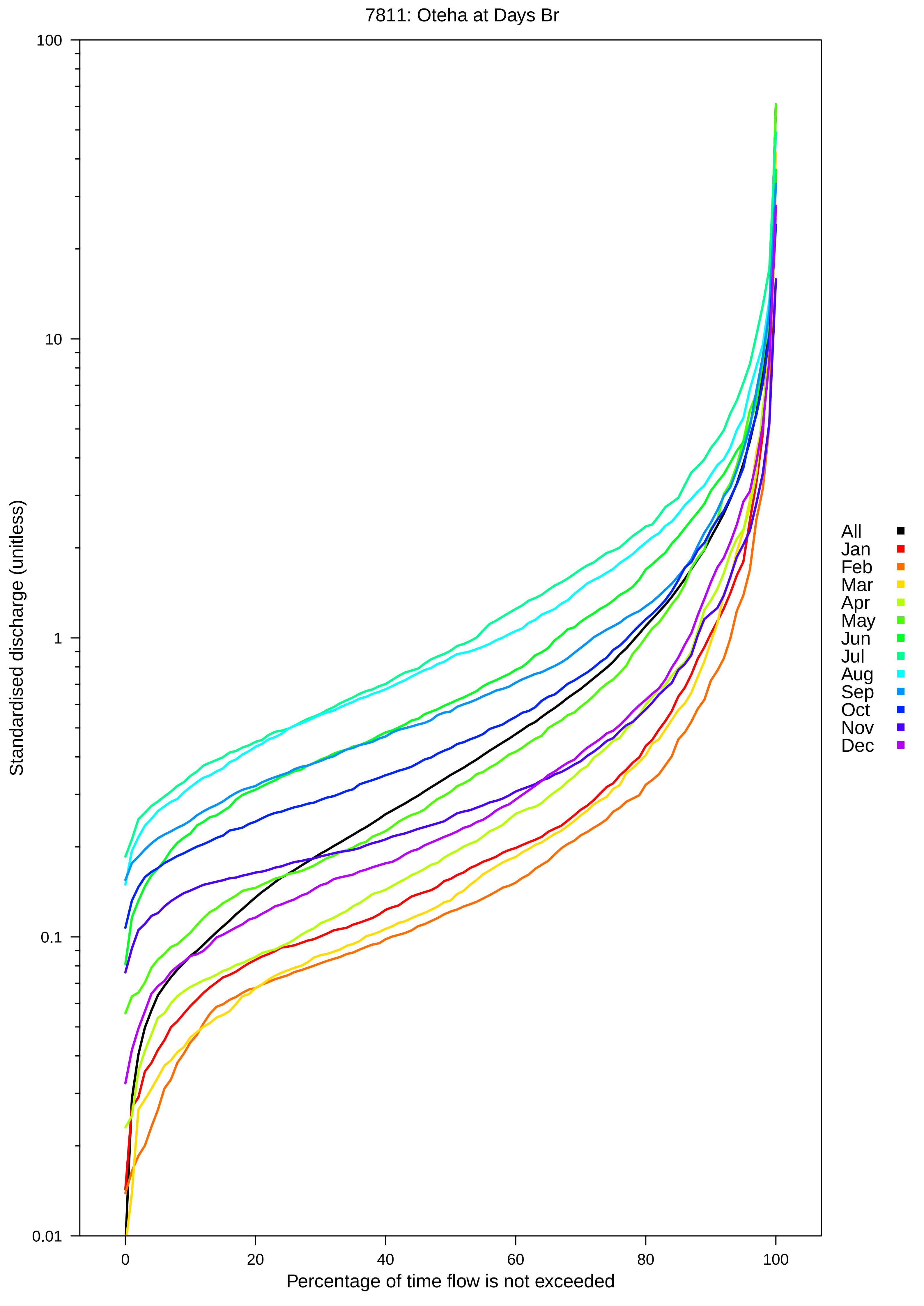

7206: West Hoe at Halls
Standardised discharge (unitless)
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

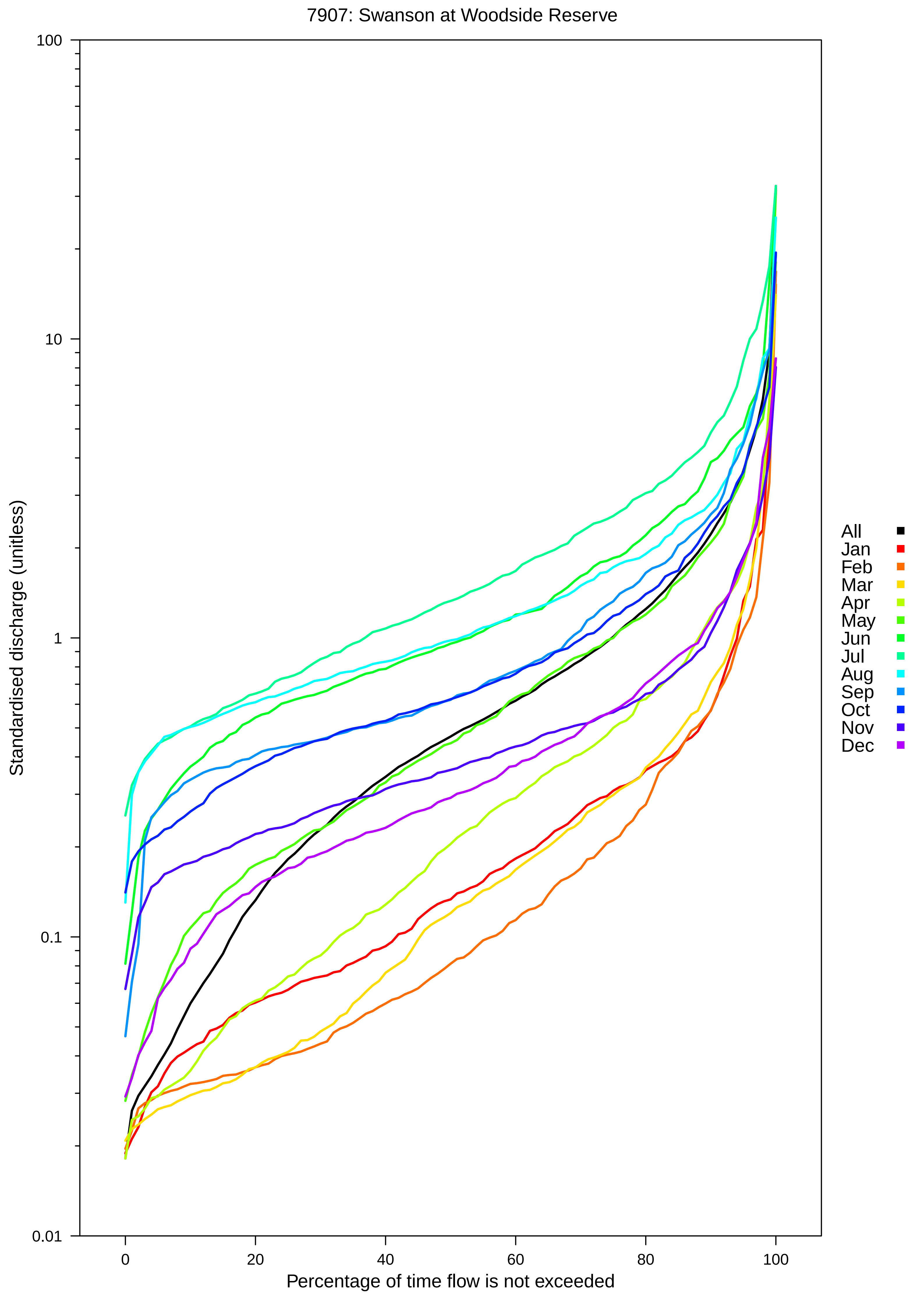


7805: Rangitopuni at Walkers
Standardised discharge (unitless)
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

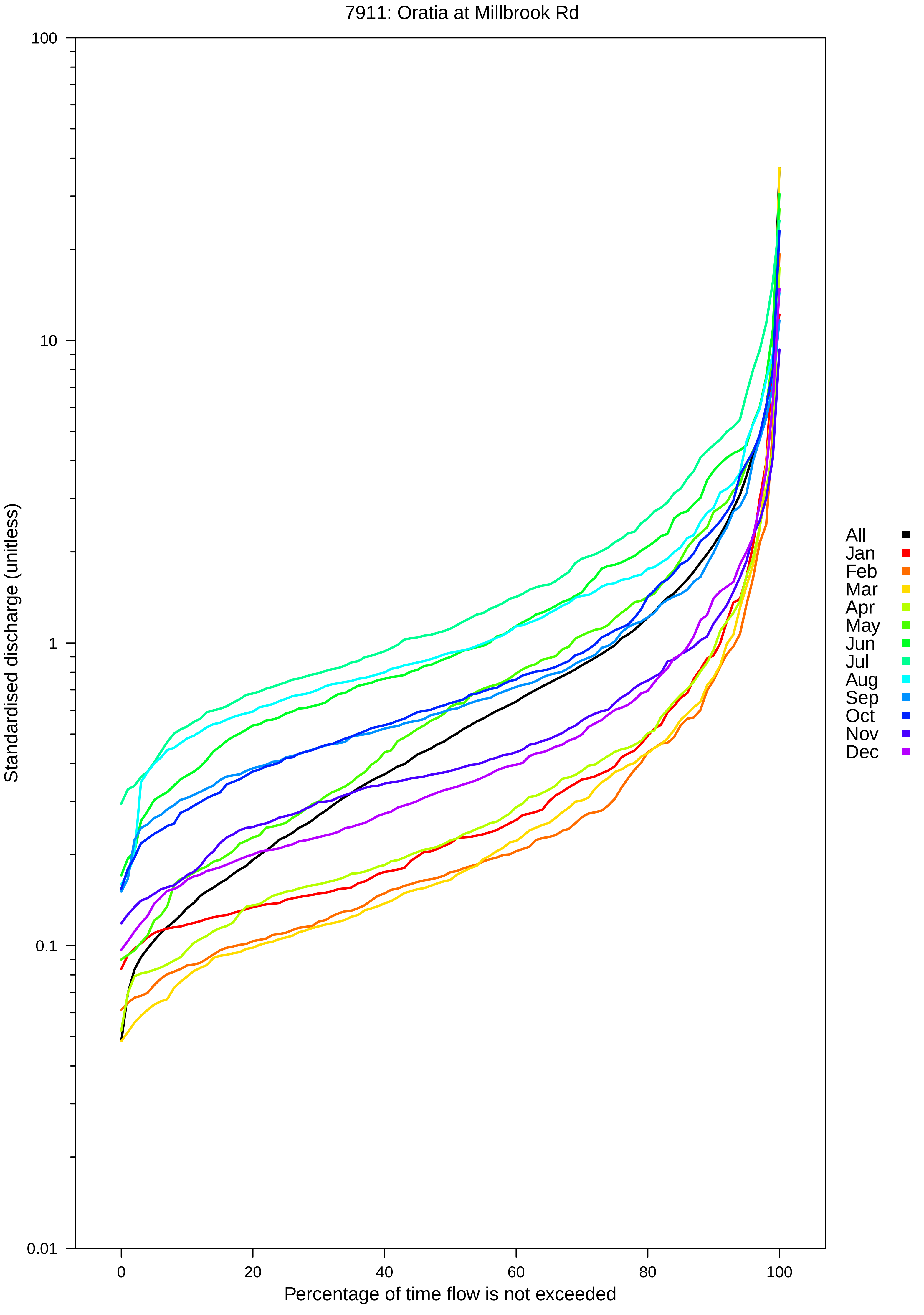


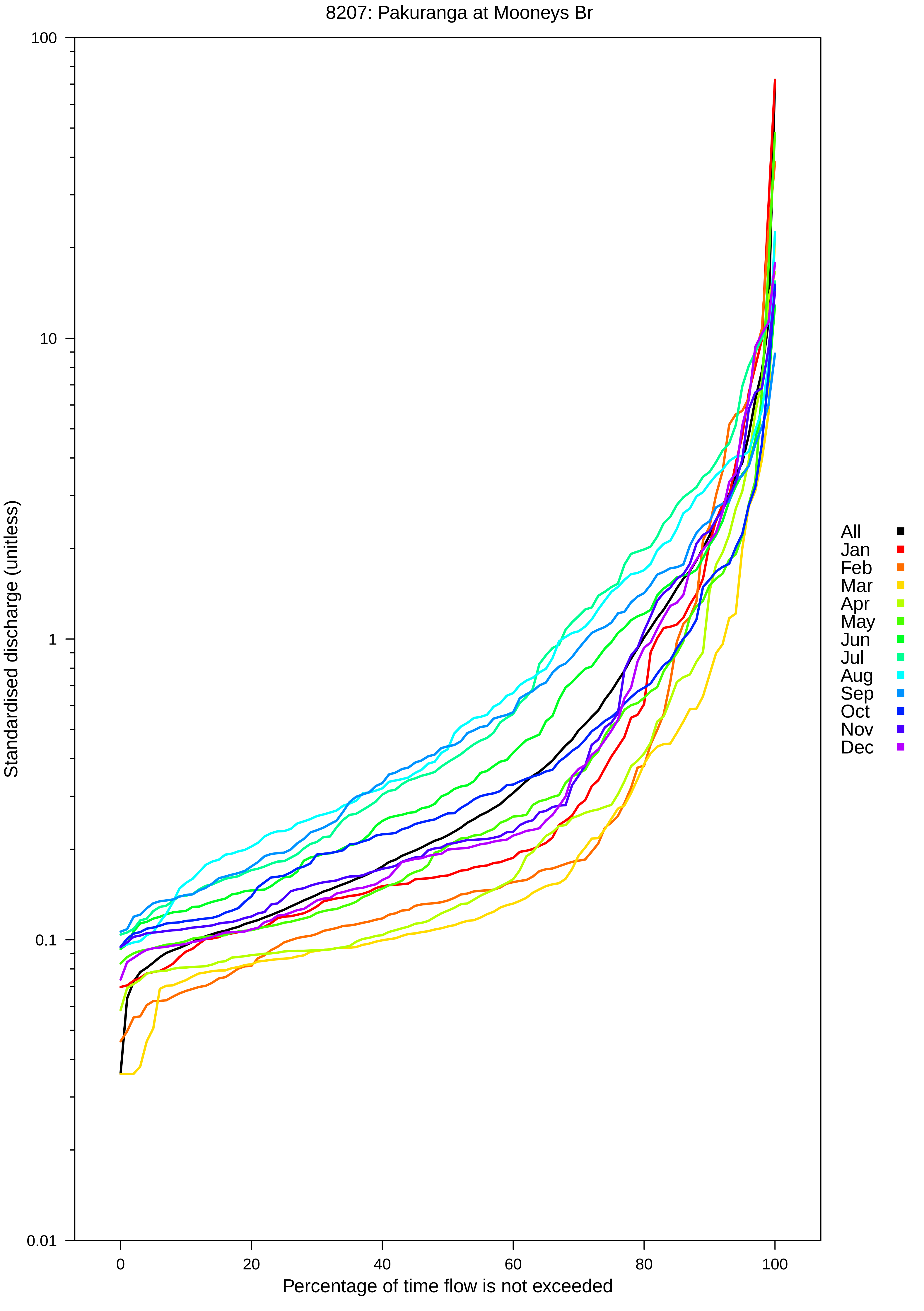
7810: Paremoremo at Block Rd
Standardised discharge (unitless)
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


7811: Oteha at Days Br
Standardised discharge (unitless)
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec



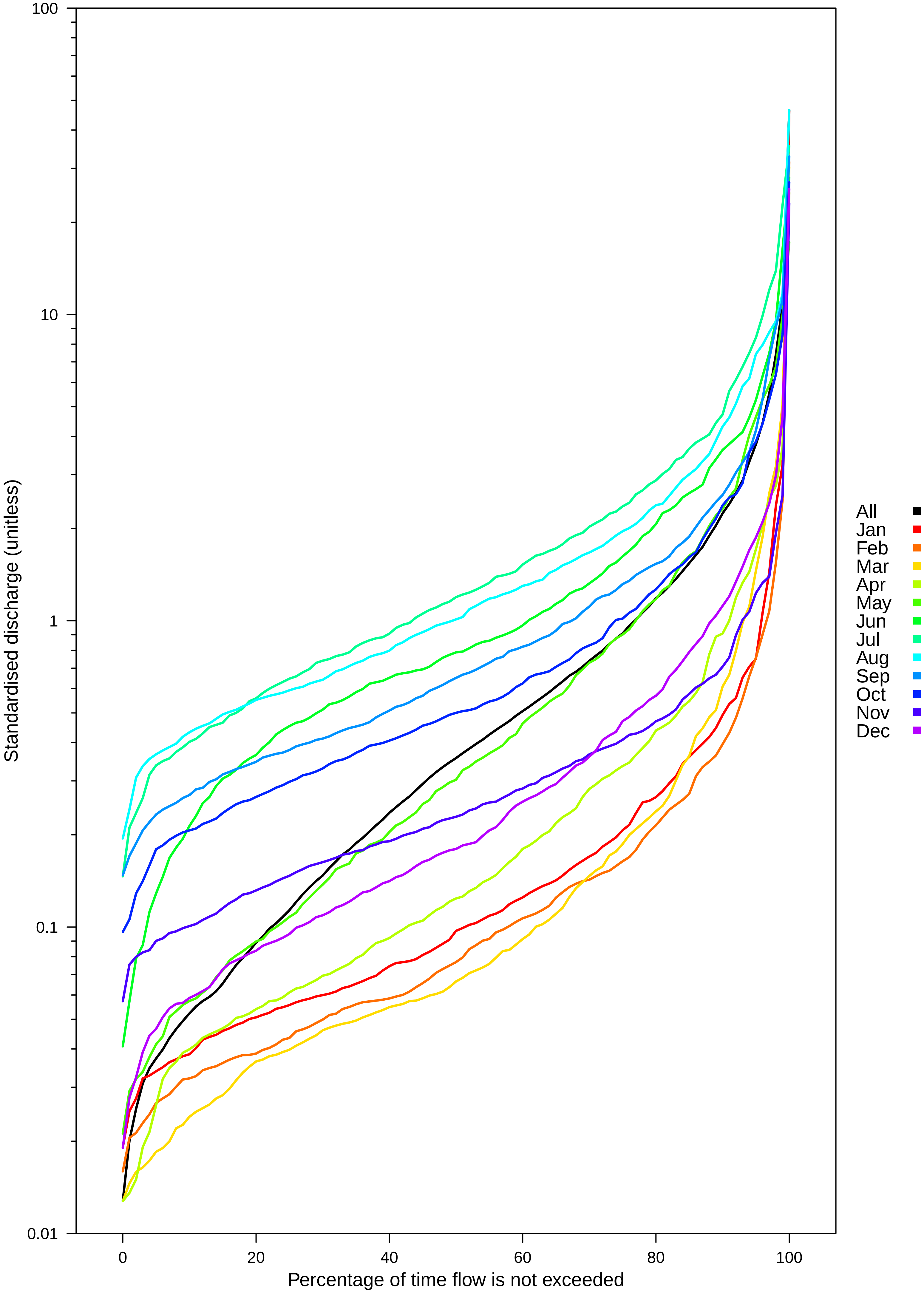
7907: Swanson at Woodside Reserve
Standardised discharge (unitless)
Percentage of time flow is not exceeded
100
10
1
0.1
0.01
0
20
40
60
80
100
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

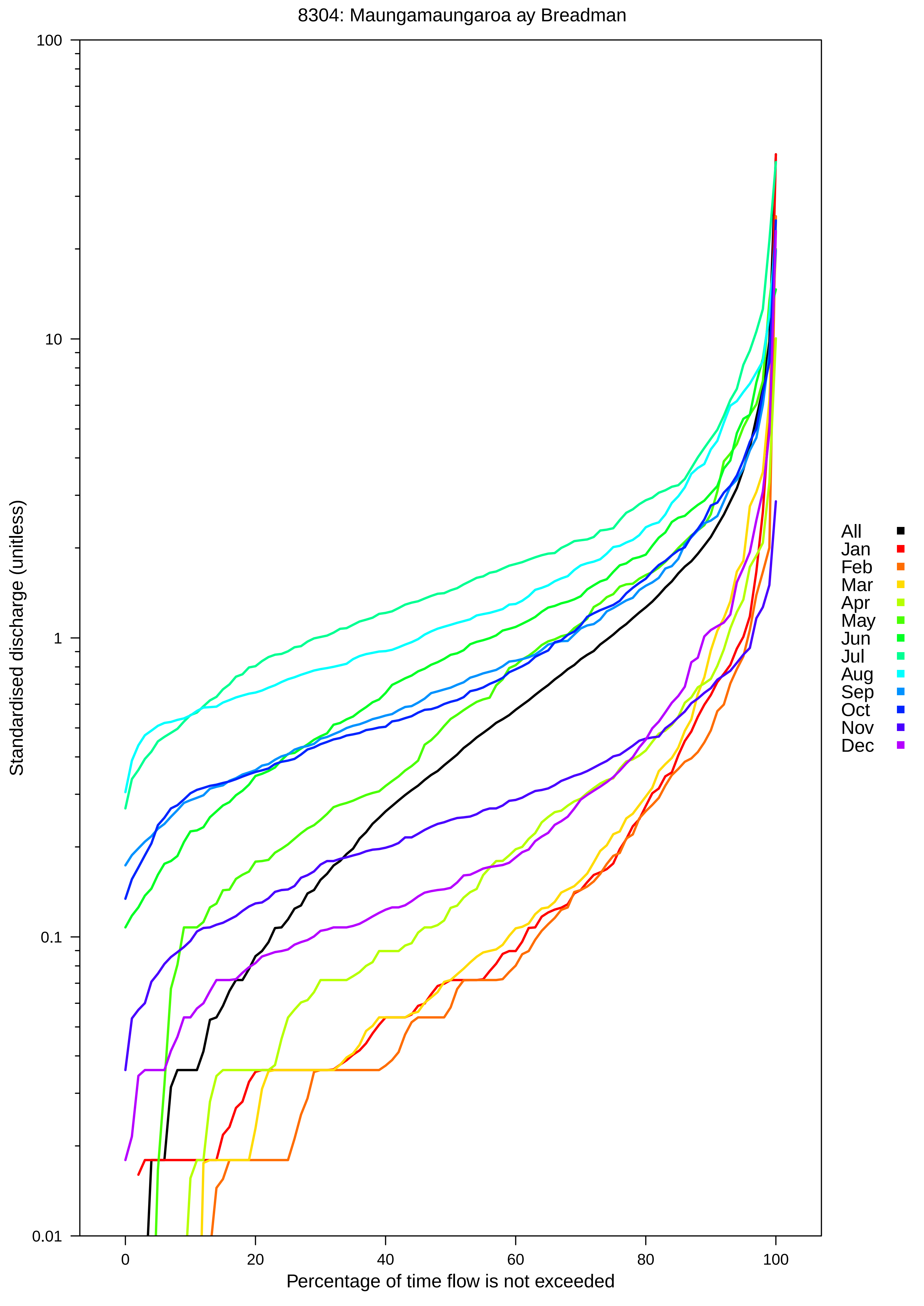

7911: Oratia at Millbrook Rd
Standardised discharge (unitless)
Percentage of time flow is not exceeded
100
10
1
0.1
0.01
0
20
40
60
80
100
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

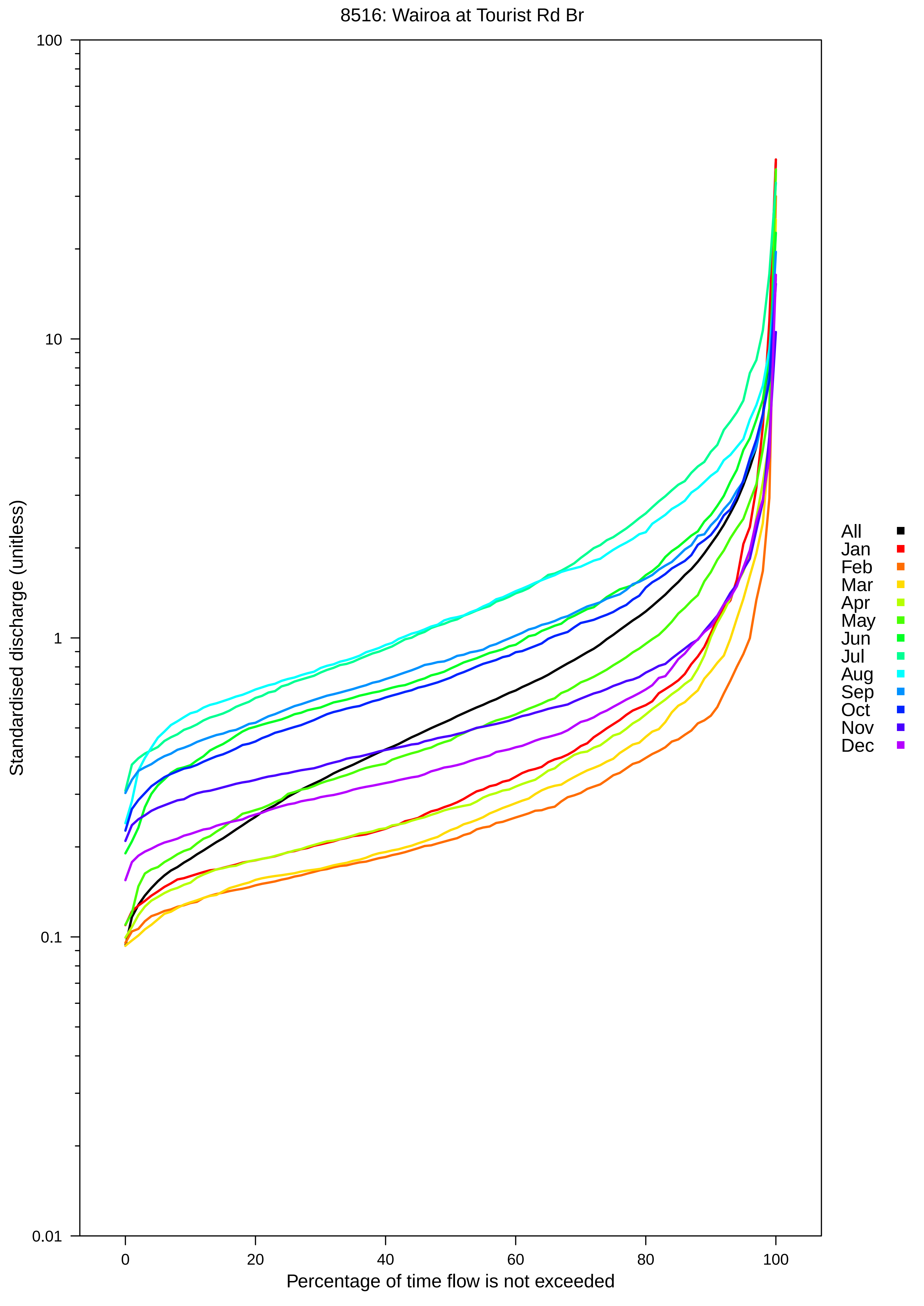


8207: Pakuranga at Mooneys Br
100
10
1
0.1
0.01
Standardised discharge (unitless)
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

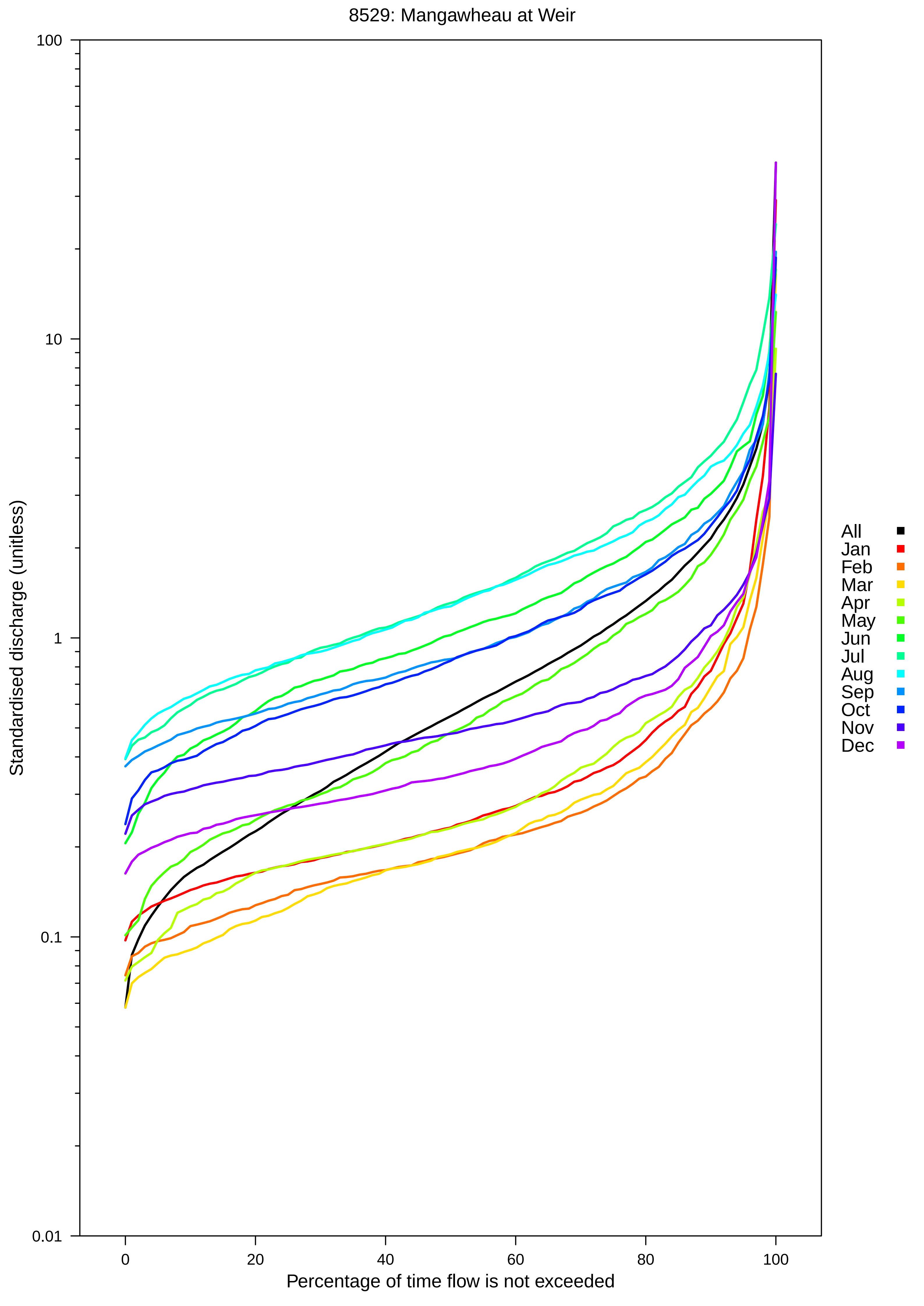
8208: Otara at Hills Rd



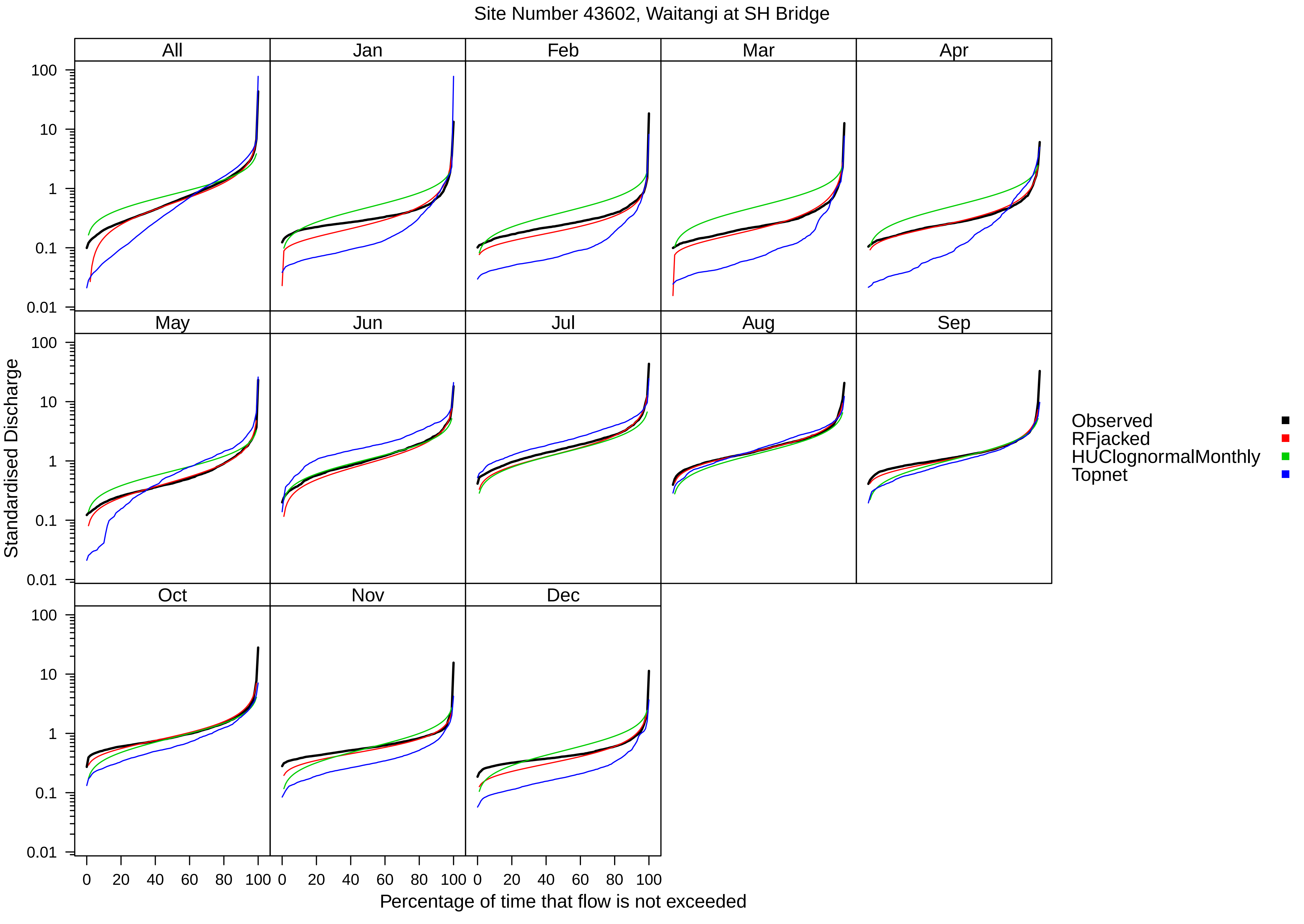

8304: Maungamaungaroa ay Breadman
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time flow is not exceeded
Standardised discharge (unitless)
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec



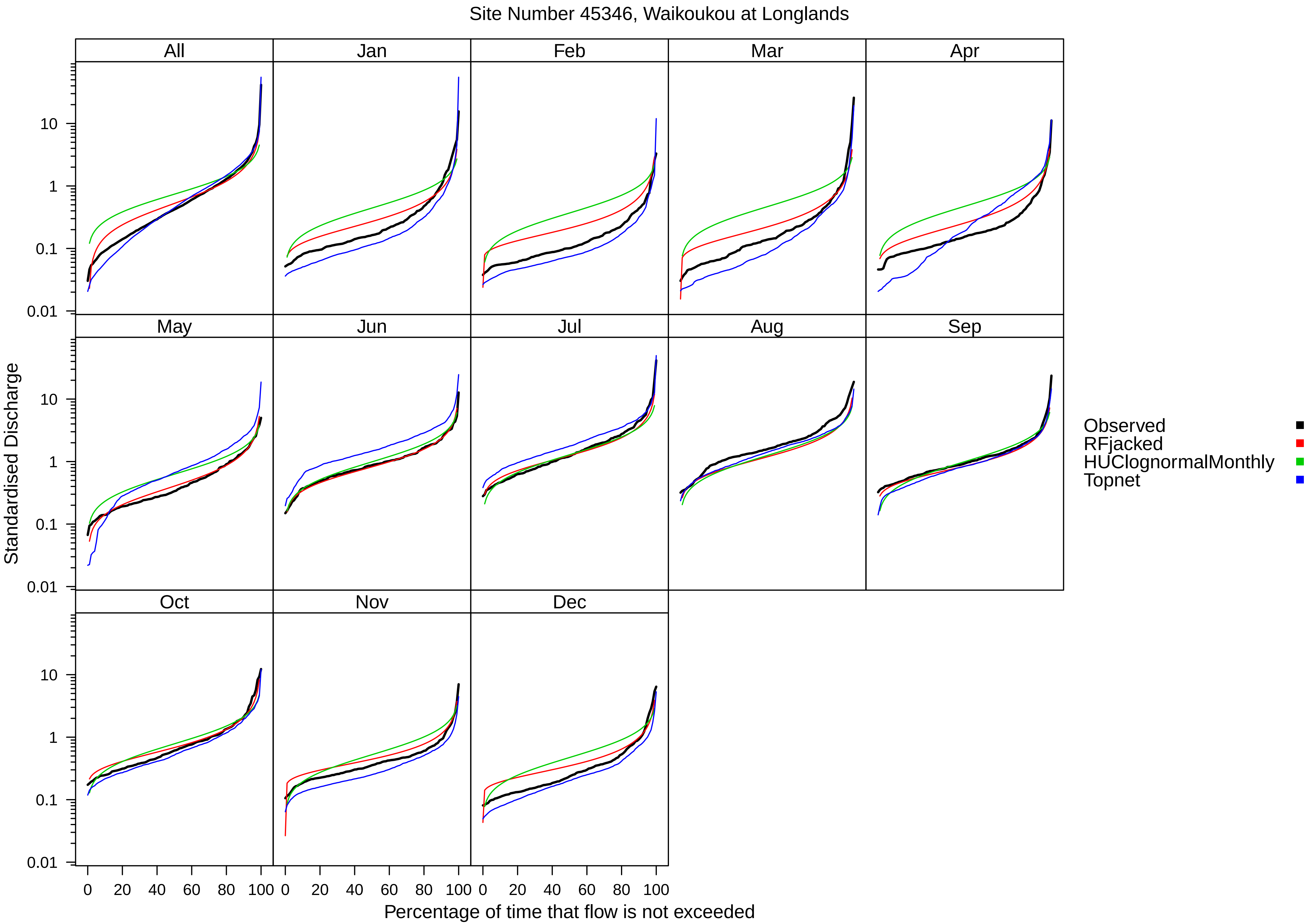
8516: Wairoa at Tourist Rd Br
100
10
1
0.1
0.01
Standardised discharge (unitless)
0
20
40
60
80
100
Percentage of time flow is not exceeded
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


8529: Mangawheau at Weir
Standardised discharge (unitless)
Percentage of time flow is not exceeded
100
10
1
0.1
0.01
0
20
40
60
80
100
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

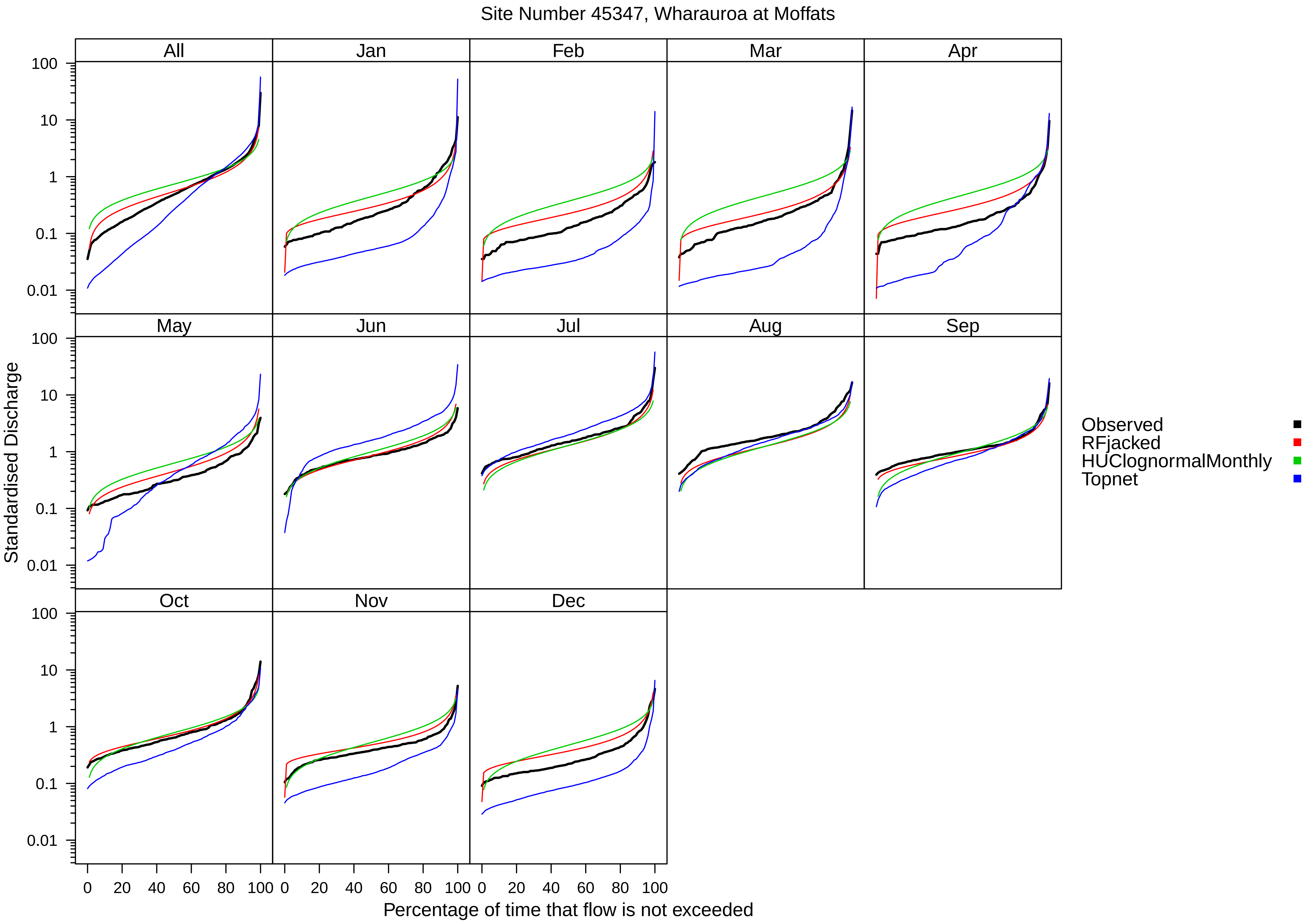
Appendix D Flow duration curve testing for Auckland



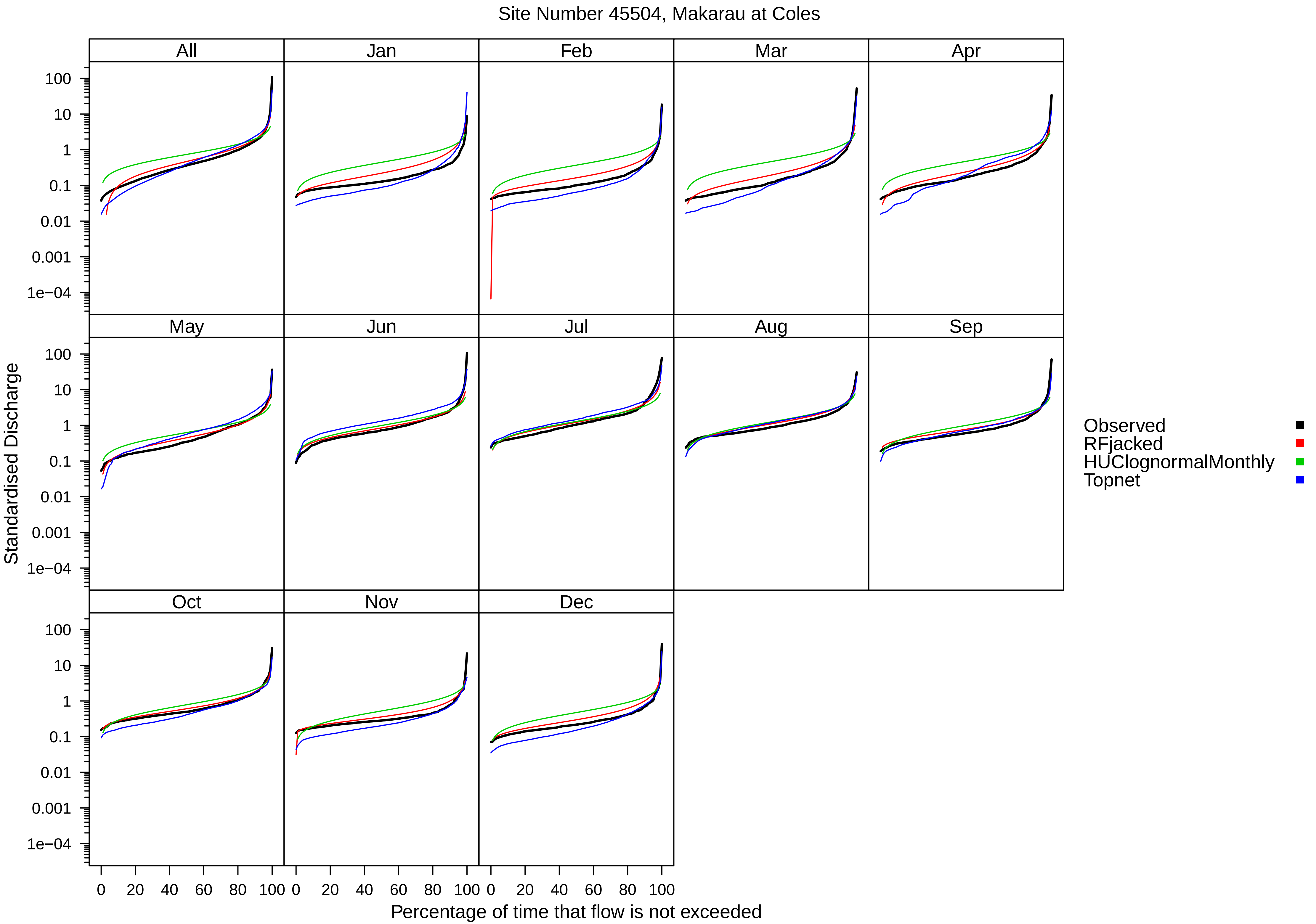
Site Number 43602, Waitangi at SH Bridge
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
100
10
1
0.1
0.01
Standardised Discharge
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet



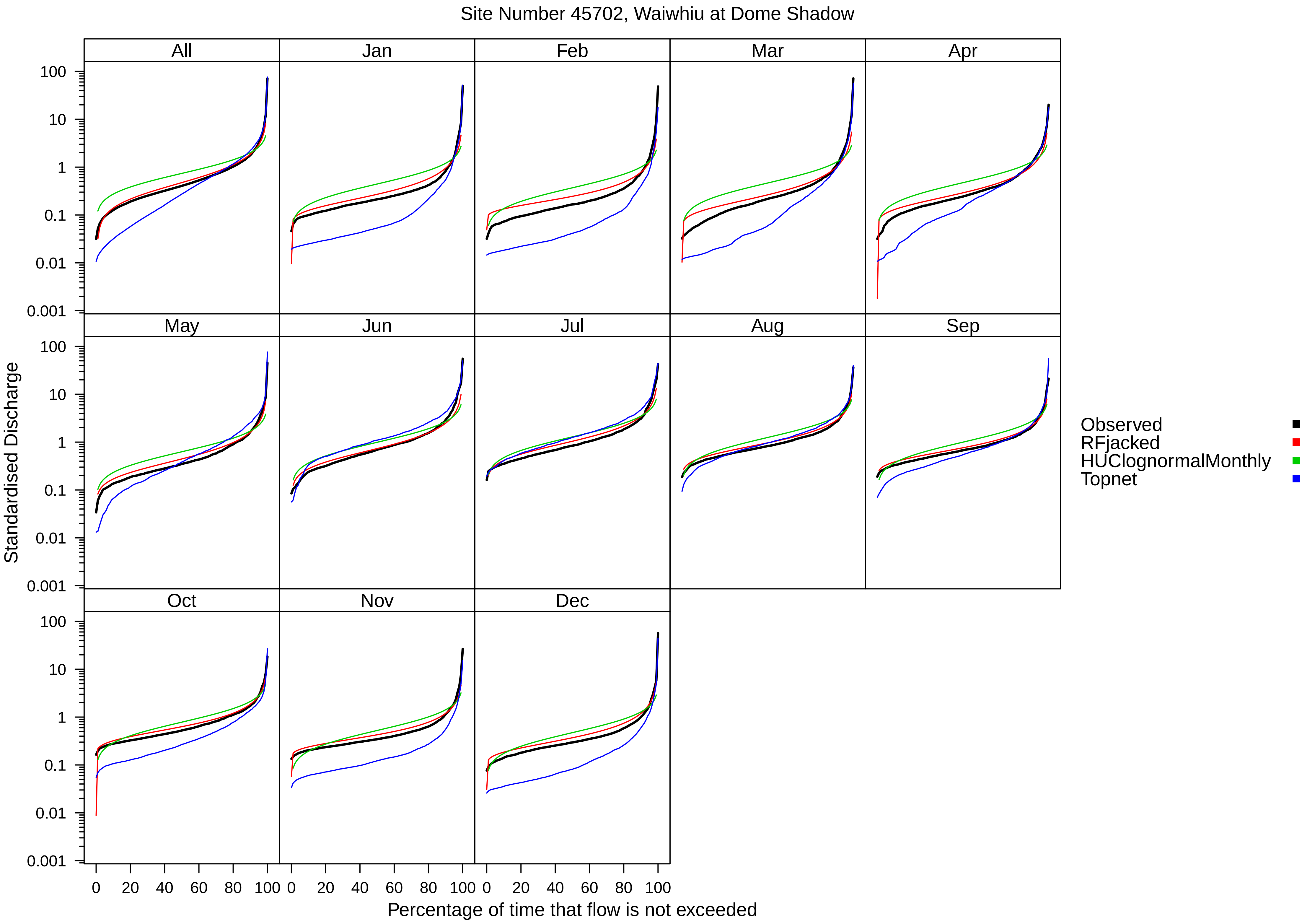
Site Number 45346, Waikoukou at Longlands
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
0.01
0.1
1
10
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet



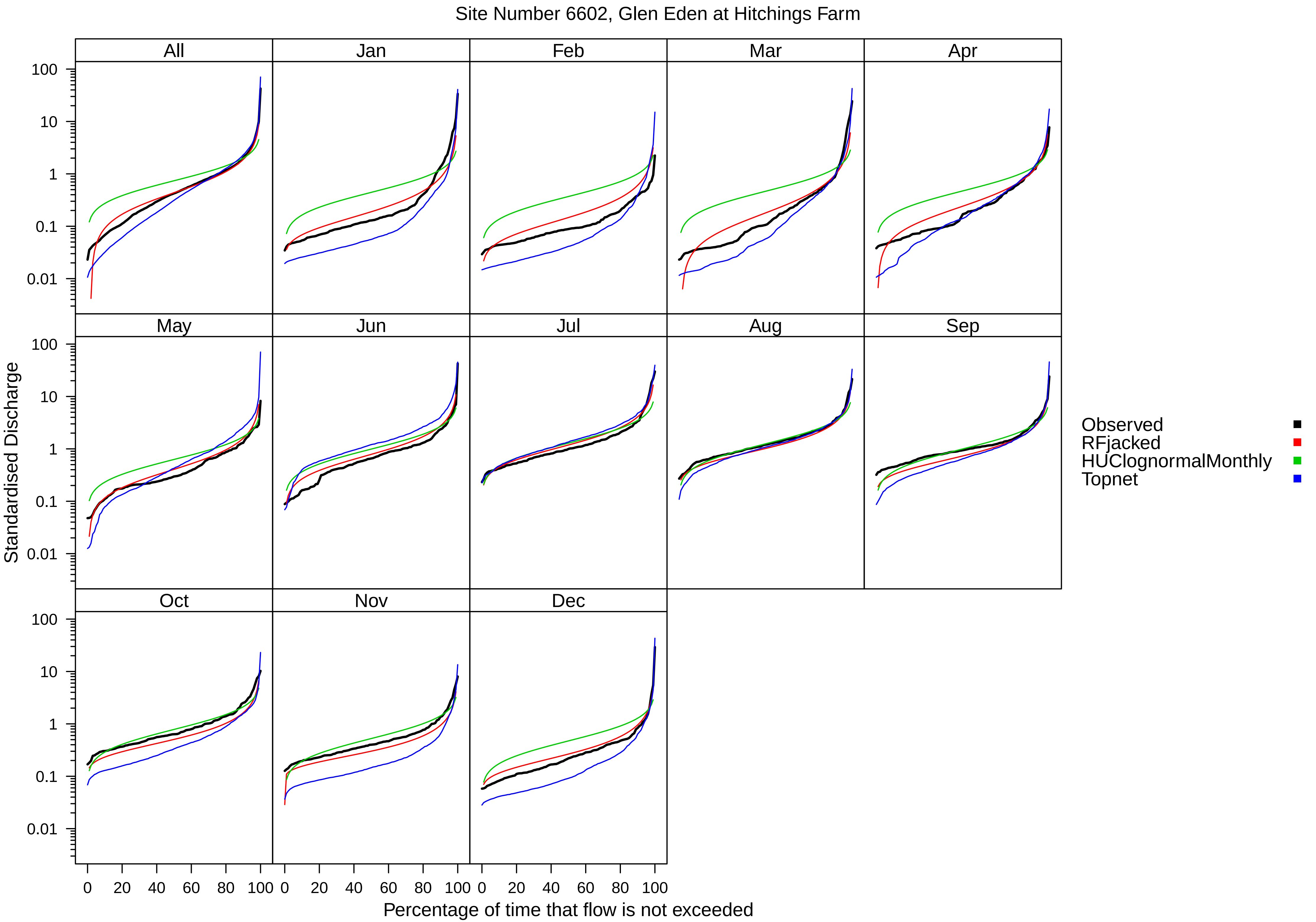
Site Number 45347, Wharauroa at Moffats
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
Percentage of time that flow is not exceeded
100
10
1
0.1
0.01
0
20
40
60
80
100
Observed
RFjacked
HUClognormalMonthly
Topnet



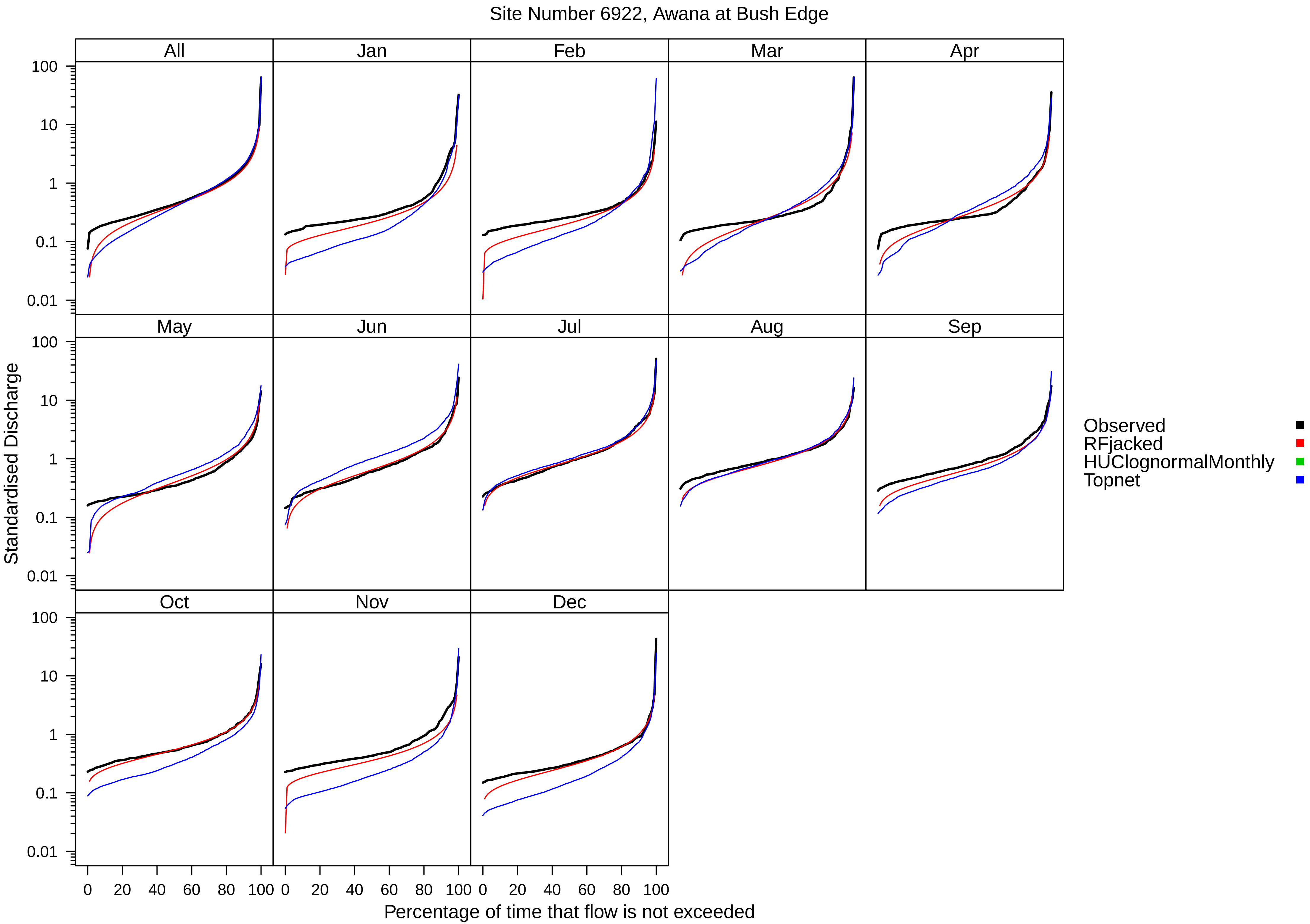
Site Number 45504, Makarau at Coles
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
100
10
1
0.1
0.01
0.001
1e−04
0
20
40
60
80
100
Standardised Discharge
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet



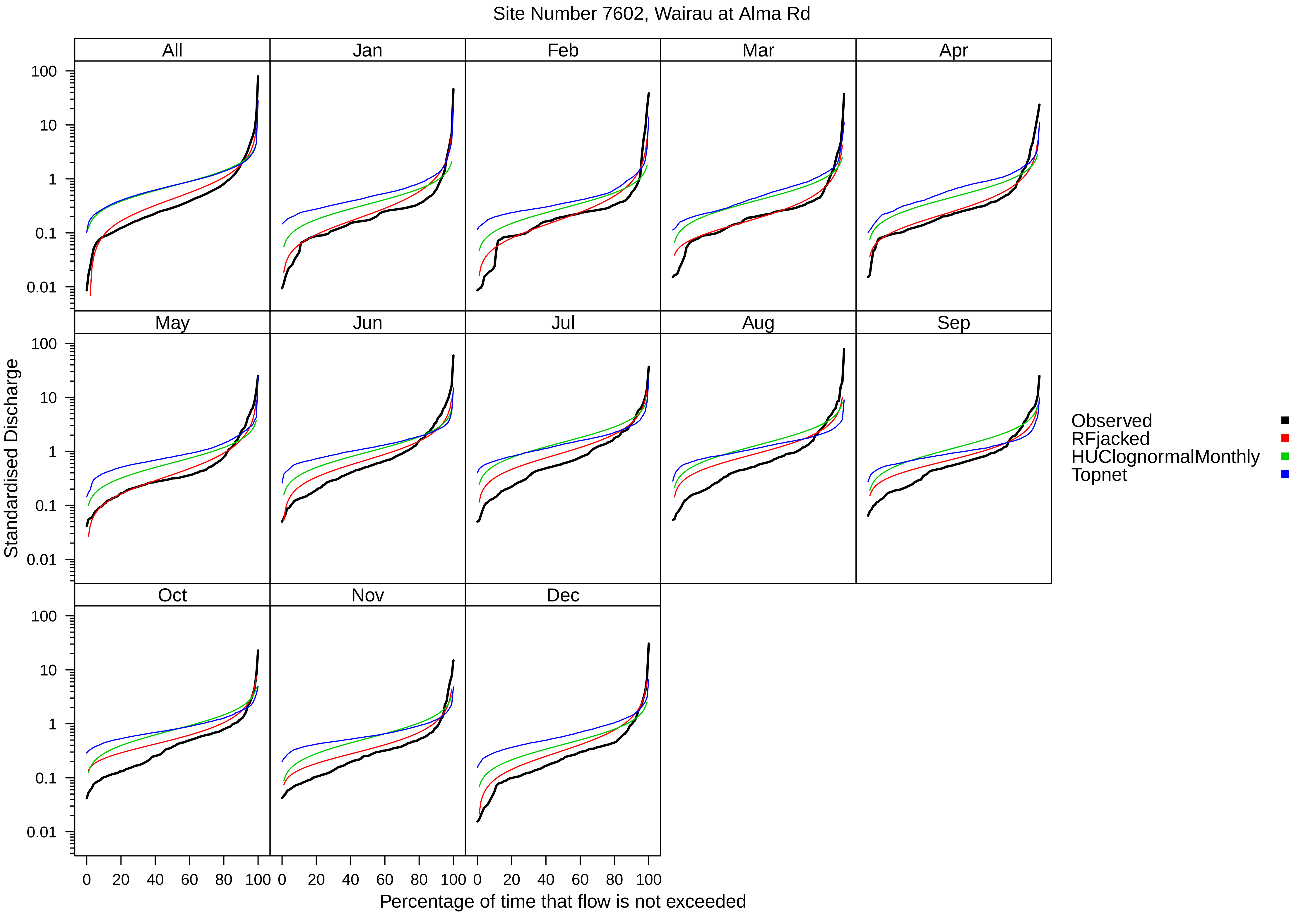
Site Number 45702, Waiwhiu at Dome Shadow
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
100
10
1
0.1
0.01
0.001
Standardised Discharge
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet

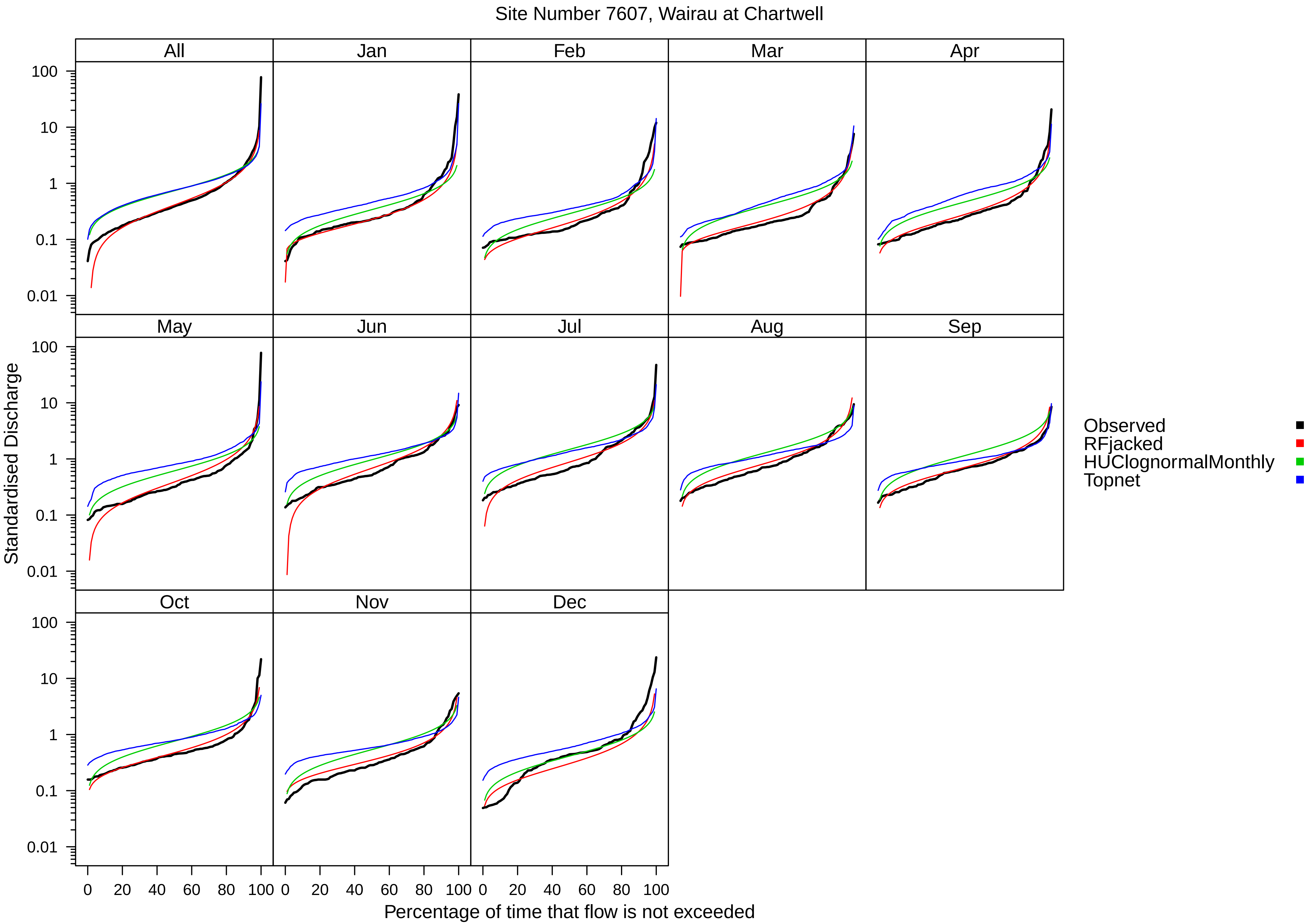


Site Number 6602, Glen Eden at Hitchings Farm
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet

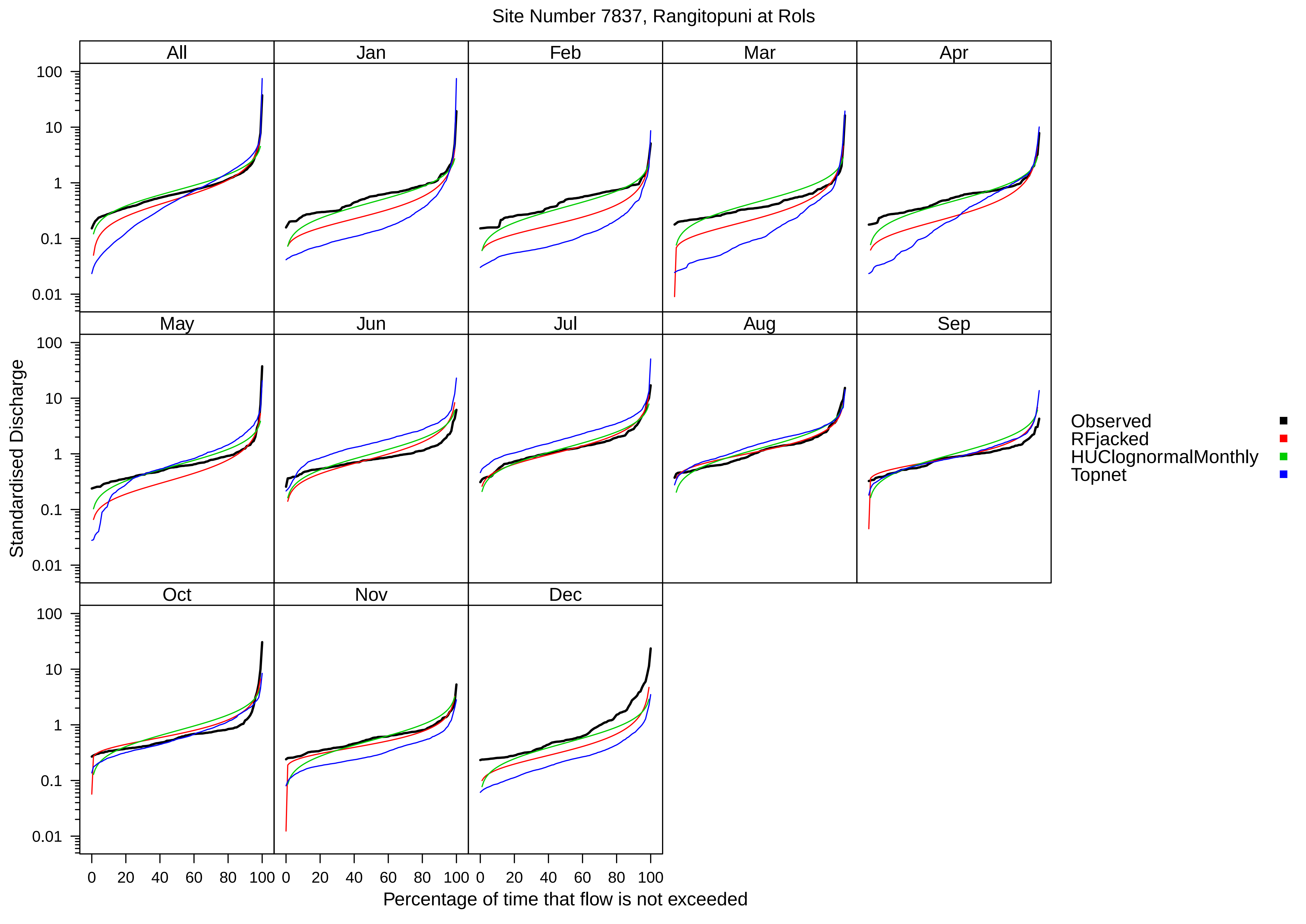


Site Number 6922, Awana at Bush Edge
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
100
10
1
0.1
0.01
Standardised Discharge
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet

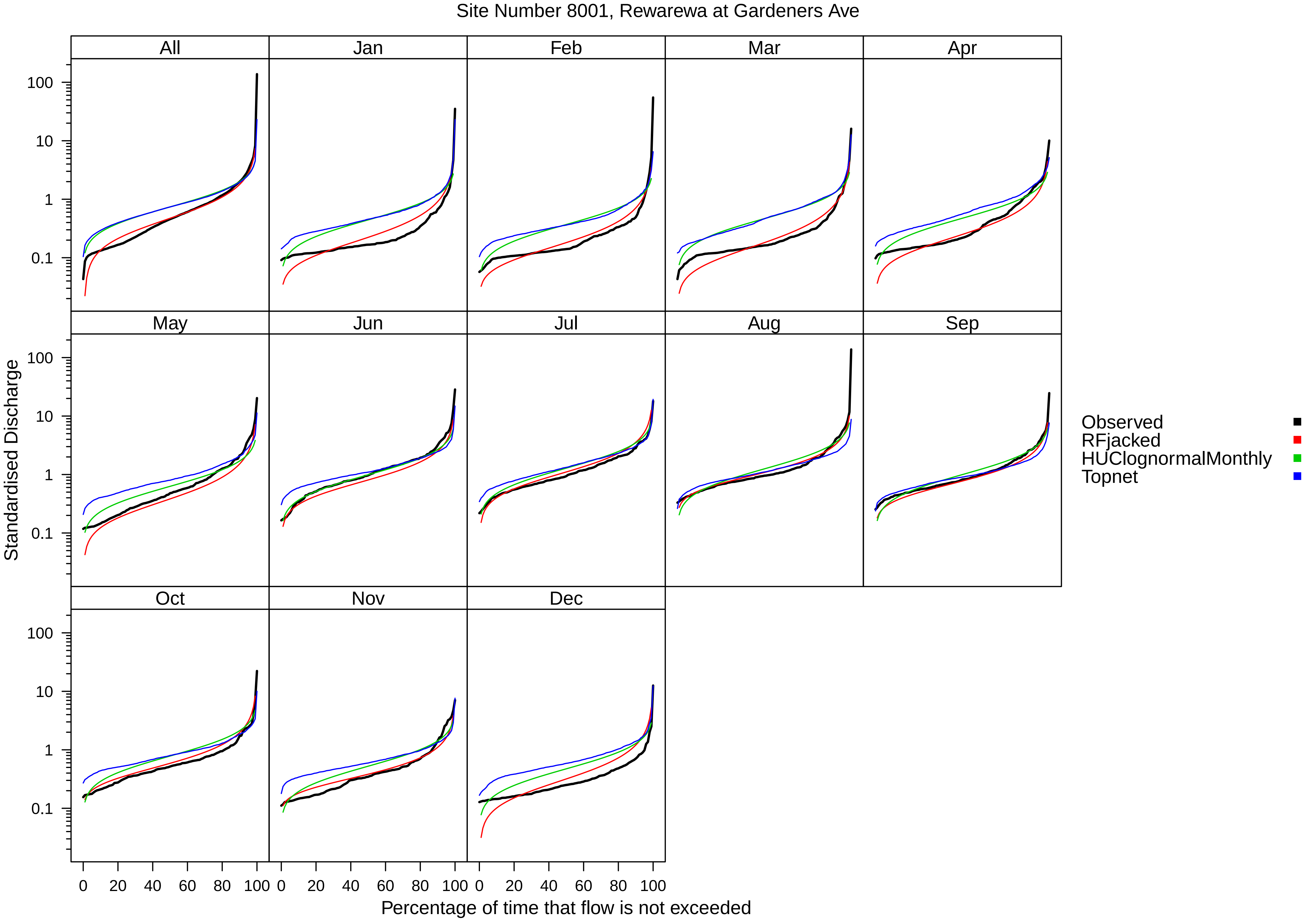

Site Number 7602, Wairau at Alma Rd
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet



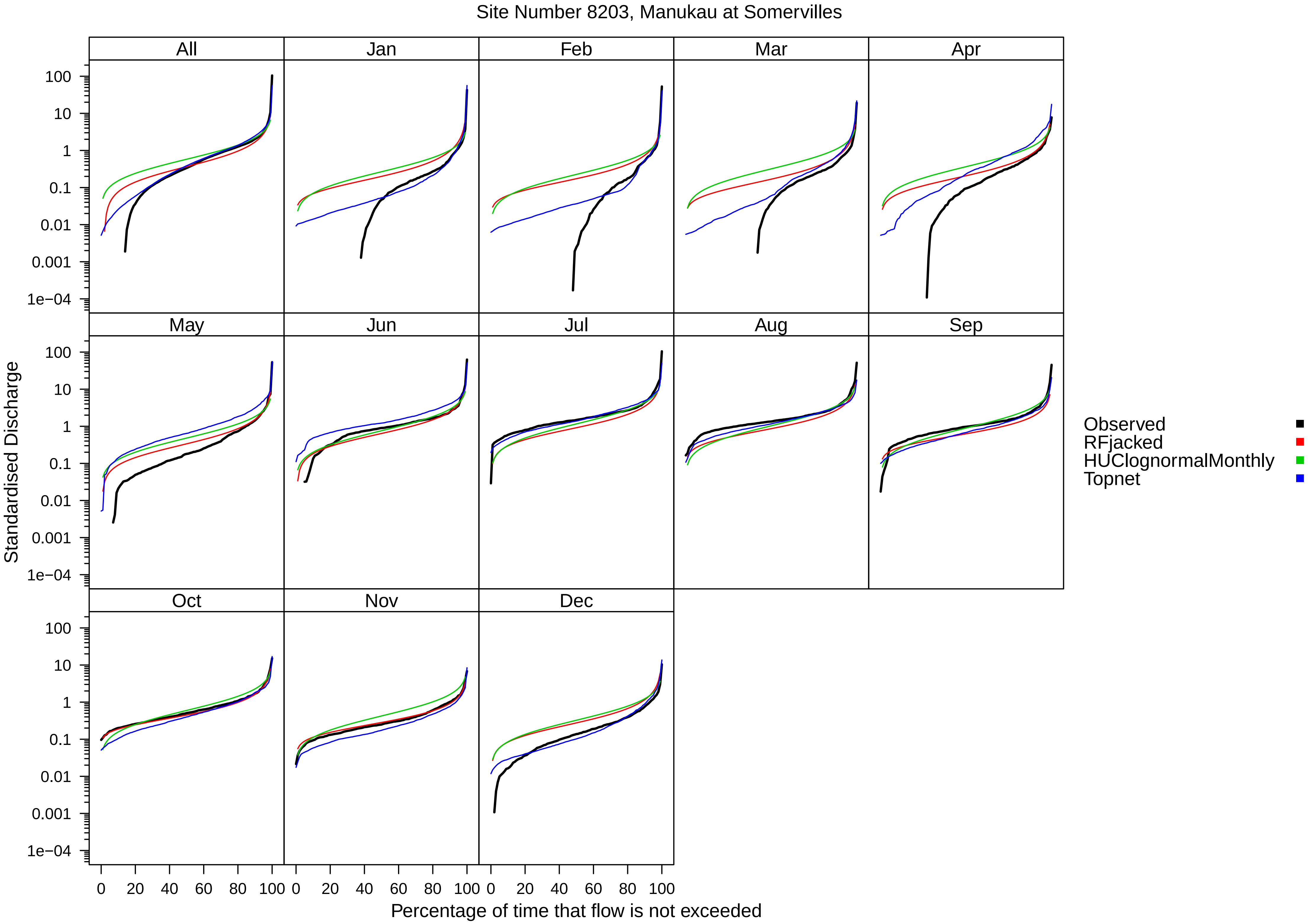
Site Number 7607, Wairau at Chartwell
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet



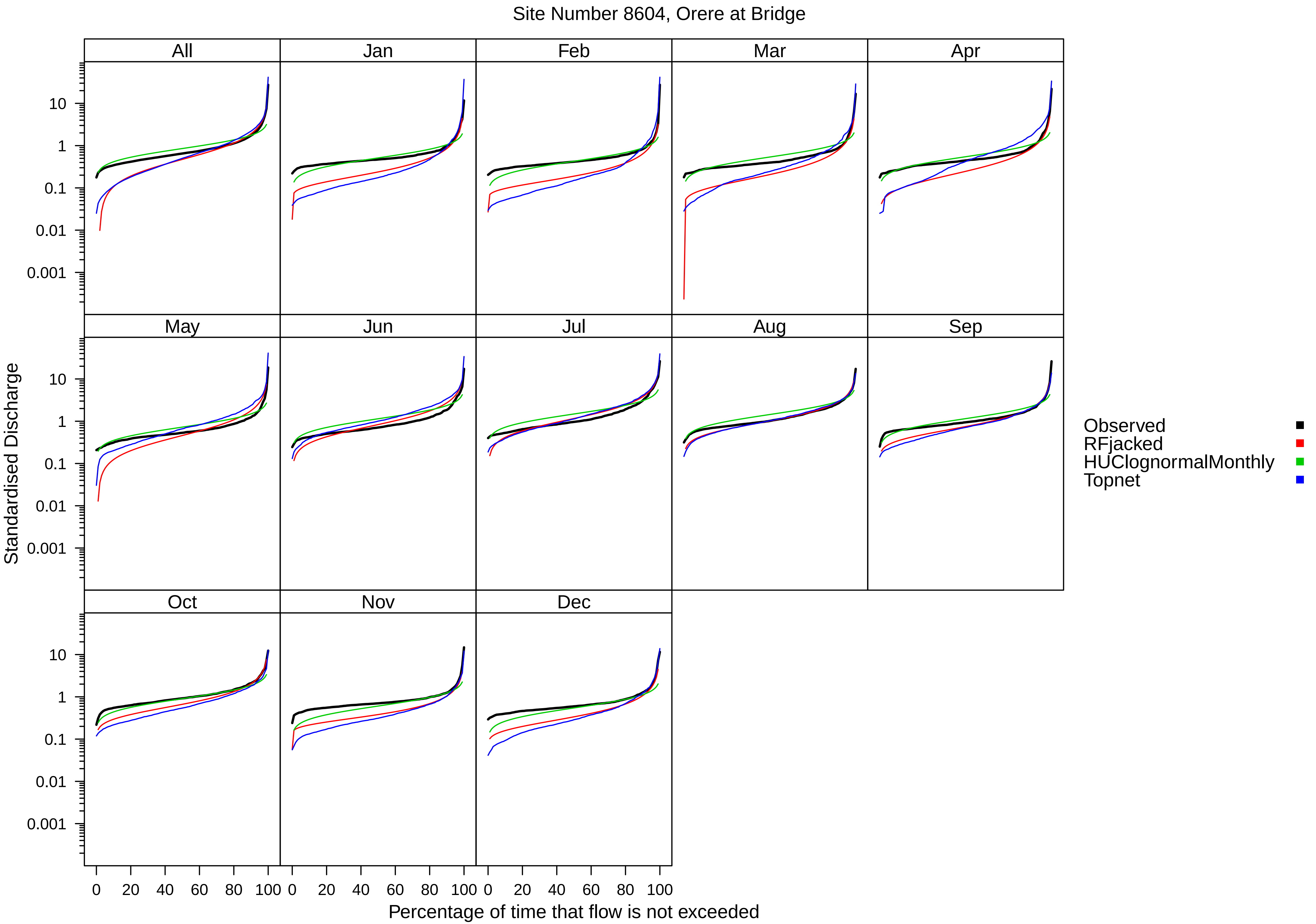
Site Number 7837, Rangitopuni at Rols
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet



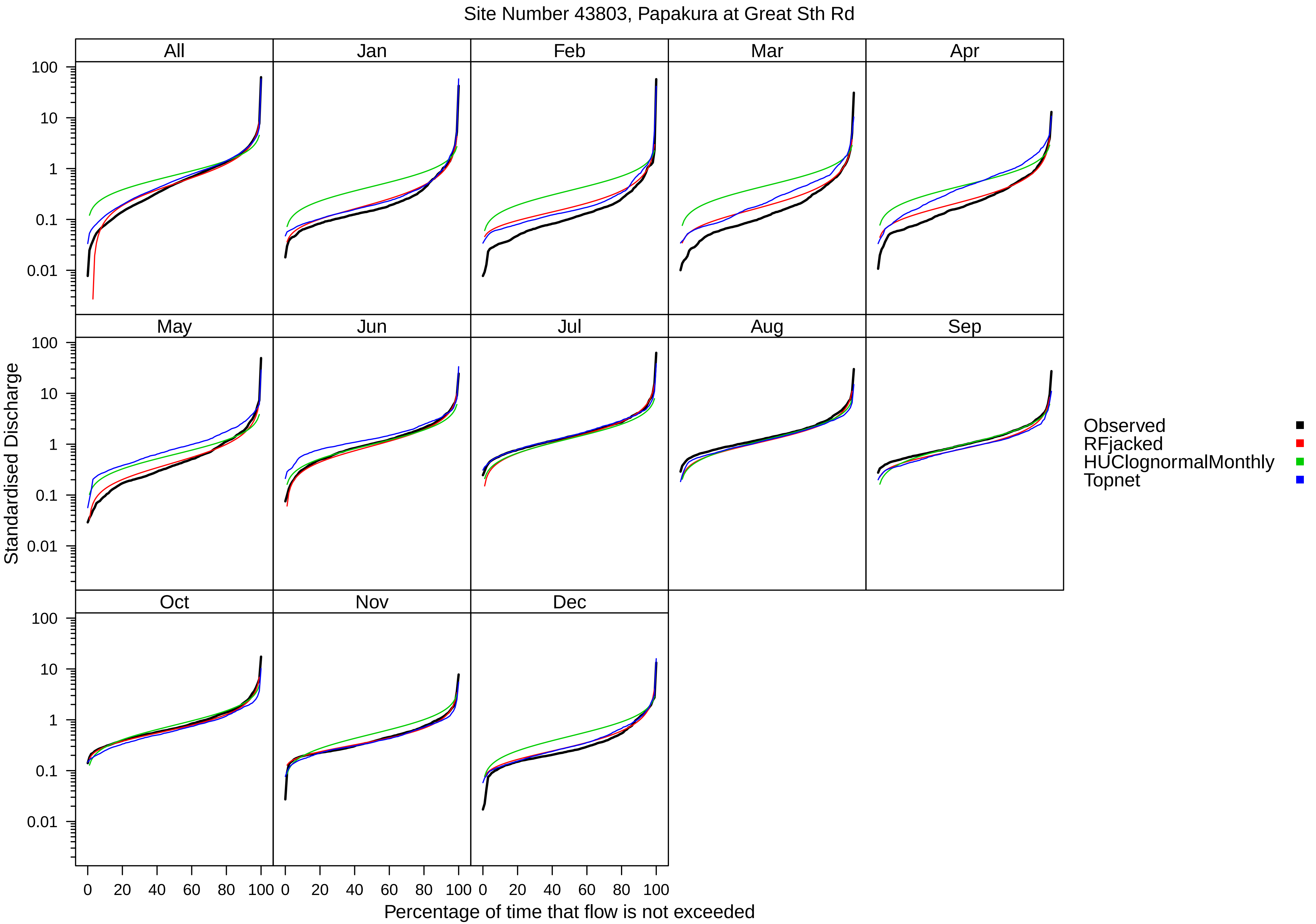
Site Number 8001, Rewarewa at Gardeners Ave
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
0.1
1
10
100
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet



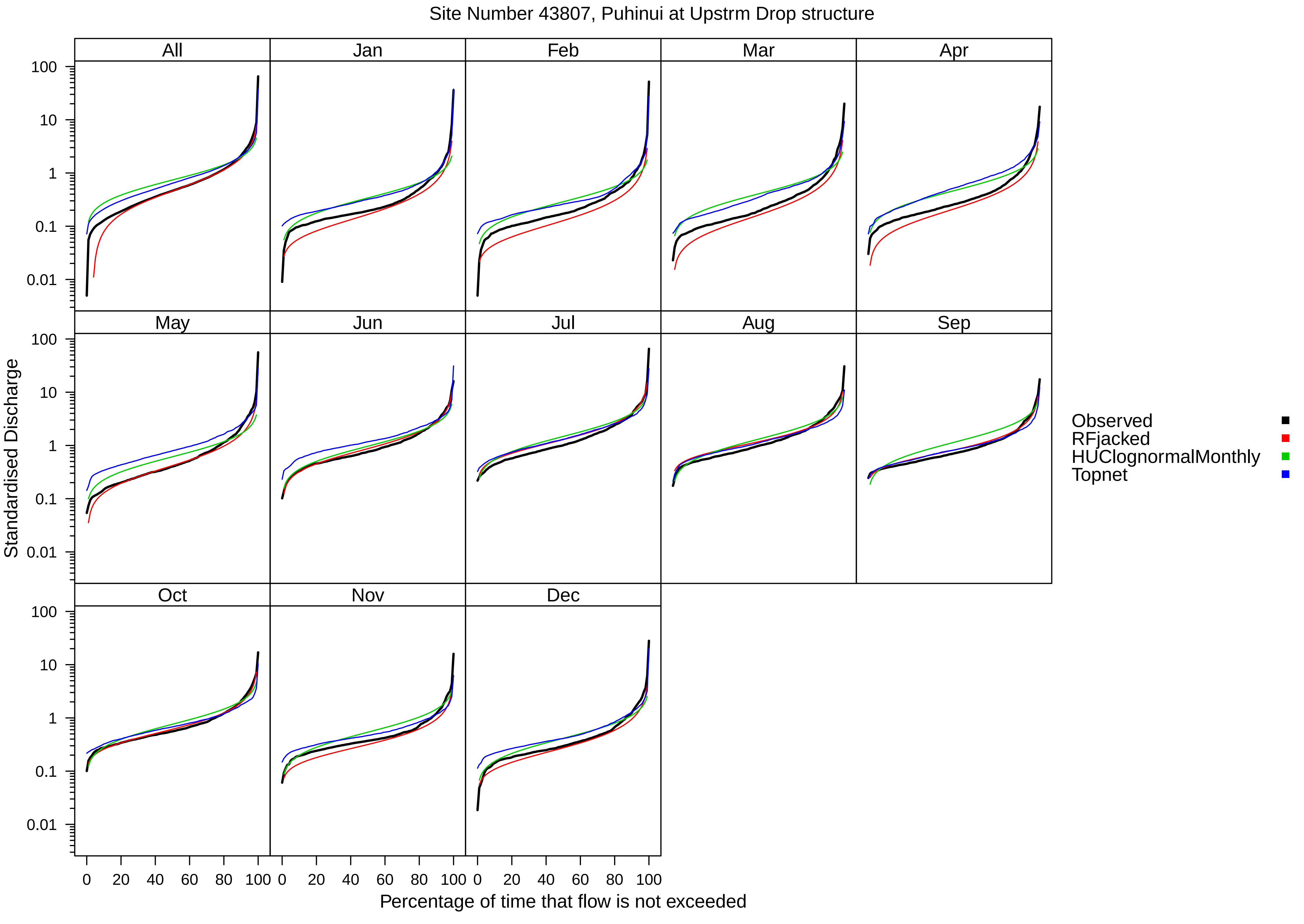
Site Number 8203, Manukau at Somervilles
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
100
10
1
0.1
0.01
0.001
1e−04
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet



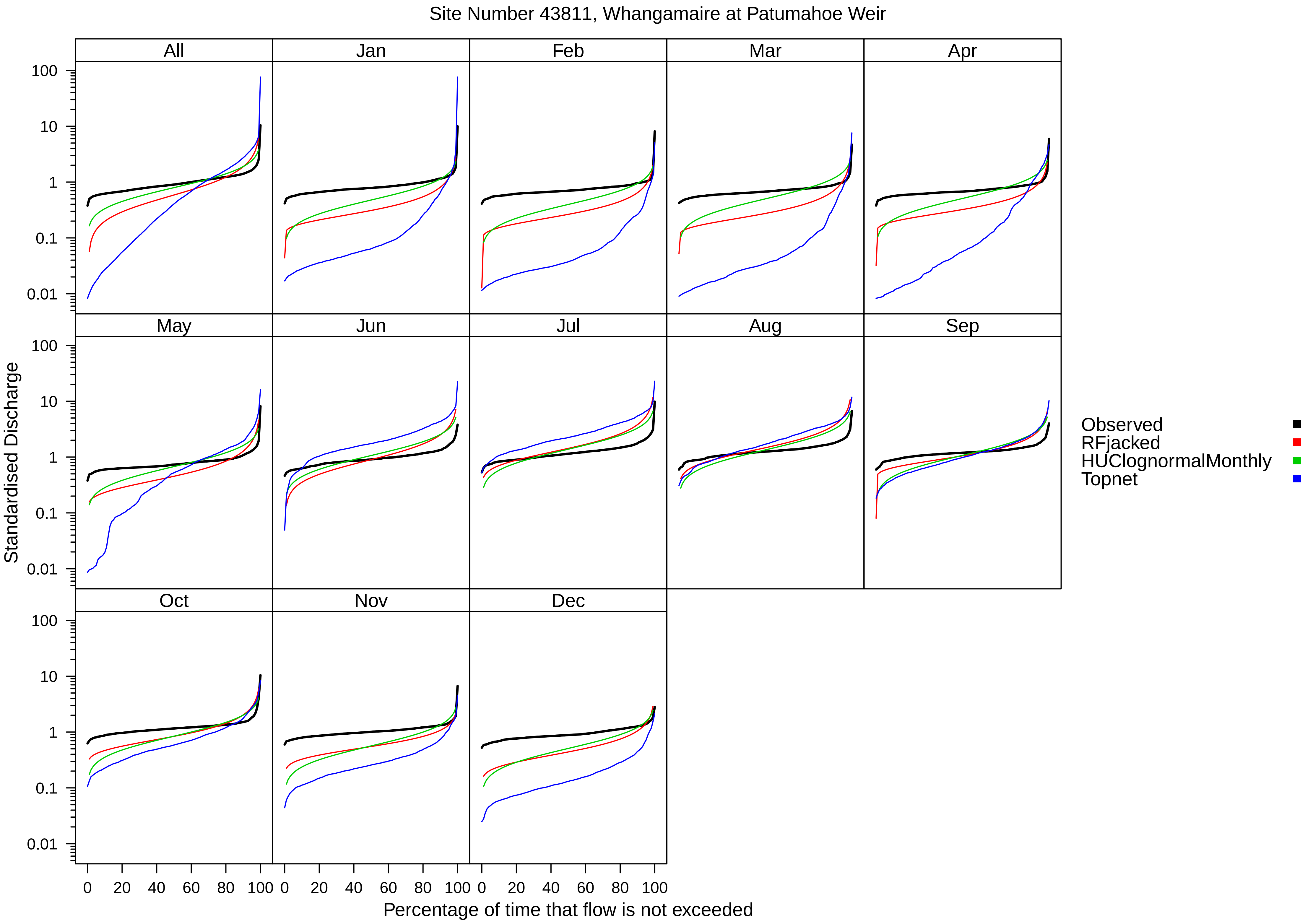
Site Number 8604, Orere at Bridge
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
10
1
0.1
0.01
0.001
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet

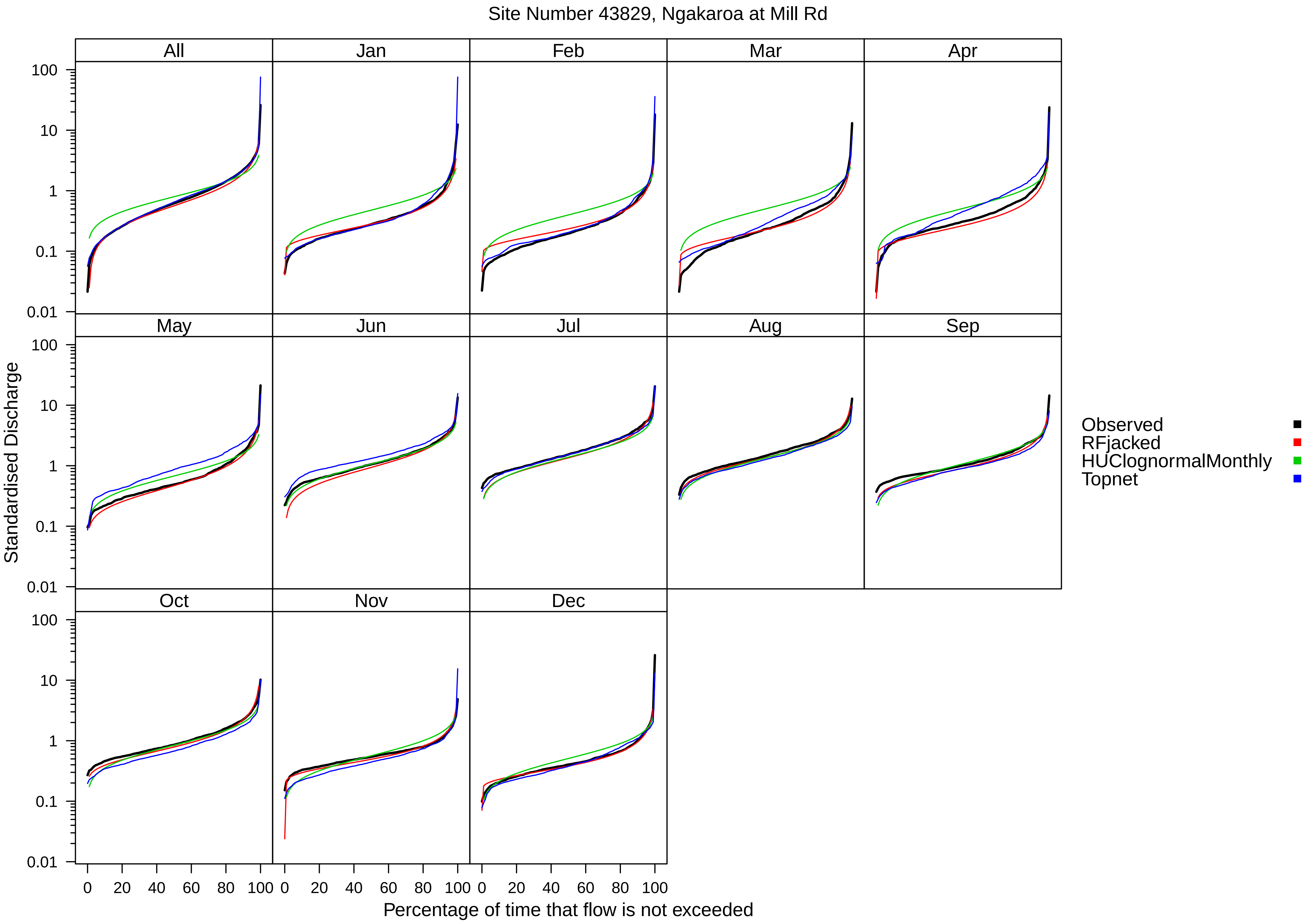


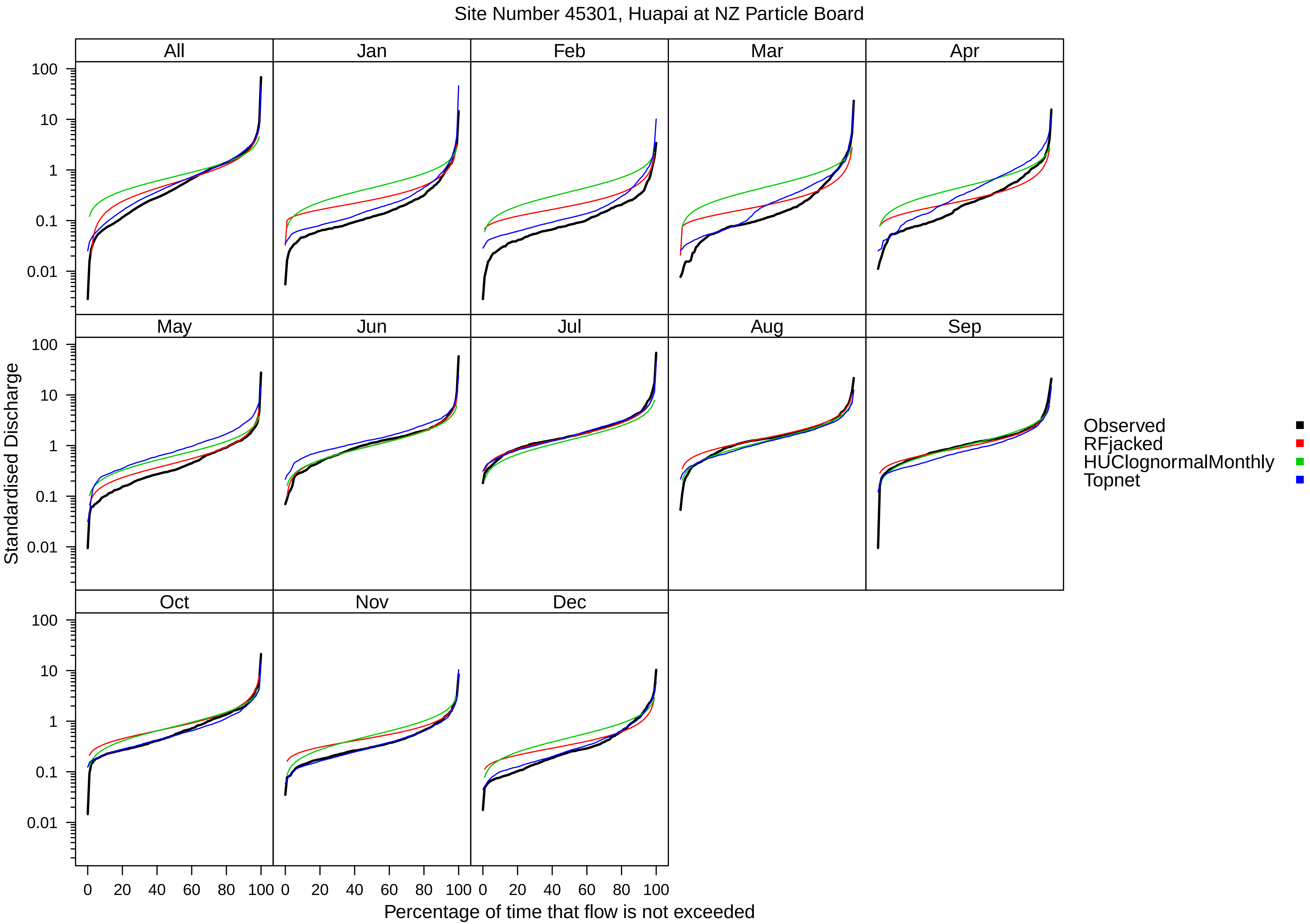
Site Number 43803, Papakura at Great Sth Rd
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet



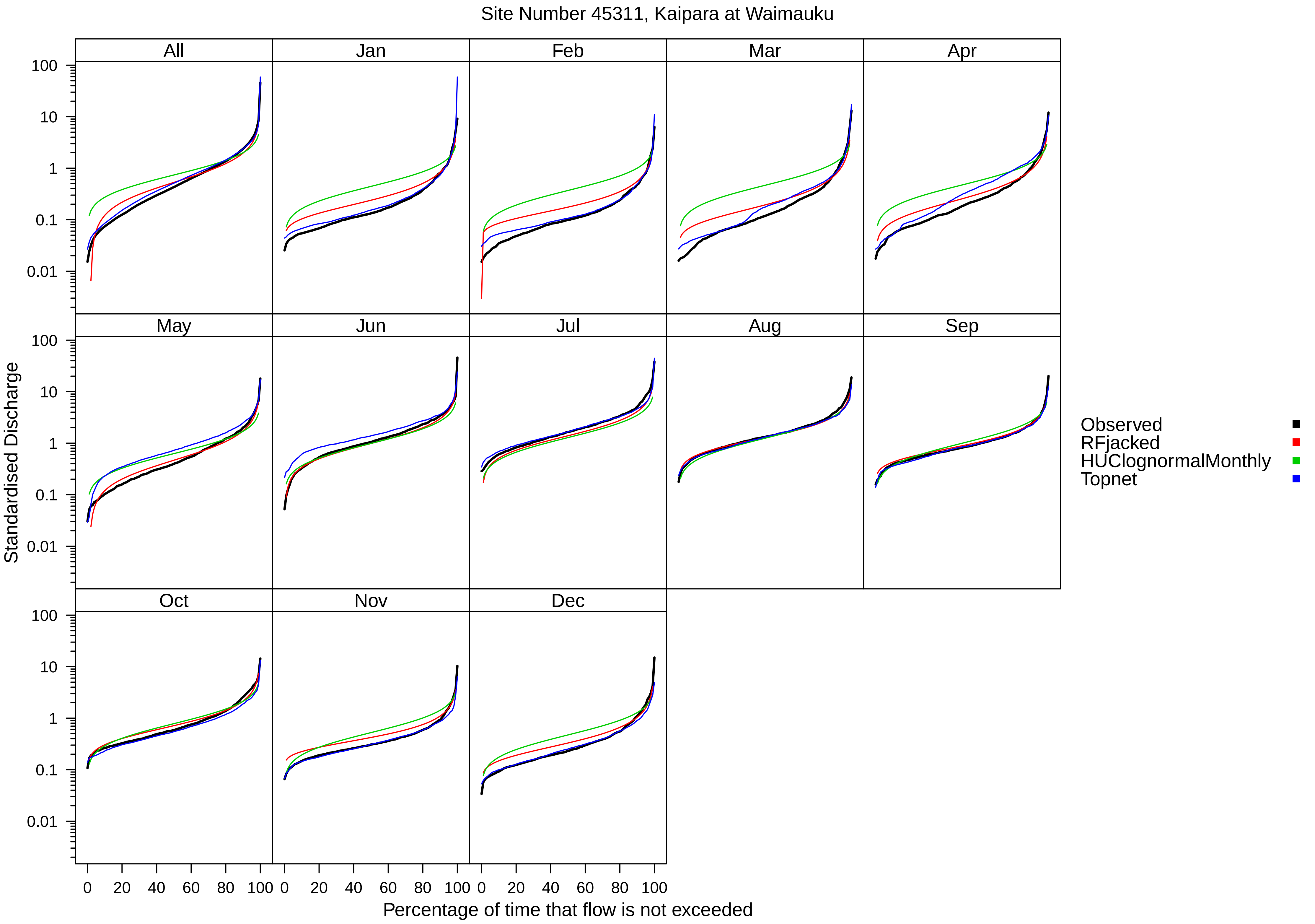
Site Number 43807, Puhinui at Upstrm Drop structure
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet

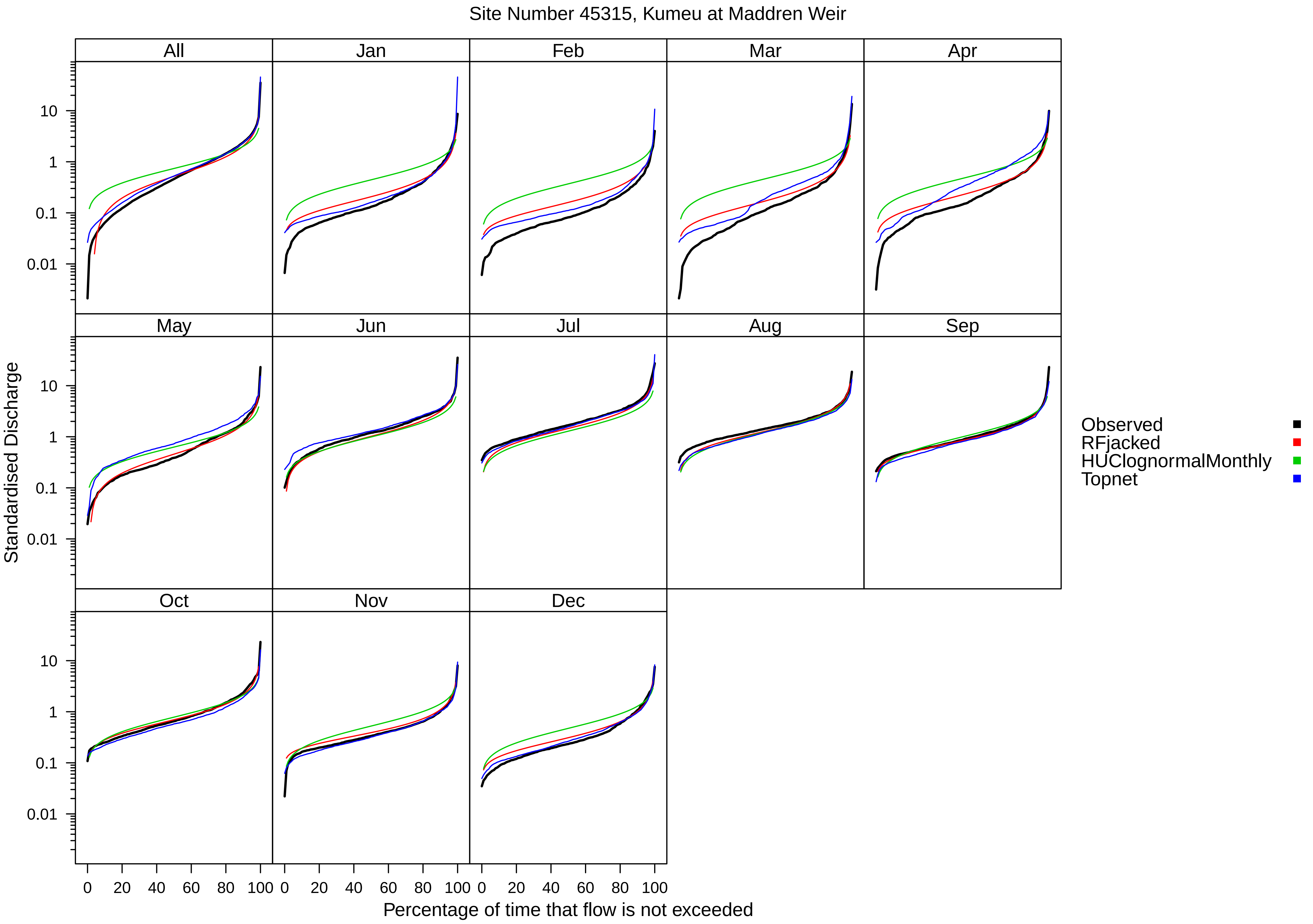

Site Number 43811, Whangamaire at Patumahoe Weir
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet


Site Number 43829, Ngakaroa at Mill Rd
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet

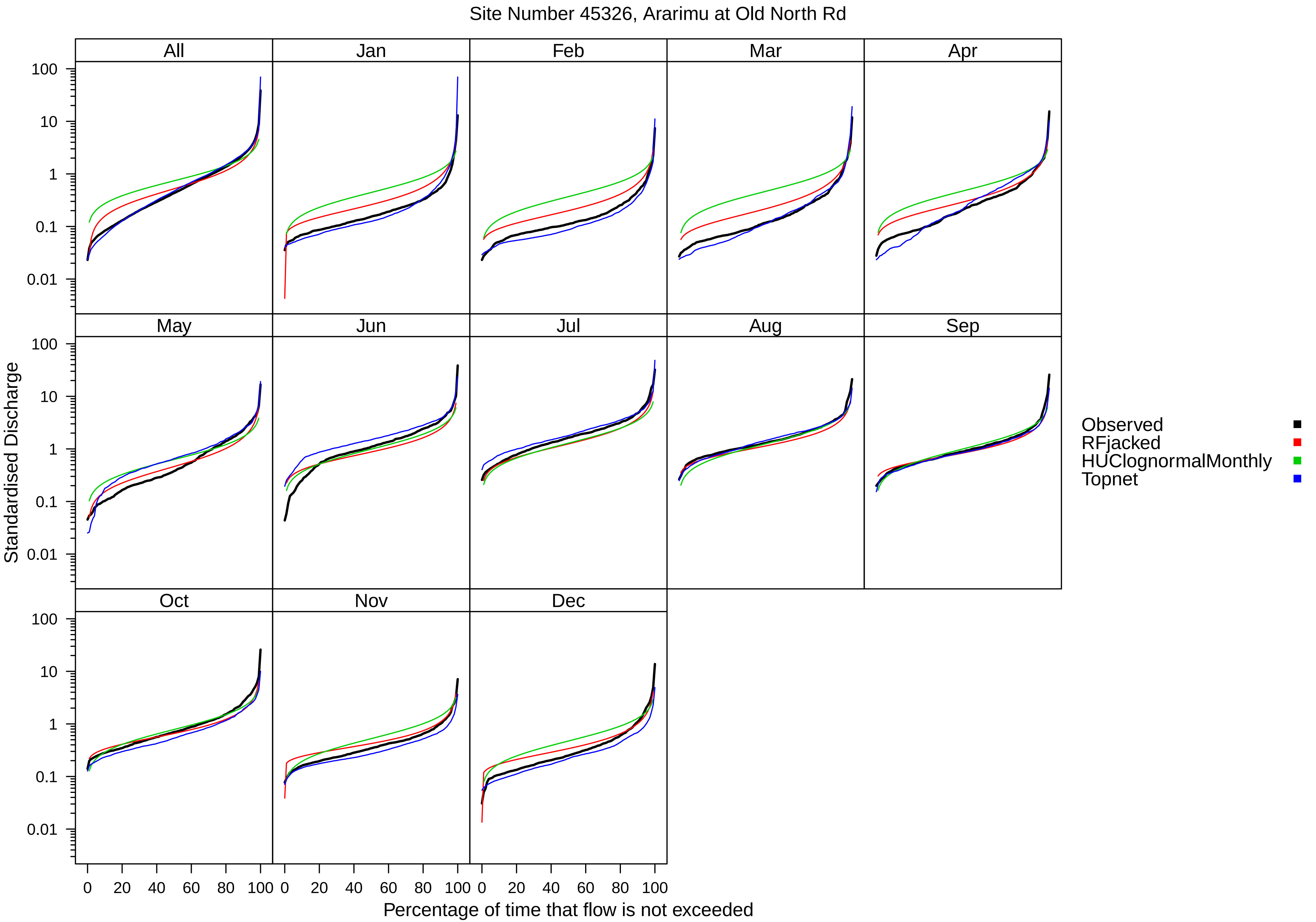


Site Number 45301, Huapai at NZ Particle Board
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet

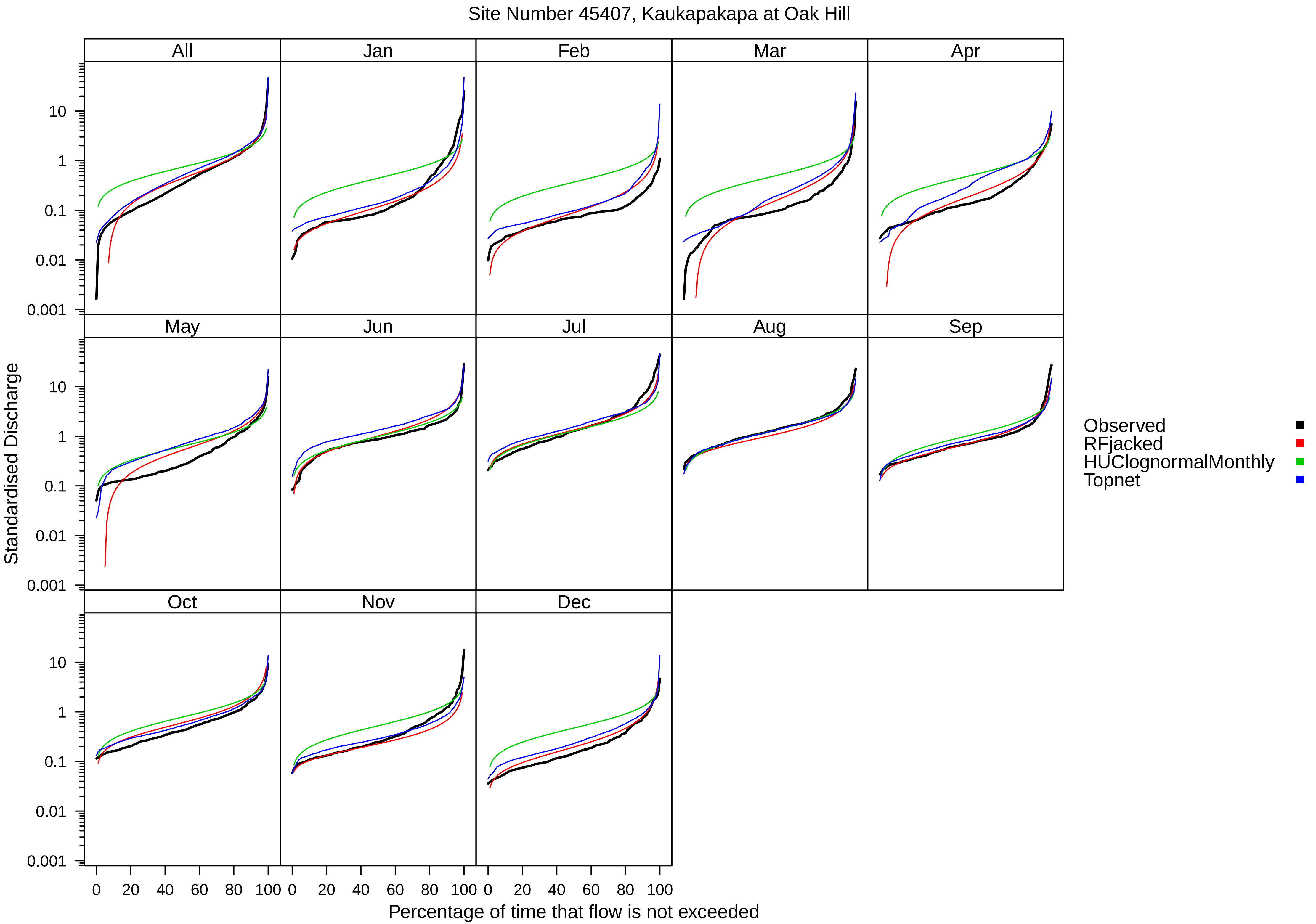

Site Number 45311, Kaipara at Waimauku
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet



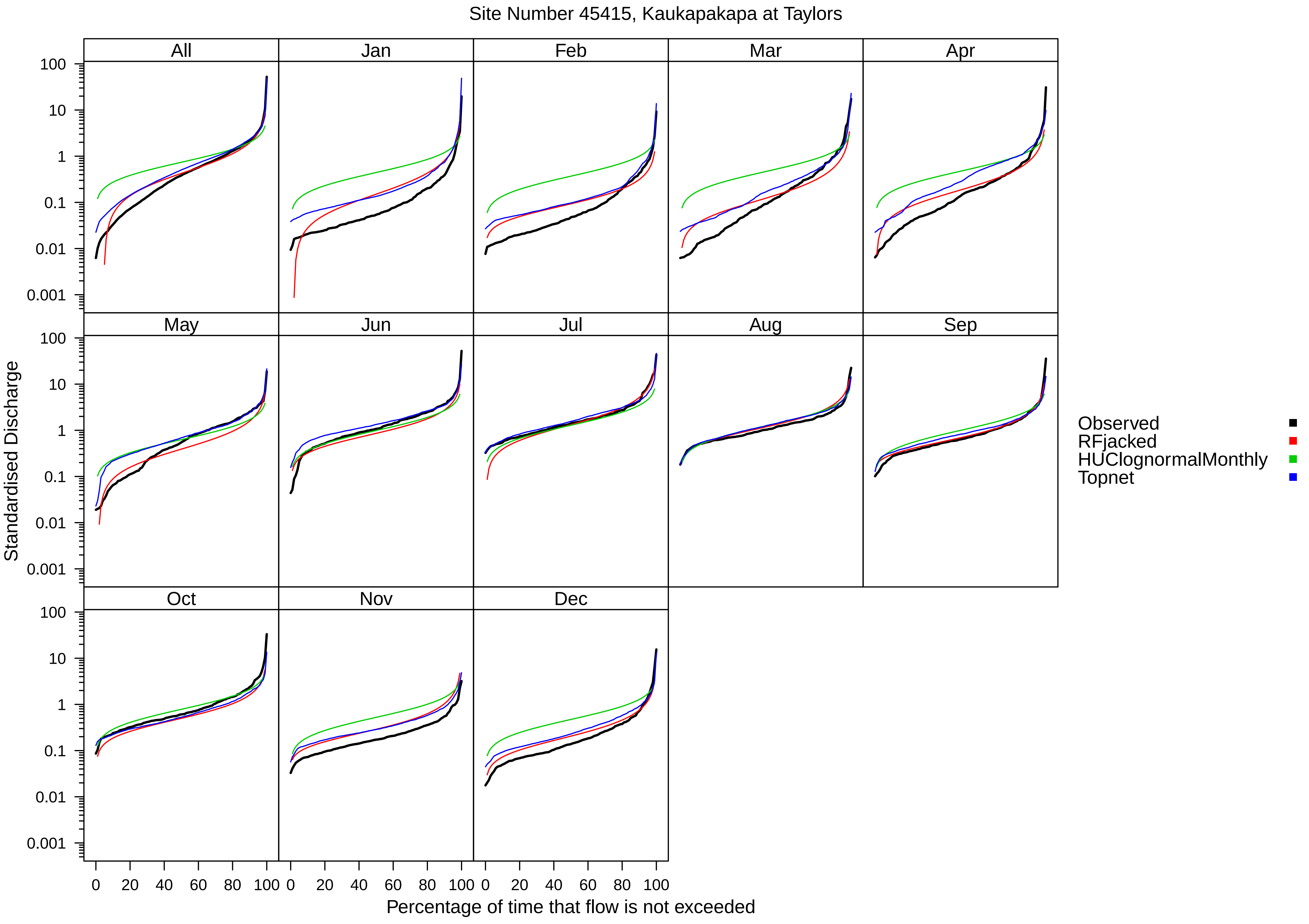
Site Number 45315, Kumeu at Maddren Weir
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet



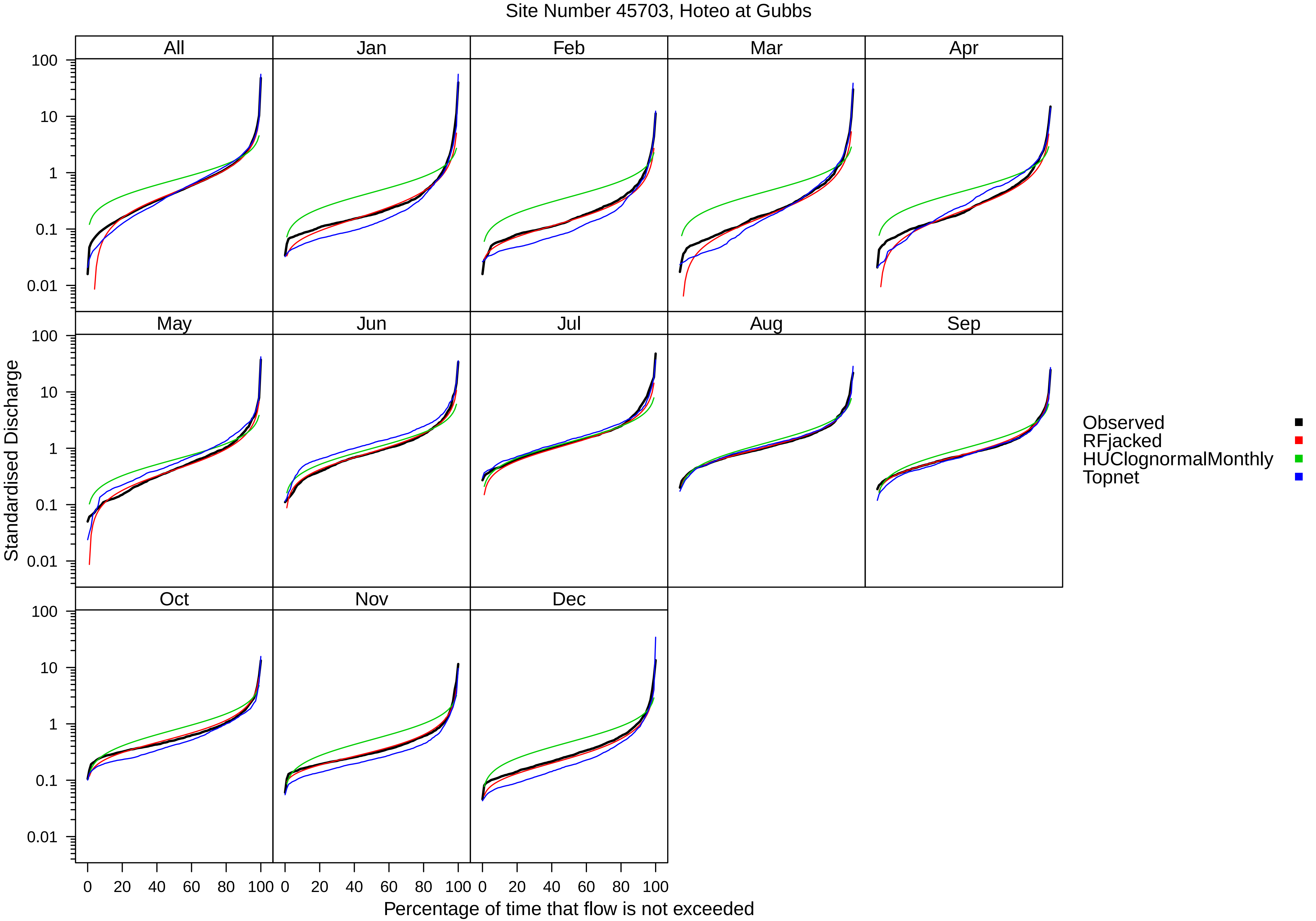
Site Number 45326, Ararimu at Old North Rd
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
100
10
1
0.1
0.01
Standardised Discharge
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet



Site Number 45407, Kaukapakapa at Oak Hill
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
0.001
0.01
0.1
1
10
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet



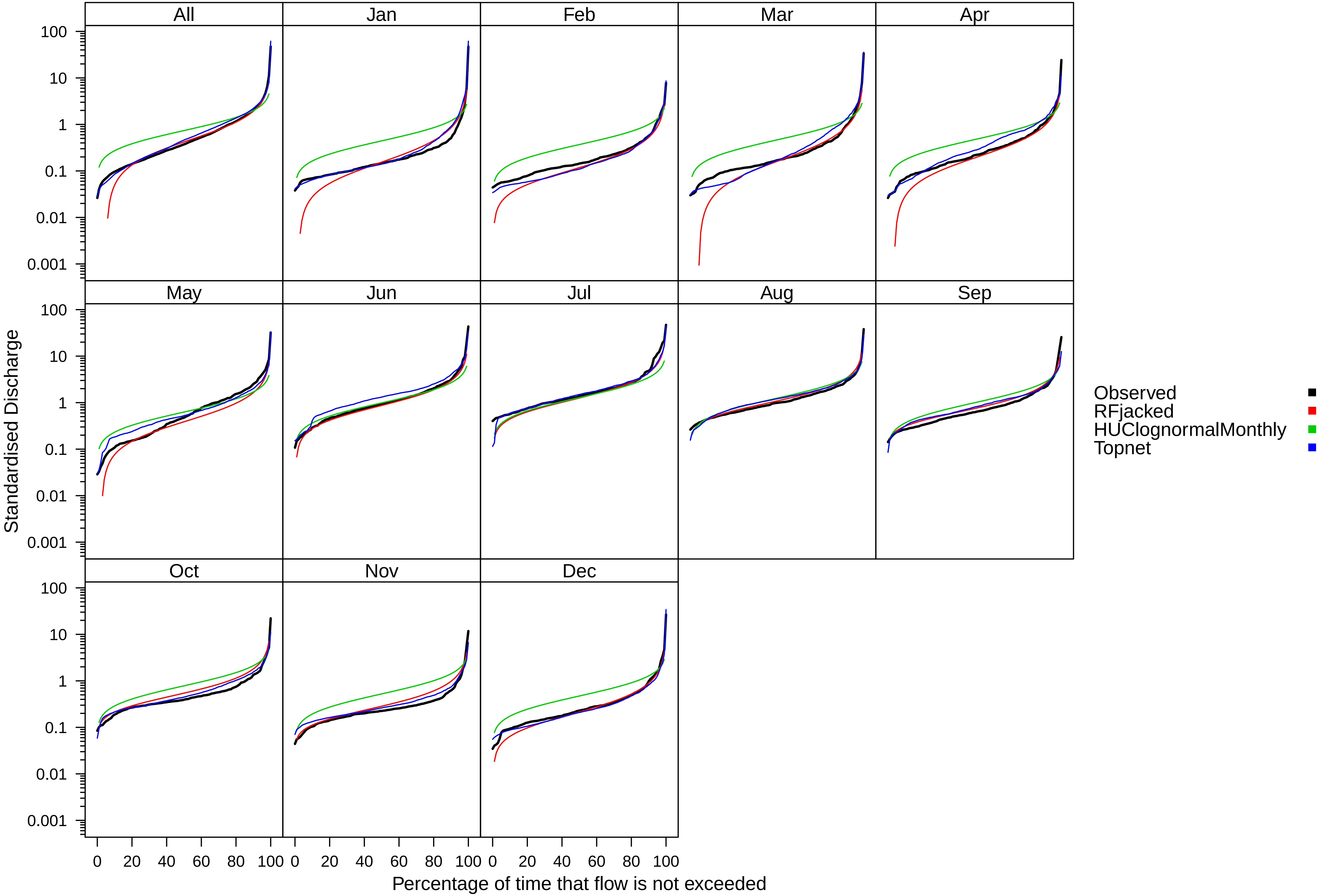
Site Number 45415, Kaukapakapa at Taylors
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
100
10
1
0.1
0.01
0.001
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet

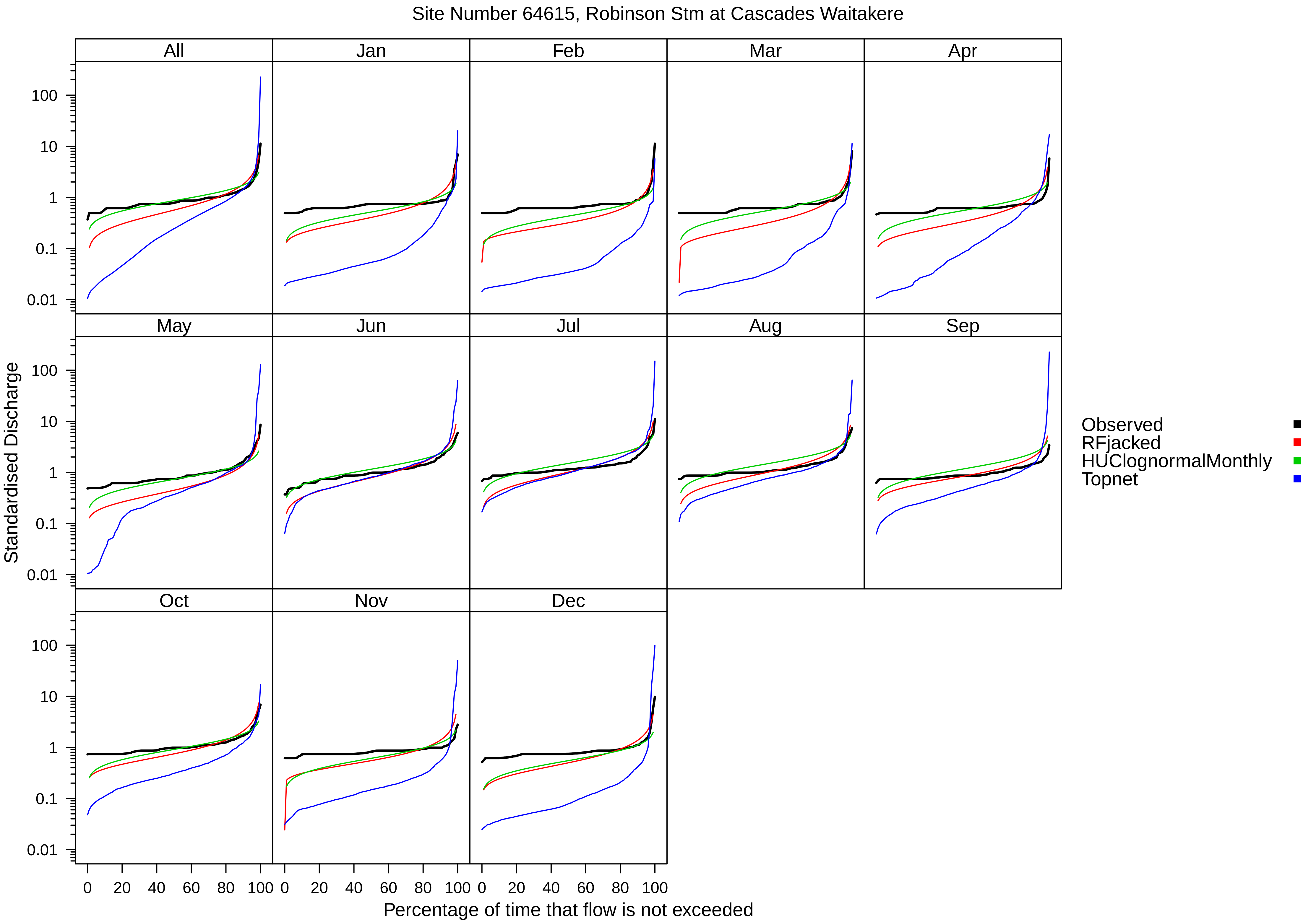


Site Number 45703, Hoteo at Gubbs
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
100
10
1
0.1
0.01
0
20
40
60
80
100
Standardised Discharge
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet

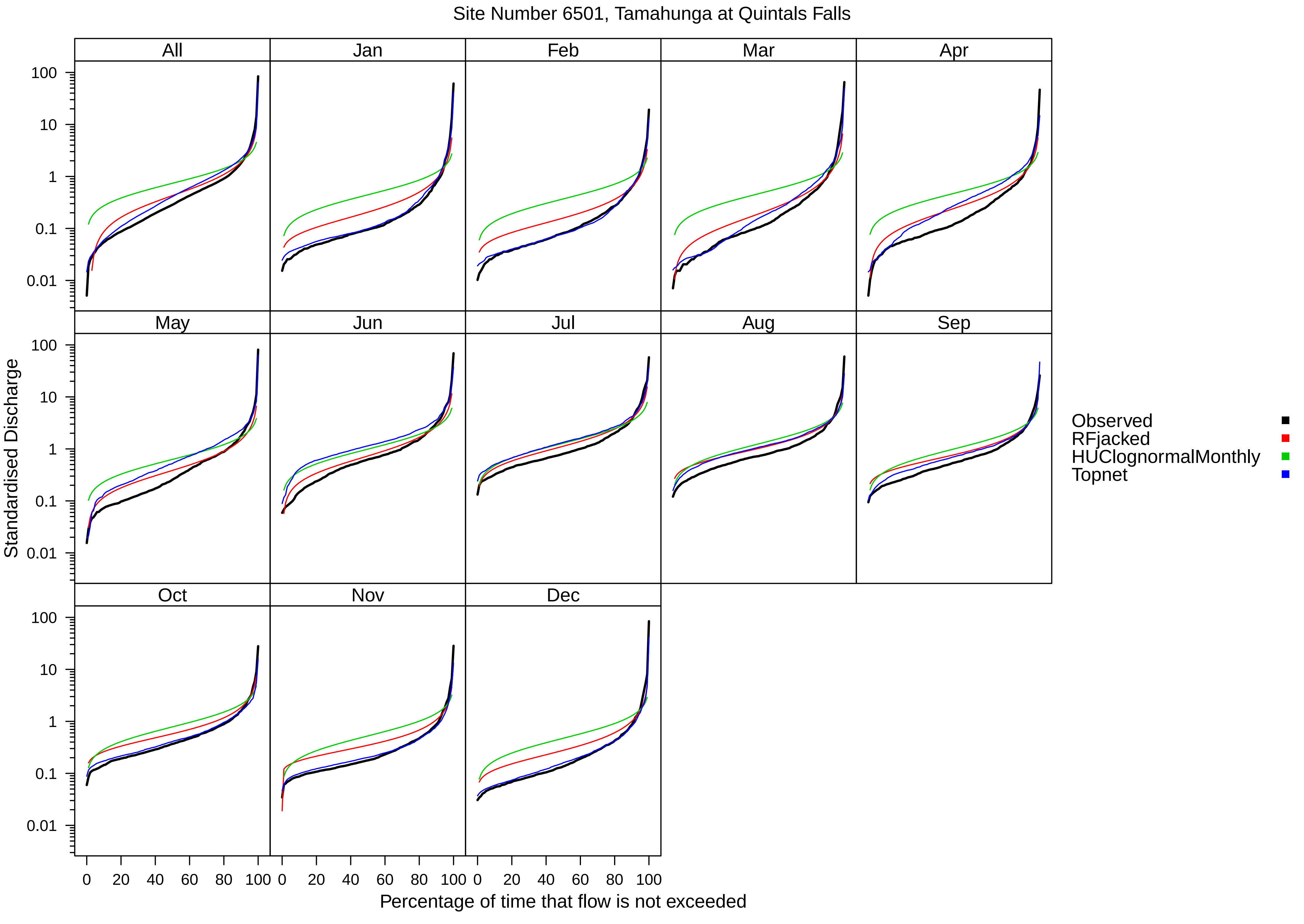
Site Number 45705, Waiteitei at Sandersons/Tomar.

Site Number 45705, Waiteitei at Tomarata Valley Rd

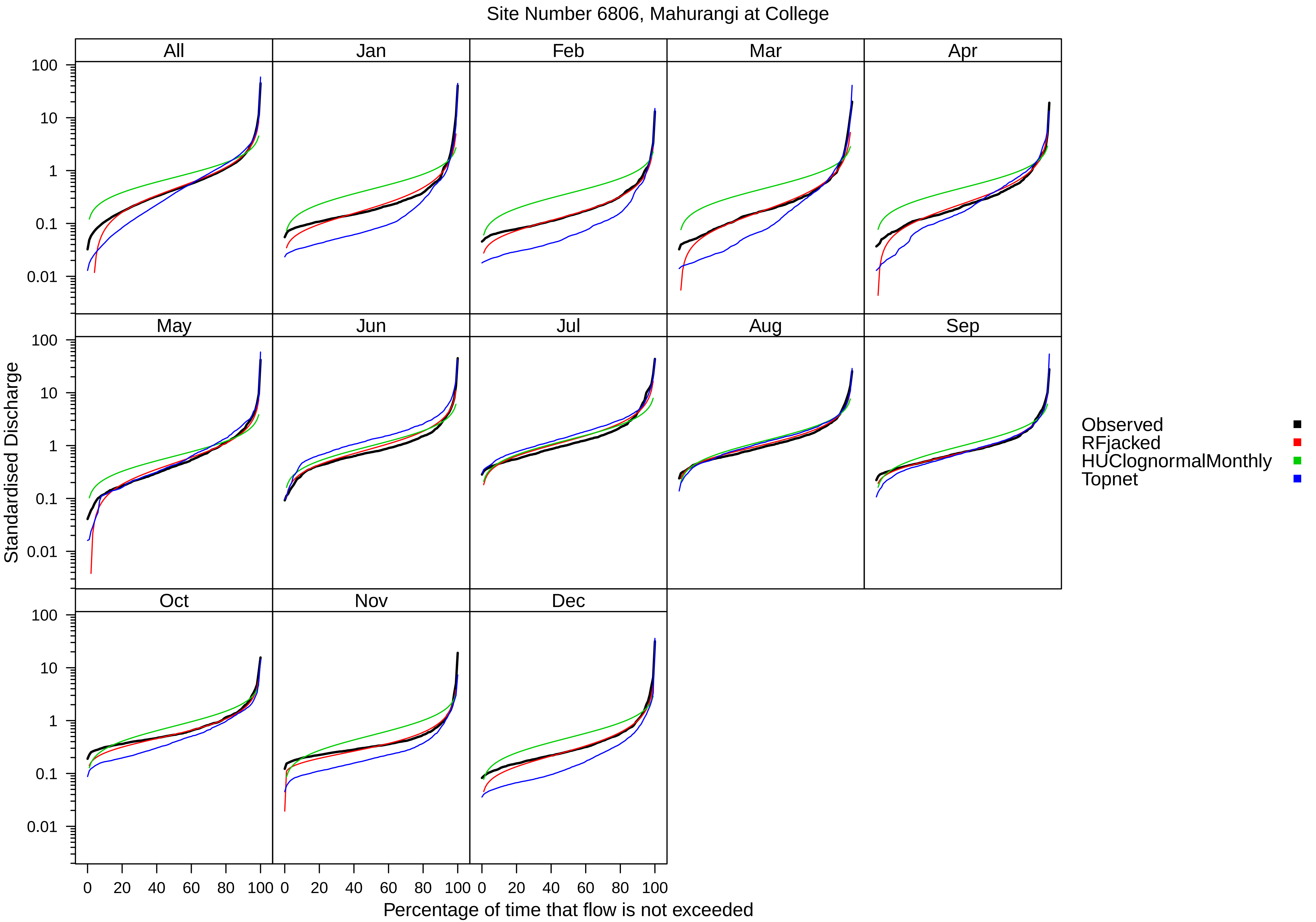


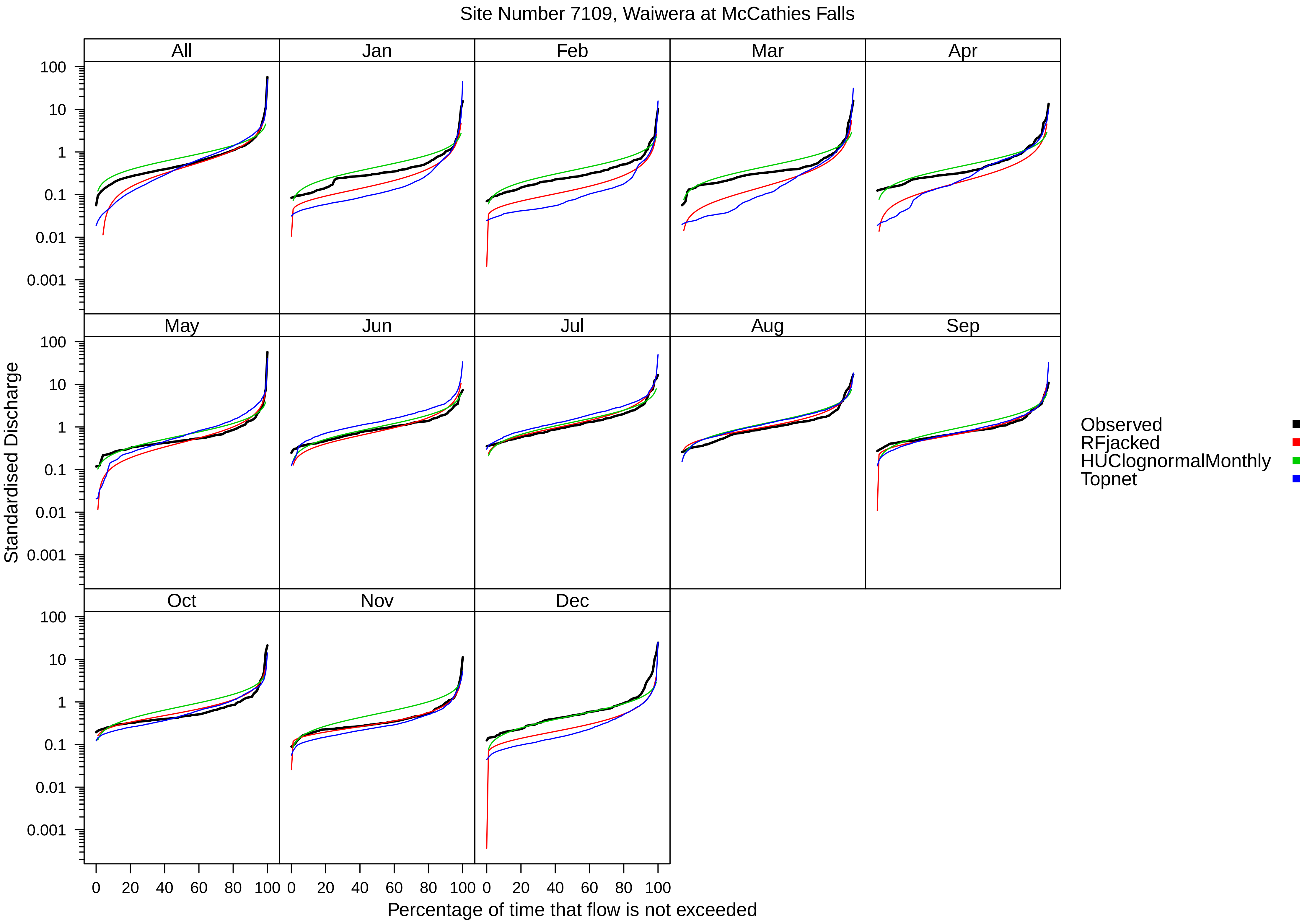


Site Number 64615, Robinson Stm at Cascades Waitakere
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
0.01
0.1
1
10
100
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet

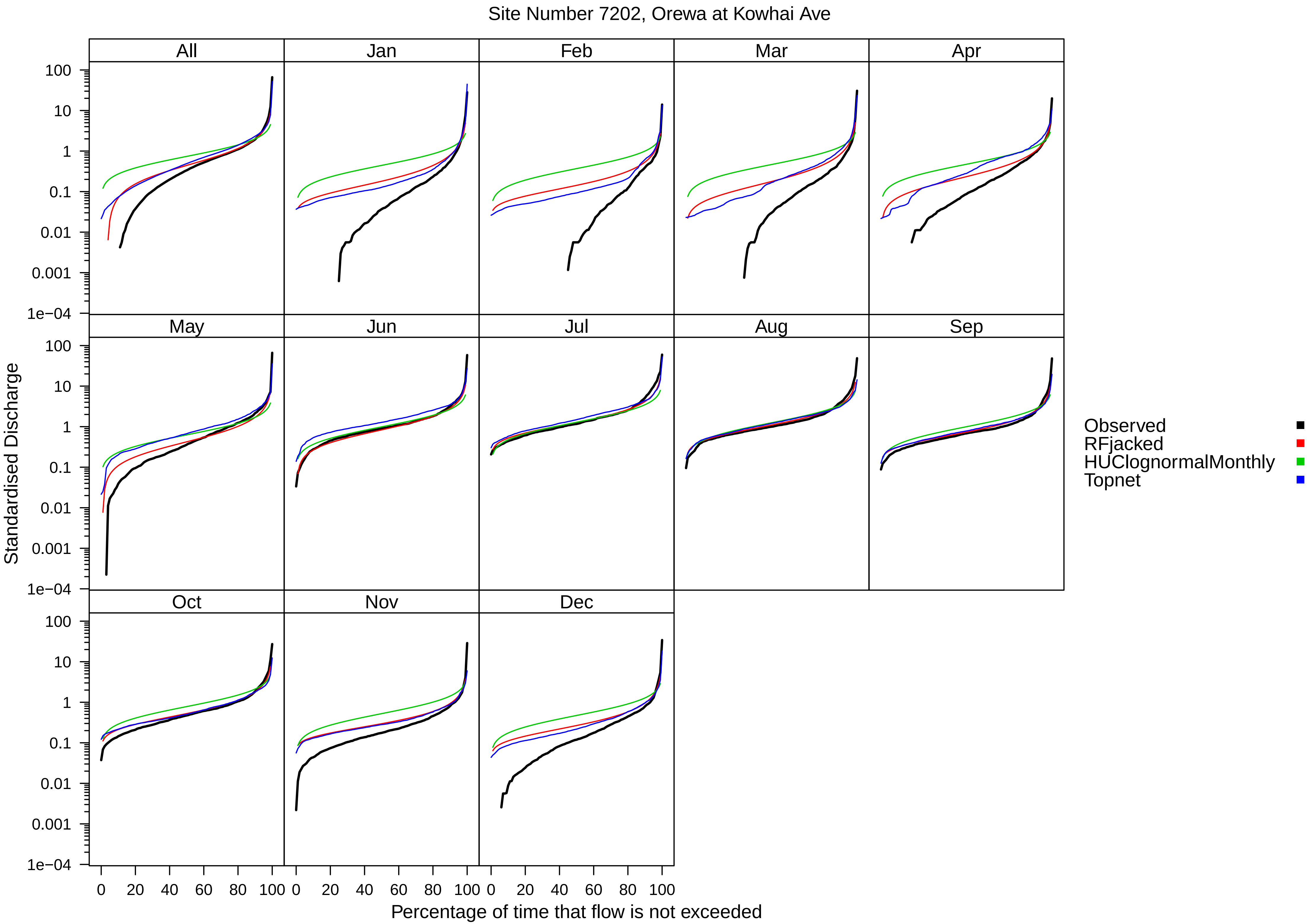


Site Number 6501, Tamahunga at Quintals Falls
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet

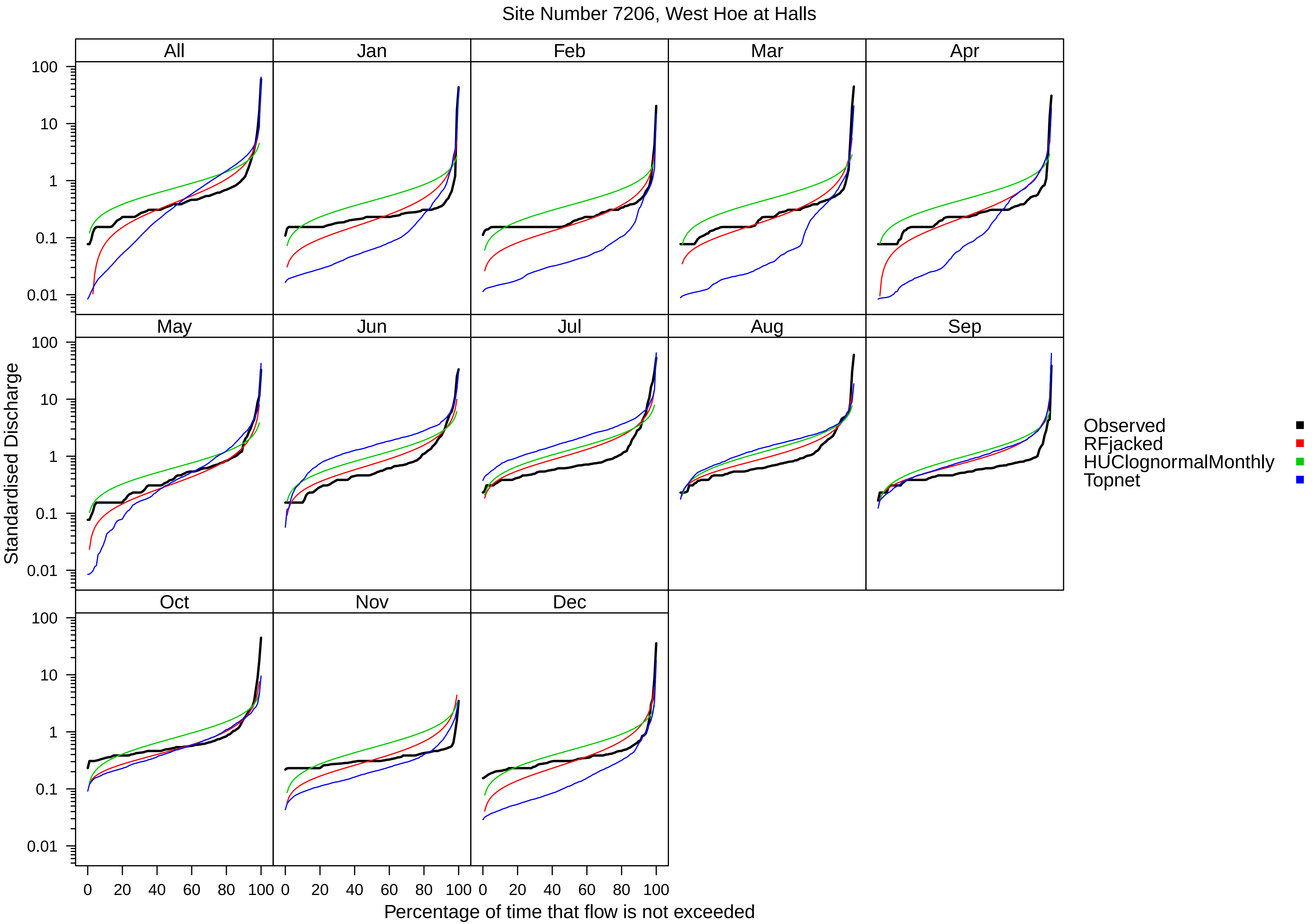

Site Number 6806, Mahurangi at College
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
100
10
1
0.1
0.01
0
20
40
60
80
100
Standardised Discharge
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet



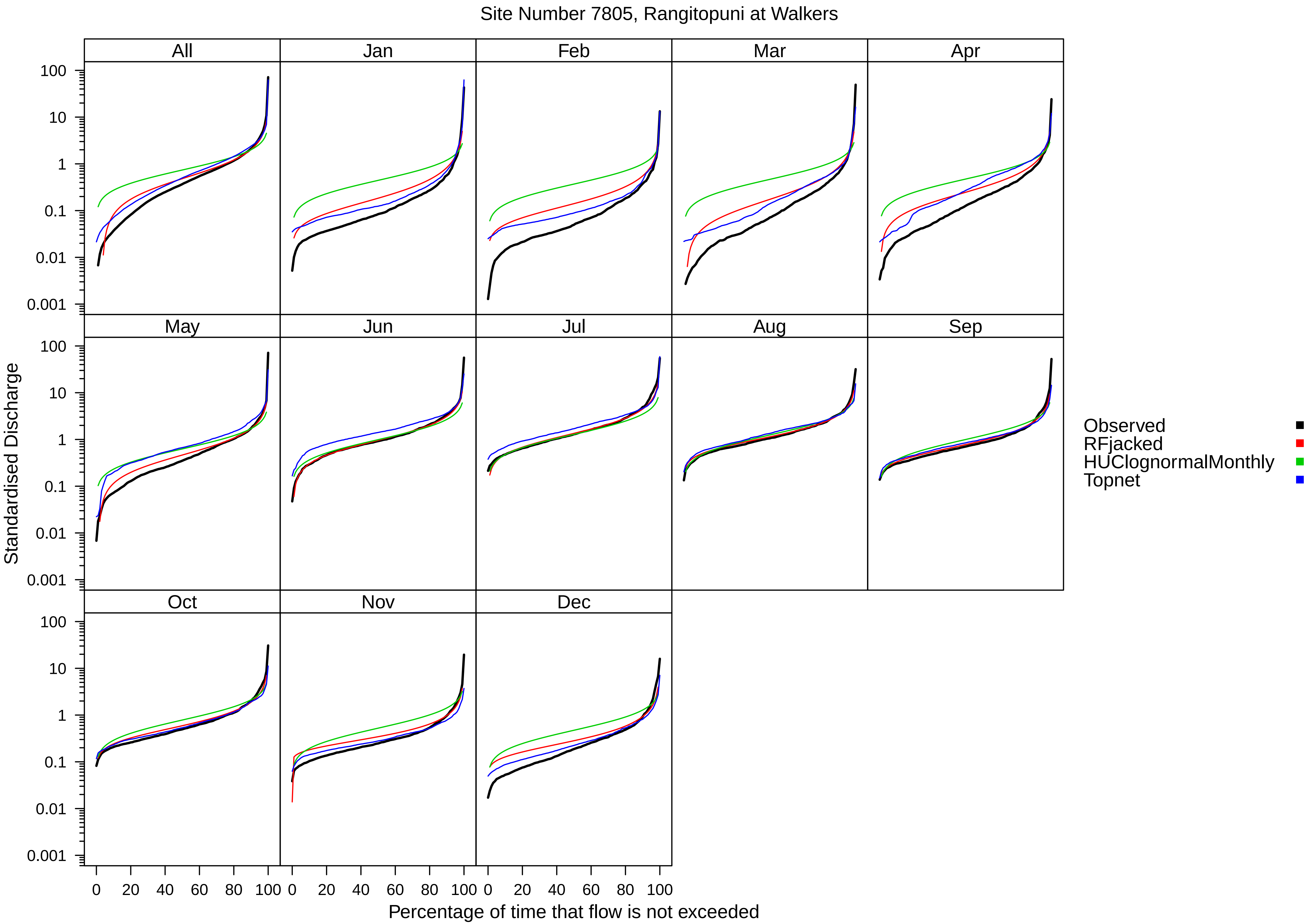
Site Number 7109, Waiwera at McCathies Falls
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
100
10
1
0.1
0.01
0.001
Standardised Discharge
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet



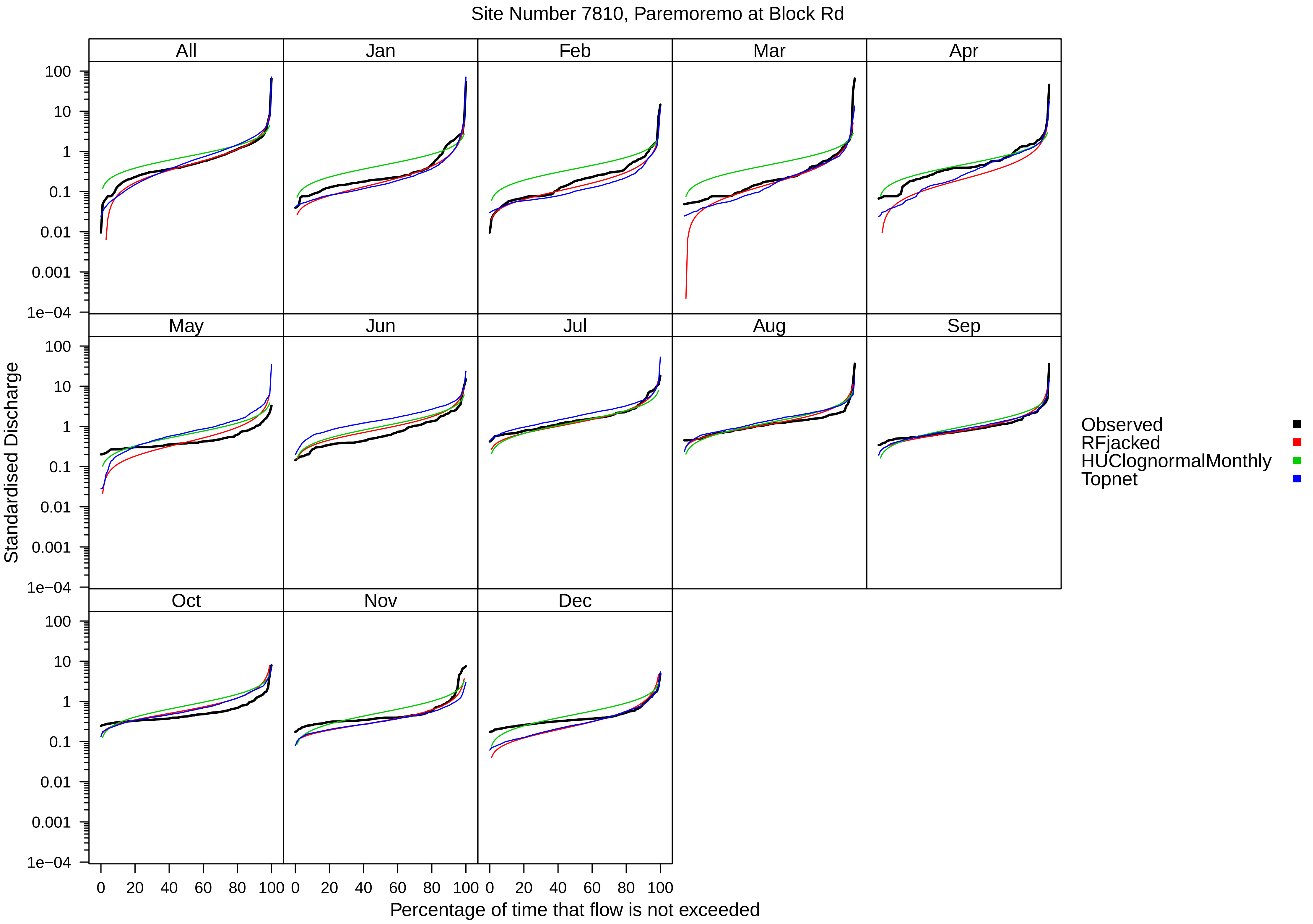
Site Number 7202, Orewa at Kowhai Ave
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
100
10
1
0.1
0.01
0.001
1e−04
Standardised Discharge
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet



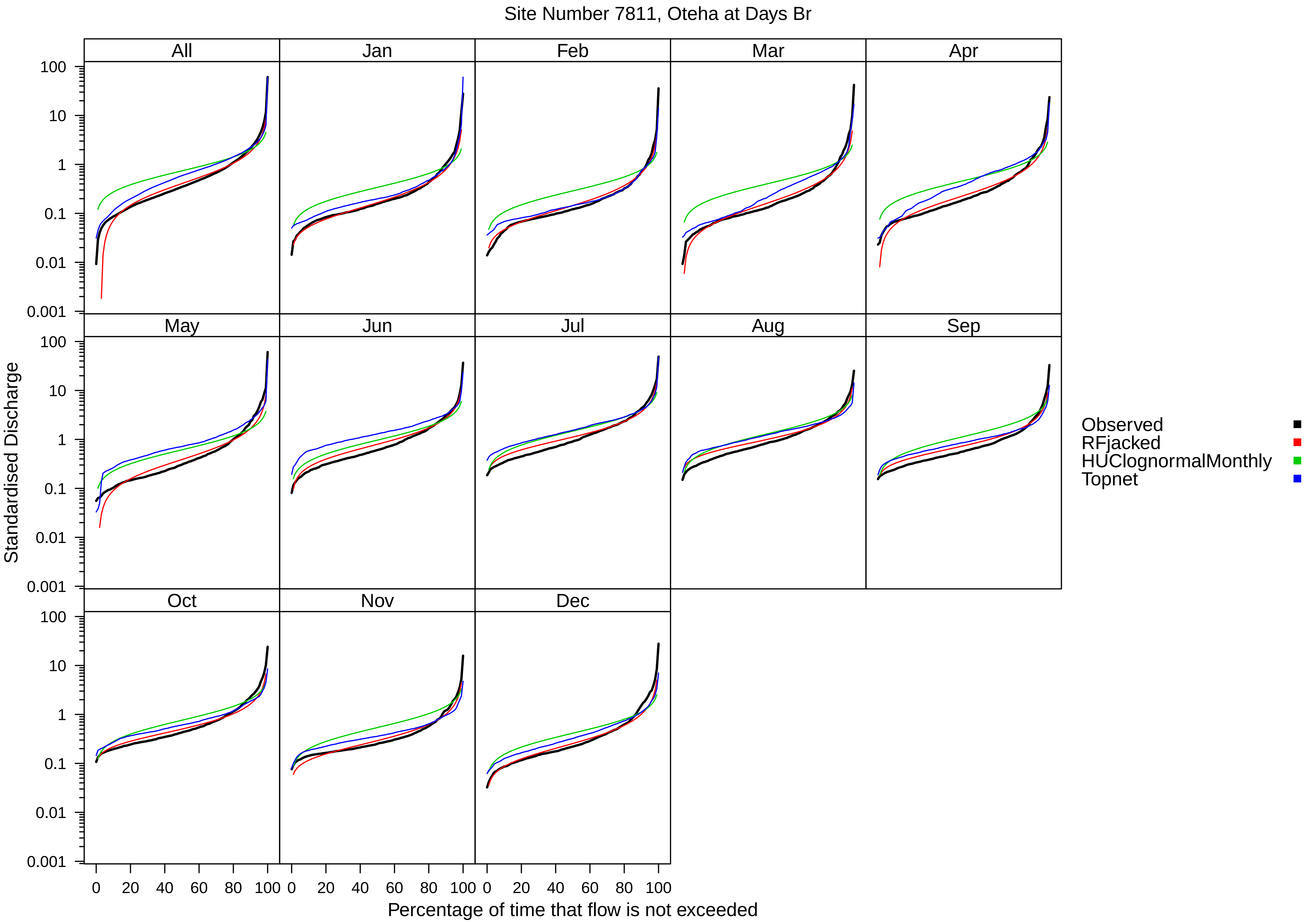
Site Number 7206, West Hoe at Halls
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
100
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet

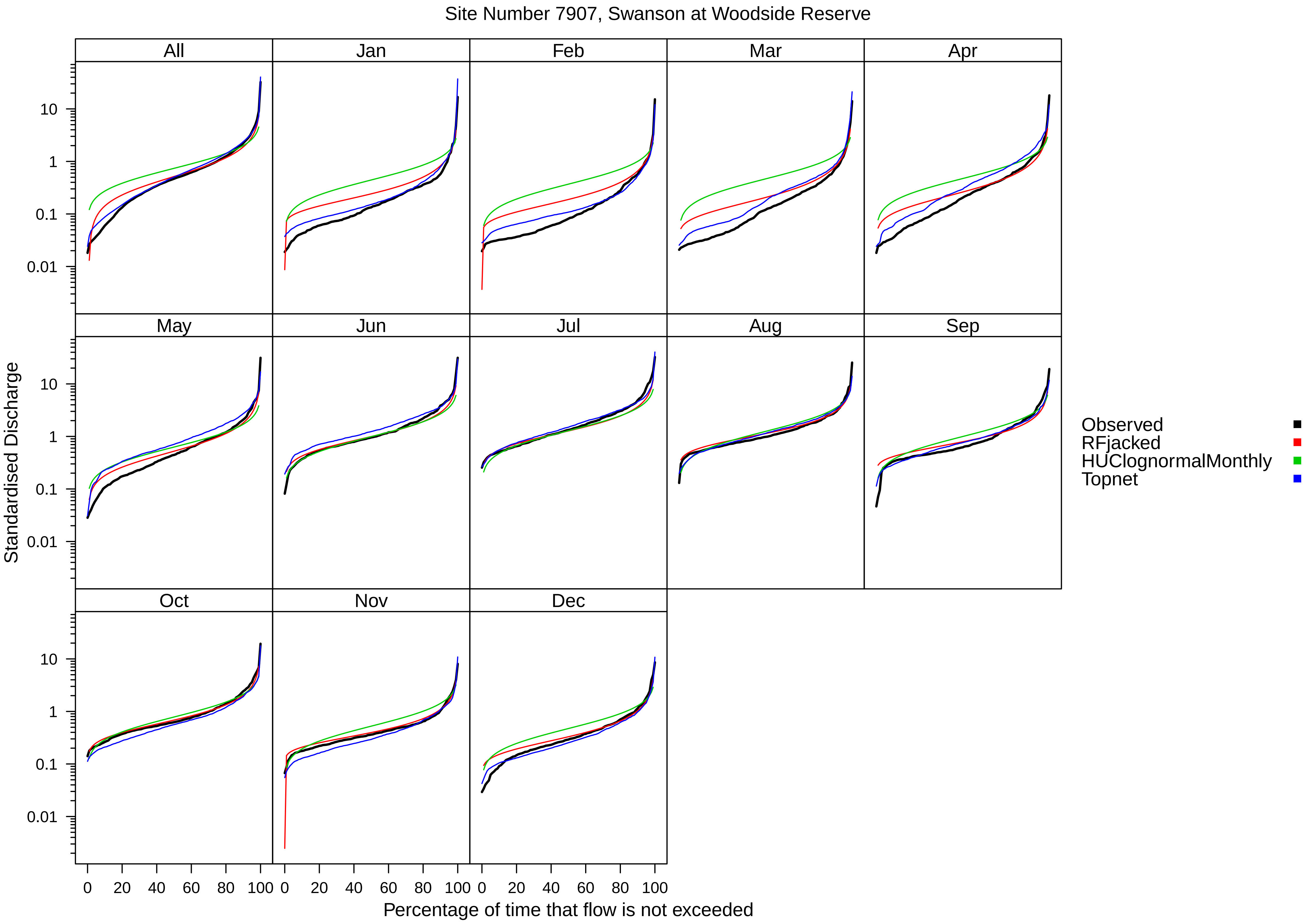


Site Number 7805, Rangitopuni at Walkers
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
100
10
1
0.1
0.01
0.001
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet

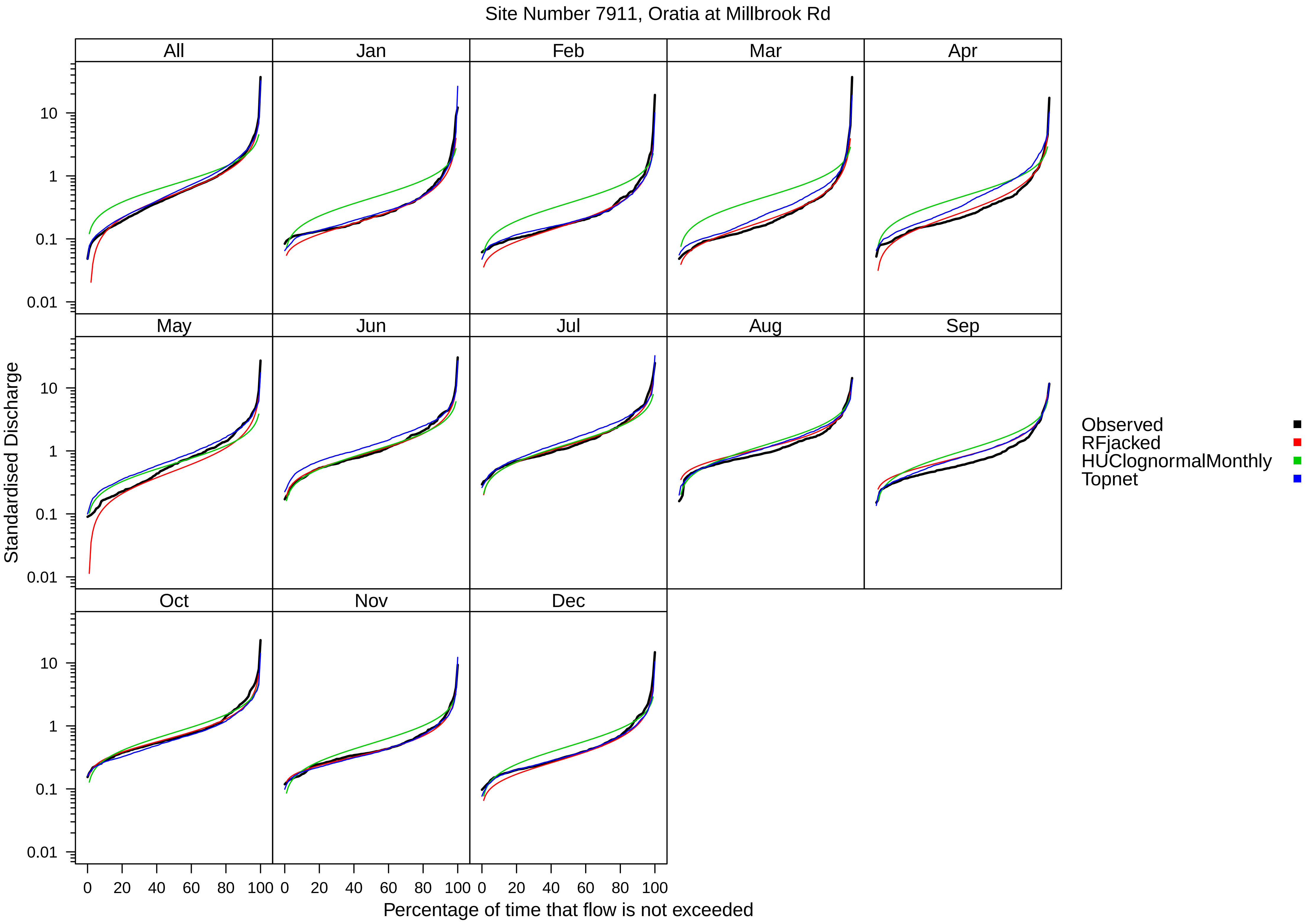


Site Number 7810, Paremoremo at Block Rd
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
100
10
1
0.1
0.01
0.001
1e−04
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet

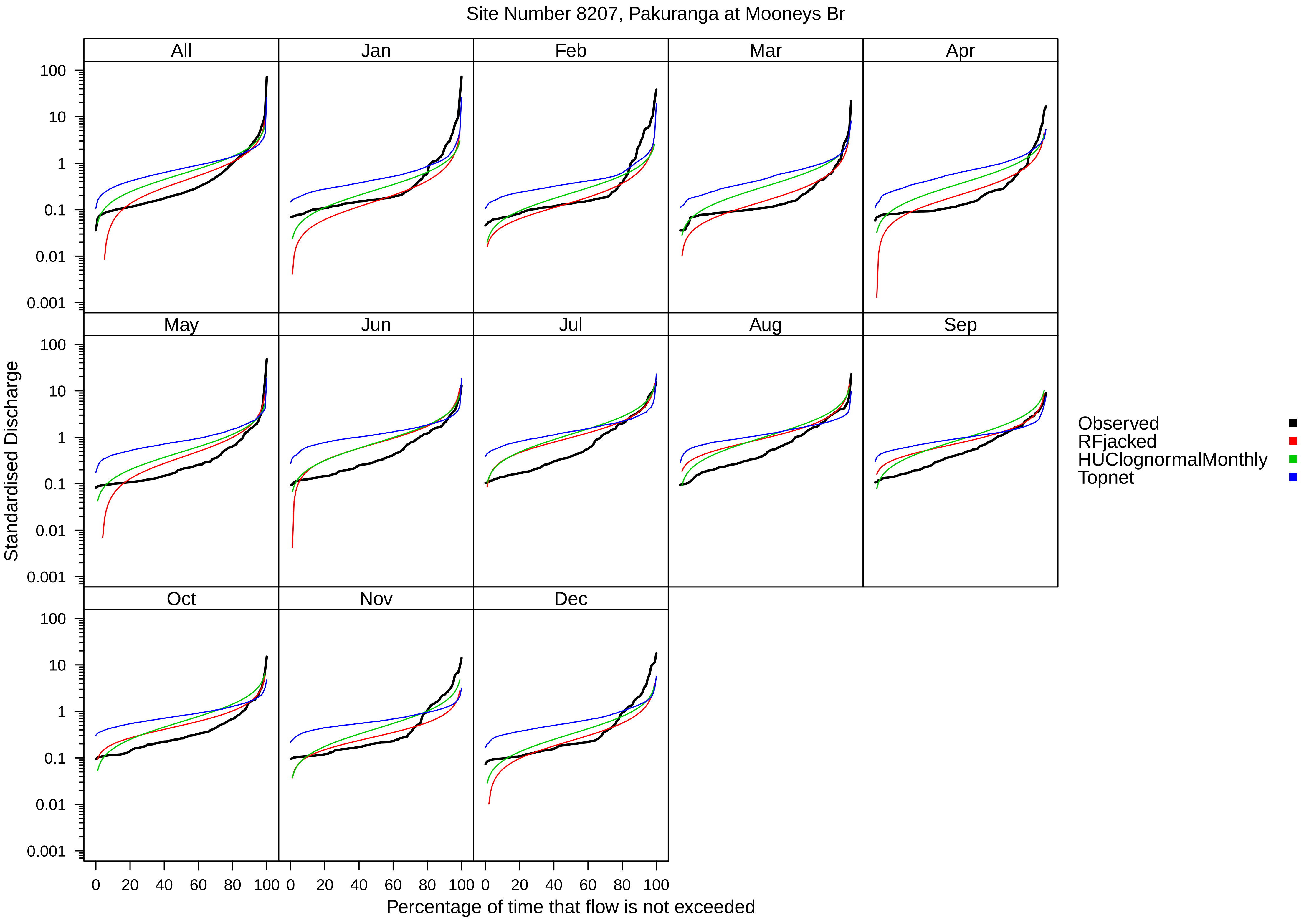

Site Number 7811, Oteha at Days Br
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet



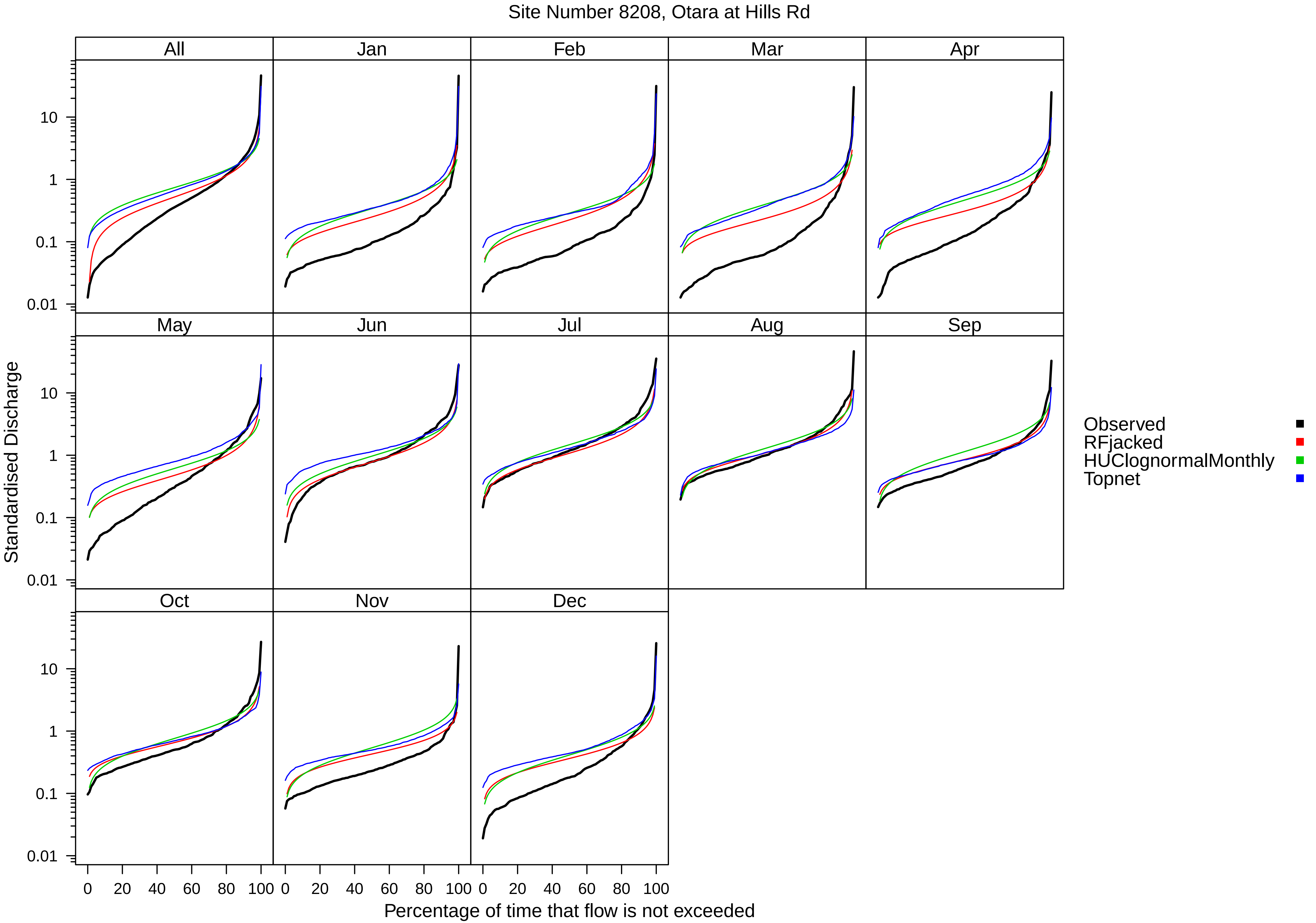
Site Number 7907, Swanson at Woodside Reserve
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
10
1
0.1
0.01
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet

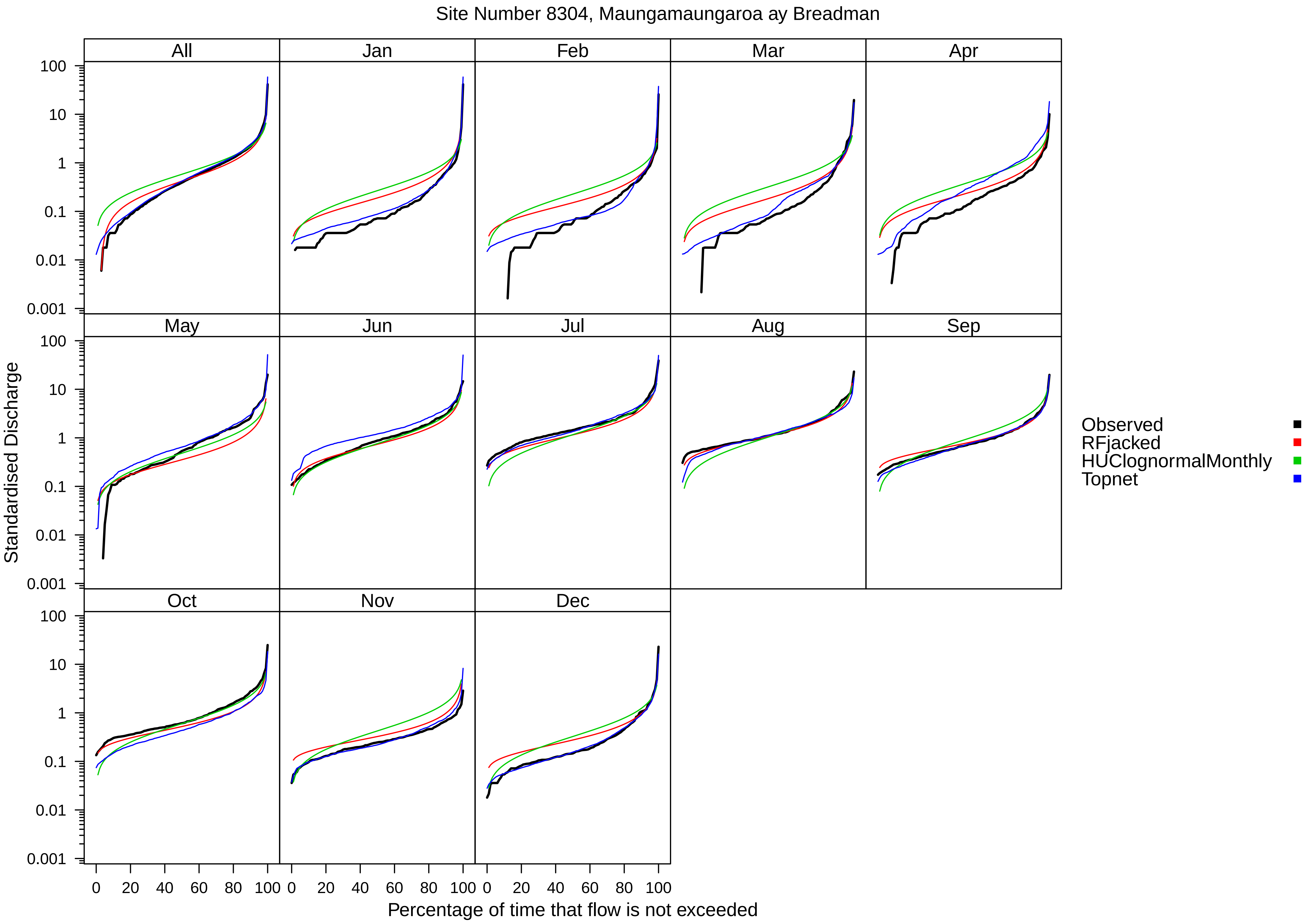


Site Number 7911, Oratia at Millbrook Rd
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
0.01
0.1
1
10
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet

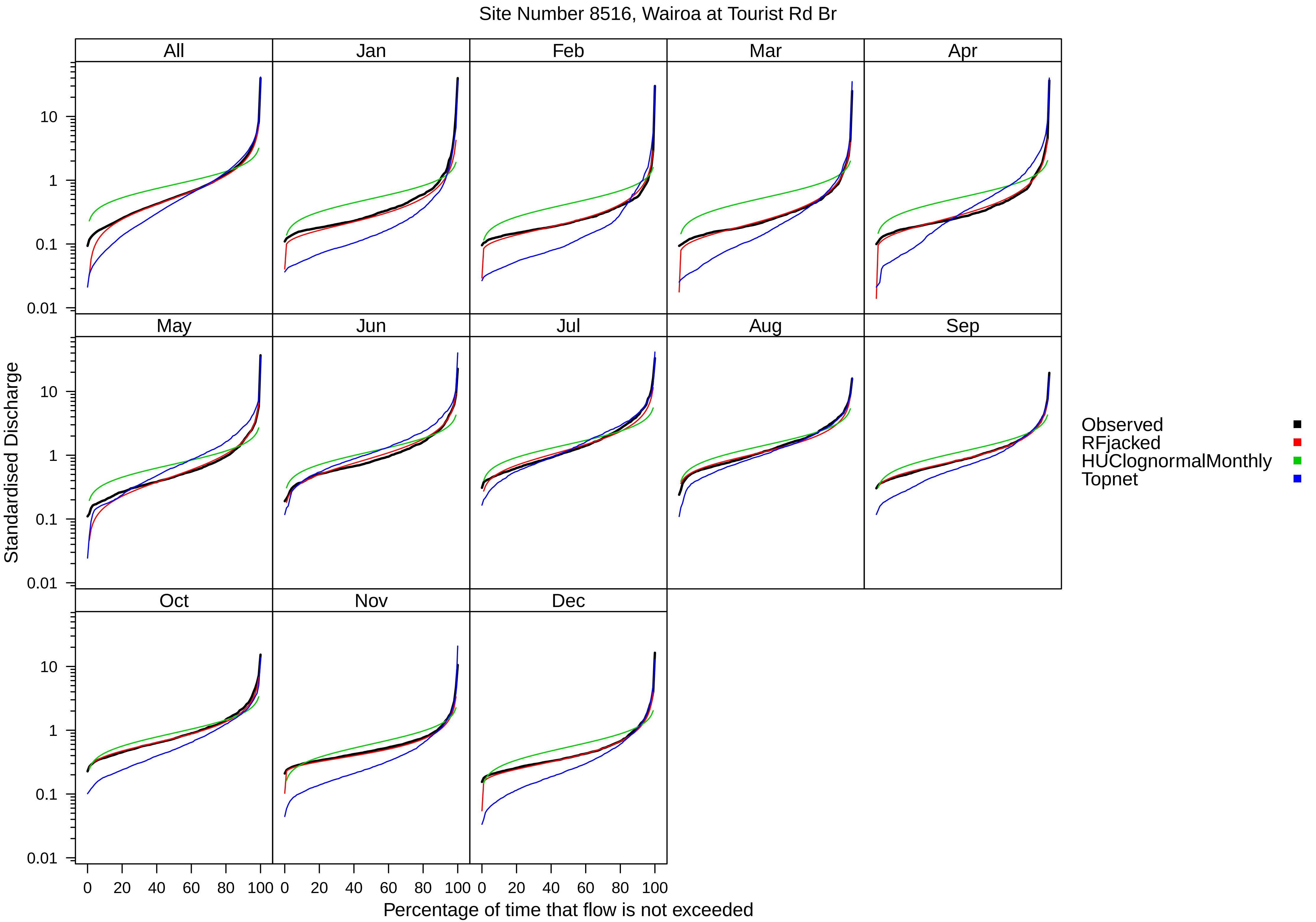


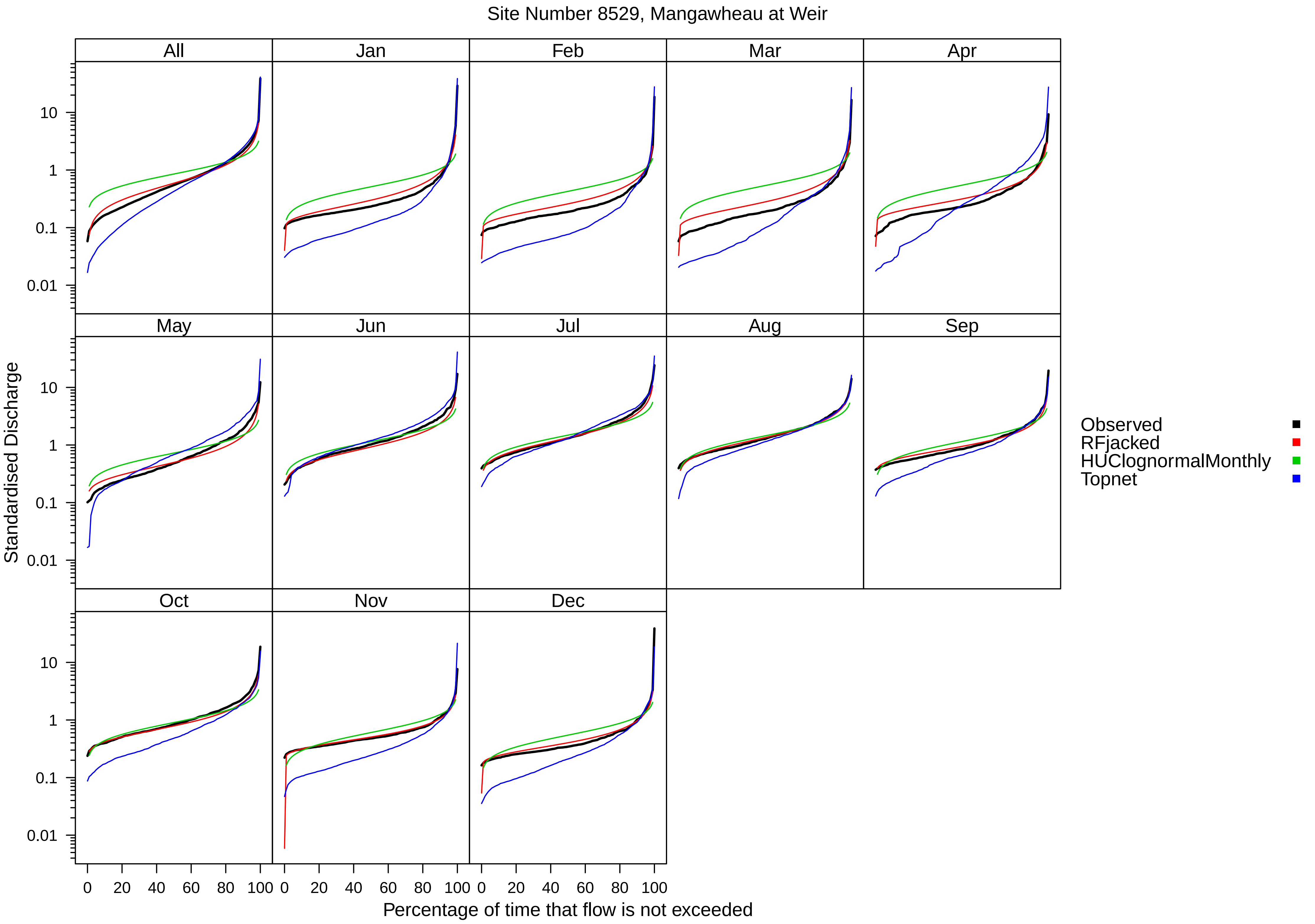
Site Number 8207, Pakuranga at Mooneys Br
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
100
10
1
0.1
0.01
0.001
Standardised Discharge
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet


Site Number 8208, Otara at Hills Rd
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
0.01
0.1
1
10
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet



Site Number 8304, Maungamaungaroa ay Breadman
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
100
10
1
0.1
0.01
0.001
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet


Site Number 8516, Wairoa at Tourist Rd Br
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
0.01
0.1
1
10
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet



Site Number 8529, Mangawheau at Weir
All
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Standardised Discharge
0.01
0.1
1
10
0
20
40
60
80
100
Percentage of time that flow is not exceeded
Observed
RFjacked
HUClognormalMonthly
Topnet

Find out more: phone 09 301 0101
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or visit www.aucklandcouncil.govt.nz

Auckland Council
Te Kaunihera o Tāmaki Makaurau