Assessing the seasonal predictability of streamflow

SRES3005 Water Resources Management (2005)

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Introduction

Flow in many rivers shows a marked seasonal pattern. This reflects seasonal cycles of climatic variables such as rainfall and air temperature. However, rivers vary widely in their seasonal pattern: some have relatively stable flow throughout the year, some have a predictable flow pulse, and some are characterised by apparently unpredictable events (Poff *et al*, 1997).

The seasonal predictability of flow conditions influences the evolution of life history strategies in native species, such as fish (Poff and Allan, 1995). Predictable flooding or low flow periods may be required by some species for effective breeding, migration and growth (Young, 2001). In contrast, species adapted to unpredictable environments tend to have opportunistic strategies, which may give them an advantage over invasive exotics (under natural conditions).

Flow and water temperature are thought to be the two most important drivers of floodplain ecosystems, and floods at different times of year may therefore have very different effects (Tockner *et al*, 2000).

On the River Murray, an experimental study (Robertson *et al,* 2001) has found evidence of different ecological responses to inundation in spring vs. summer. Differences included the rate of production of River Red Gums, aquatic macrophyte production and species richness, and the growth of biofilms. All of these components are primary producers and so support higher trophic levels.

Many studies have involved a characterization of the seasonality and regularity of river flow regimes. Some focus on 'flood' events, defined by a long return period (*e.g.* Castellarin *et al*, 2001), while others include both high and low flows. Poff (1996) considered the seasonal concentration of extreme high and low flow conditions; to complement this he also calculated the proportion of the year which is reliably free of these extremes. Many different statistics have been used to represent subtly different aspects of predictability, regularity and variability (*e.g.* Puckridge *et al* (1998) used variations on 23 different measures).

There is a clear need for comparative and analytic studies of these different statistics. For example, Colwell's (1974) predictability indices are often applied to streamflow, but they are known to be sensitive to the length of record used in their calculation (Gan *et al*, 1991). Clausen and Biggs (2000) speculated that the predictability index may give a consistent ranking of different sites, even though its absolute value takes a long time (~40 years) to stabilise. Poff (1996) found that the index, in some cases, gives inconsistent rankings of sites depending on the temporal scale of assessment.

To inform the selection of robust and meaningful measures of seasonality, this study proposes to analyse and compare several measures across a case study region. The study region chosen is the Gwydir Basin in NSW, a major subcatchment of the Murray-Darling Basin. This is of interest partly because of the ecological significance of its terminal wetlands (Young, 2001). McCosker (2001) listed the main factors determining floristic composition of the Gingham watercourse as flood frequency, depth and season.

Specifically, this study will calculate a set of flow statistics at several unregulated sites in the Gwydir basin. To address key issues in the application of these measures, the study will:

- examine the relationship between statistics;
- assess the effect of record length; and
- assess the effect of temporal resolution.

The conclusions should inform future hydroecological studies by highlighting robust and useful measures of seasonality.

Seasonal flow statistics

Seasonal flow statistics are used to assess the consistency of an annual flow pattern. This general definition allows a great many possible ways to quantify it. Following Colwell (1974), seasonal predictability comprises two components:

- the contrast between flow conditions at different times of year (“contingency”);
- the overall variability of flow conditions (“constancy”).

Furthermore, the assessment of seasonal predictability can range from general to specific. The measure used would likely depend on the availability of information concerning environmental flow requirements, the scale of the study, etc. A general assessment might be applied at a broad scale to contrast regular baseflow-dominated systems with more unpredictable, flashy rivers. Specific assessments can assess seasonal predictability:

- with respect to a given flow threshold (e.g. overbank or zero flow);
- at certain times of year (e.g. during a known spawning season).

Many different threshold-based statistics can be found in the hydroecological literature. Poff (1996) calculated the proportion of days above a threshold, in each of six 60-day windows. The maximum of these proportions then represents the “seasonal predictability of flooding”. He also calculated the same measure with respect to very low flow conditions.

Poff (1996) also highlighted the importance of the seasonal predictability of non-flooding, referred to as a “flood-free period”. This is the longest consecutive portion of the year in which a flood event (i.e. flow above a given threshold) has never been recorded. Again, he calculated the same measure with respect to very low flows. Combining occurrence and non-occurrence, Young (1999) suggested considering the "evenness" of proportions of floods in each season or month.

A different approach can be taken to the same idea: rather than calculating the proportion of (say) floods that occur in a given season, to calculate the proportion of years in which river was in flood in the given season. For example, Cardinale *et al* (2005) adapted Colwell's (1974) predictability index, calculating the daily predictability of flooding. They used a single threshold to define the number of years in which each day was 'in flood', or not.

Another example was defined by Fritz and Dodds (2005) for application to ephemeral streams. For each day of the year, they calculated the proportion of years in which the stream was flowing (*i.e.* not zero flow). They then took the maximum of these proportions, which represents the best reliability of flow of any time of year.

General seasonal predictability is often assessed with Colwell's (1974) index. This represents the consistency between years of the seasonal pattern of all flows (not based on a single threshold). The index was designed to represent predictability of general periodic phenomena, using information theory. For application to continuous phenomena (such as flow), discrete classes need to be defined. The year must also be divided into discrete time periods (typically months).

An alternative, avoiding the need for discrete flow classes, is the use of seasonal flow distributions. The predictability of flow in each calendar month corresponds (inversely) to its variability over years. Overall predictability is then the average of predictability values for all months.

Taking a measure quite different to any others listed here, Pusey *et al* (1995) found the predictability (in Colwell's sense) of the range of flow conditions experienced within each month. The range, as a measure of intra-month variability, was expressed as the maximum divided by minimum flows within each month. This statistic attempts to capture the seasonal predictability of stable and unstable flow conditions.

The approach taken here is based on seasonal flow distributions, considering all flow conditions rather than thresholds. In this sense, a holistic approach to the flow regimes is taken. Furthermore, information about ecologically relevant flow levels was not available. The approach is also temporally general, in examining average predictability over the year (although individual months are also assessed – see below). In this sense it is analogous to Colwell's index, but is continuous rather than discrete.

Method

In order to examine and compare statistics, a set of rivers was identified to provide a case study dataset. The rivers are located in the Namoi and Gwydir basins, NSW, Australia. Only unregulated streams were chosen, to avoid artificial effects of dam releases.

To compare flow statistics between rivers, the confounding effect of different climatic inputs should be avoided. Accordingly, I selected unregulated sites with available data in a common period. The period covered the 20 water years 1967-1986 (inclusive). Water years were defined to begin on 1 October of the named calendar year. Any site with at least 15 available years in the period was selected. A year was defined as "available" if fewer than 10% of its daily values were missing. The final set of 24 sites is displayed on Figure 1 (showing the data record of each site).

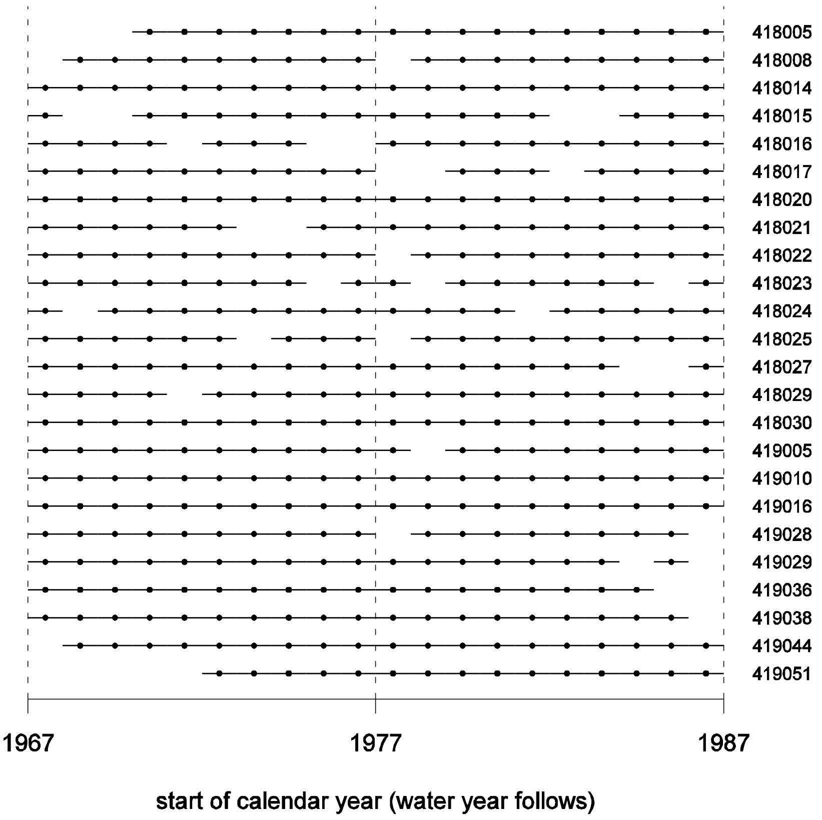

Figure 1: Available data at each site in a common 20-year period (covering water years 1967-1986, inclusive). Years were defined as being available if fewer than 10% of their daily values were missing. The point following a marked year (such as "1977") represents the water year beginning 1 October in that calendar year.

Details of the selected sites, including name, catchment area and location, are shown on Table 1 and Table 2. The full period of record is given for each site, although only a common 20-year period is used in this study.

Table 1: Namoi stream gauging stations selected.

station ID	river name	station name	catchment area	period of record	latitude	longitude
419005	Namoi	North Cuerindi	2538	1915-	-30.68	150.78
419010	Macdonald	Woolbrook	844	1927-	-30.97	151.35
419016	Cockburn	Mulla Crossing	900	1936-	-31.06	151.13
419028	Macdonald	Retreat	1760	1965-1987	-30.63	151.11
419029	Halls Ck	Ukolan	376	1965-	-30.71	150.83

419036	Duncans Ck	Woolomin	93	1965-1986	-31.32	151.16
419038	Macdonald	Cobrabald	358	1965-1987	-31.19	151.45
419044	Maules Ck	Damsite	45	1968-1992	-30.53	150.30
419051	Maules Ck	Avoca East	667	1972-	-30.50	150.08

Table 2: Gwydir stream gauging stations selected.

station ID	river name	station name	catchment area	period of record	latitude	longitude
418005	Copes Ck	Kimberley	259	1929-	-29.92	151.11
418008	Gwydir	Bundarra	3990	1936-	-30.17	151.07
418014	Gwydir	Yarrowyck	855	1954-	-30.47	151.36
418015	Horton	Rider (Killara)	1970	1957-	-29.84	150.35
418016	Warialda Ck	Warialda No.2	544	1972-1991	-29.55	150.55
& 418050	*Warialda Ck*	*Warialda No.1*	*483*	*1964-1972*	*-29.55*	*150.58*
418017	Myall Ck	Molroy	842	1964-	-29.80	150.58
418020	Boorolong Ck	Yarrowyck	311	1965-1987	-30.48	151.43
418021	Laura Ck	Laura	311	1965-	-30.23	151.19
418022	Georges Ck	Clerkness	518	1965-1989	-30.19	151.14
418023	Moredun Ck	Bundarra	656	1965-1988	-30.14	151.14
418024	Roumalla Ck	Kingstown	487	1965-1989	-30.48	151.15
418025	Halls Ck	Bingara	156	1965-	-29.94	150.57
418027	Horton	Horton Dam Site	220	1967-	-30.21	150.43
418029	Gwydir	Stonybatter	1940	1967-1988	-30.32	151.14
418030	Copes Ck	Tingha	86	1967-1989	-29.95	151.25

This study aims to assess measures of seasonal predictability of flow. As noted above, the approach here is based on seasonal flow distributions. Five of such distributions were defined, each potentially representing different aspects of predictability. They are listed and given code names here:

- inter-annual variability of mean flows in each month (VAR_MEAN);
- inter-annual variability of maximum flows in each month (VAR_MAX);
- inter-annual variability of minimum flows in each month (VAR_MIN);
- overall variability of daily flows (lumped over years) in each month (VAR_DAYS);
- inter-annual mean of variability of daily flows within single months – i.e. the average *instability* of flows in each month (INSTAB).

These distributions represent the unpredictability of flow in each month of the year. The distribution of VAR_MEAN is similar to that often used in calculating Colwell's index. The variants VAR_MAX, VAR_MIN and INSTAB are similar to the variants of Colwell's index defined by Pusey *et al* (1995). I am not aware of any previous use of VAR_DAYS.

It should be noted that monthly maxima and minima here refer to the highest and lowest daily flow, respectively. The indices defined by Pusey *et al* (1995) instead make use of instantaneous peaks and troughs: differences between the two approaches would occur in small catchments, where peak recession is rapid. However, instantaneous data was not available for the period of record, so daily data was used throughout.

The term “variability” was used in the definitions just given, without specifying how this is calculated. Many measures of variability are possible: Young (1999) recommends the use of a spread statistic (difference between high and low percentiles, divided by the median), and the coefficient of variation (CV) is widely used (e.g. Poff, 1996). In most cases, the variability of flow is calculated without transformation. However, flow distributions are generally skewed unless log-transformed. This transformation is also recommended on the basis of ecological relevance (Gordon *et al*, 2004), effectiveness of bed sediment disturbance (King *et al*, 2003) and the relative error in streamflow measurement (Chapman, 1986).

The measure of variability used here is the standard deviation (σ) of log-transformed flows. This represents the number of orders of magnitude typically spanned by flow conditions. It is necessary to impose a lower bound, since the logarithm is undefined when flow drops to zero. The measure is defined as follows:

$$\sigma_{\log}(x)=\sigma(\log_{10} z)$$

where $z=\max(\varepsilon, x)$. I took ε = 0.1 ML/day, which is the approximate limit to resolution of flow gauges. It is expected that visible surface flow would cease at about this level.

On each of the five seasonal distributions described above, two measures were defined:

- mean unpredictability over all months of the year;
- minimum unpredictability from all months in the year.

The first of these is (the inverse of) general predictability in the sense of Colwell (1974). The second may be important if biota are adapted to predictable conditions are certain times of year. Temporarily predictable conditions are not apparent from a simple average. Thus, for every site two measures are calculated, each of which has five versions.

To understand these flow features, it was helpful to visualize them in a small number of example rivers. The chosen example rivers were 418017, 418025 and 418027, all in the Gwydir basin. Their headwaters are in different parts of the catchment: 418017 drains flat plains to the north, 418028 rises in Mt Kaputar to the south, and 418025 is a small subcatchment to the east of Mt Kaputar.

Comparison of measures

Overall flow variability is used much more widely than seasonal predictability. It is therefore useful to know how different these measures of predictability are (i.e. the extra information contained in seasonal patterns). Accordingly, the mean of each distribution was compared to overall flow variability at each of the 24 sites listed above. Variability was calculated as $\sigma_{\log}$ of daily flow. Rank correlations were computed in each case, showing the degree to which statistics put sites in the same order as each other (and thus capture essentially the same information).

Although five different distributions of seasonal predictability were defined above, some may measure the same thing. It is of interest to compare these and determine which contain unique information, and which are redundant.

Such comparison is straightforward: graphically, the measures were plotted against each other (scatter plots). To back this up, rank correlations were computed. This is useful in pair-wise comparisons, but to assess the whole set, Principal Components Analysis was used. This analysis determines the number of measures (principal components) that are required to represent some proportion of the variance in the data set. Typically the vast majority of variance can be represented by one or a few components and the rest are largely redundant.

As a final comparison, the mean (overall predictability) and minimum (temporary predictability) of each distribution were compared. The same method was used as described for overall variability.

Effect of temporal resolution on ranking of sites

An arbitrary parameter in the definition of seasonal predictability measures is the use of calendar months. Obviously, these have no particular relevance for a river. Therefore, it is important to assess their sensitivity to minor changes in the definition of months (i.e. temporal resolution). The effect of changing “month” size was assessed (the number of intervals that the year is divided into). As this was changed, statistics were re-calculated. The effect was expressed in terms of rank correlation between the new values and the original set (with 12 months). Deviations in rank correlation indicate that sites are put in a different order when the year is divided up differently (with finer or coarser resolution).

Effect of record length on ranking of sites

Another assumption that should be tested when comparing rivers is the specific period of record (i.e. temporal extent). The effect of contracting the period of record was assessed. A common period was maintained, but it was contracted from the end (1986), year by year, and the statistics recalculated. The effect was again expressed in terms of rank correlation between the new values and the original set (with a 20-year period).

Results

The flow regime of three example sites is introduced here. Figure 2 shows a representation of the seasonal flow pattern of each site. Time series are shown, aligned by years in order to highlight seasonally specific flow conditions. Inter-annual distributions of mean monthly flow are also shown. The former makes it easy to see low flow patterns, as well as complex sequences of dry and wet years. The latter displays the seasonal probabilities of high flow months, mid-range conditions and minima.

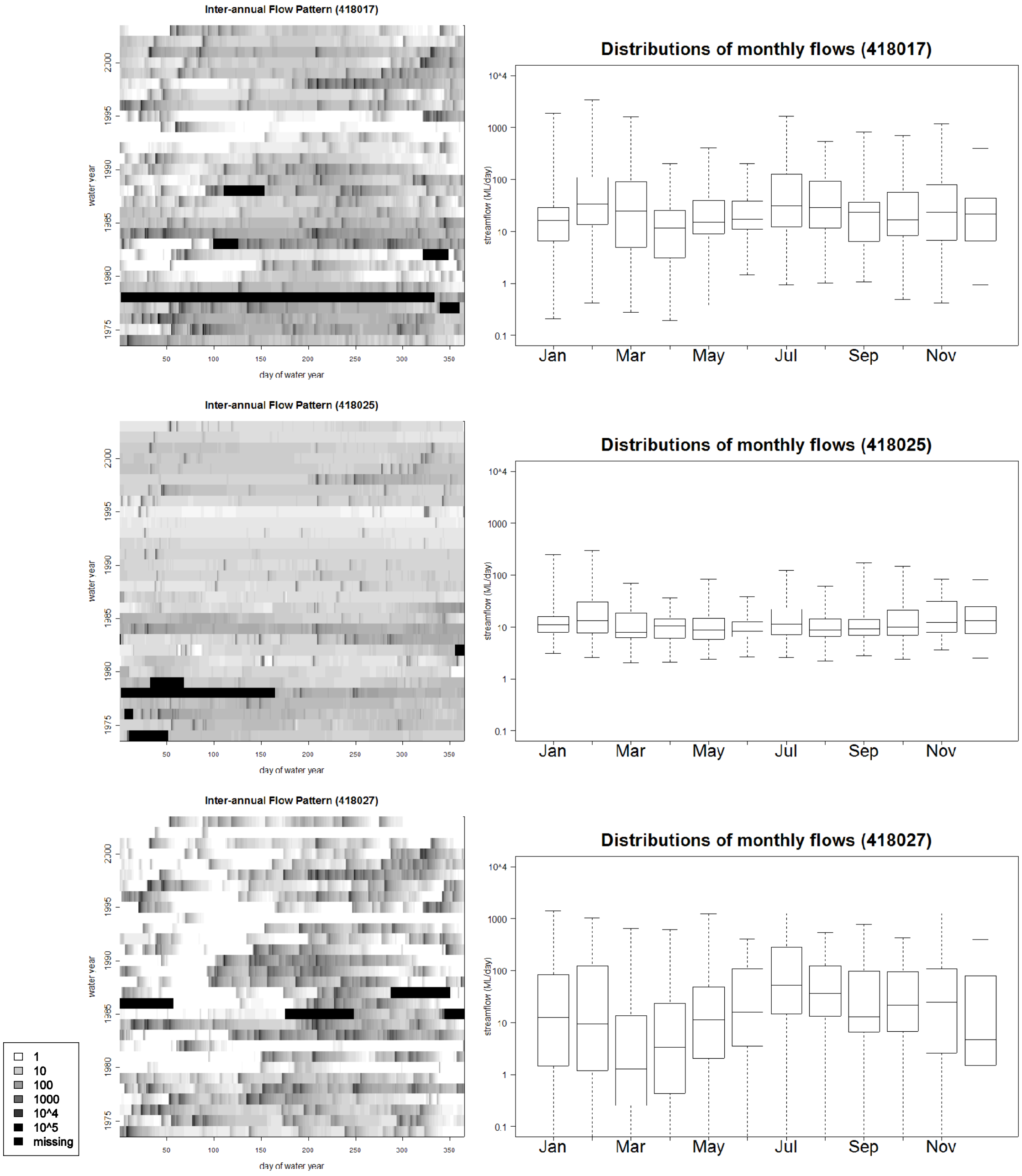

Figure 2: Seasonal flow time series and monthly distributions for the three example sites.

It can be seen from Figure 2 that site 418017 has quite a strong baseflow component, but that there is a marked contrast between the flow rate from year to year. High and low monthly flow conditions vary over the year, while the median is relatively constant. Site 418025 is remarkably stable, with mean monthly flow never dropping below 2 ML/day. High flow months do however show a seasonal pattern. Site 418027 is the most variable. Zero flows have occurred in all months of the year, as have high flows, but the mid range of flows does show a strong seasonal pattern.

Monthly distributions of seasonal predictability are shown in Figure 3 for the three example sites. The five distributions do seem different, at least in magnitude. The order of decreasing variability is generally: VAR_MAX, VAR_MEAN, VAR_DAYS, VAR_MIN, INSTAB. As expected, 418027 is the most unpredictable on these measures, except perhaps in some monthly minima and some monthly instabilities. 418025 is the most predictable.

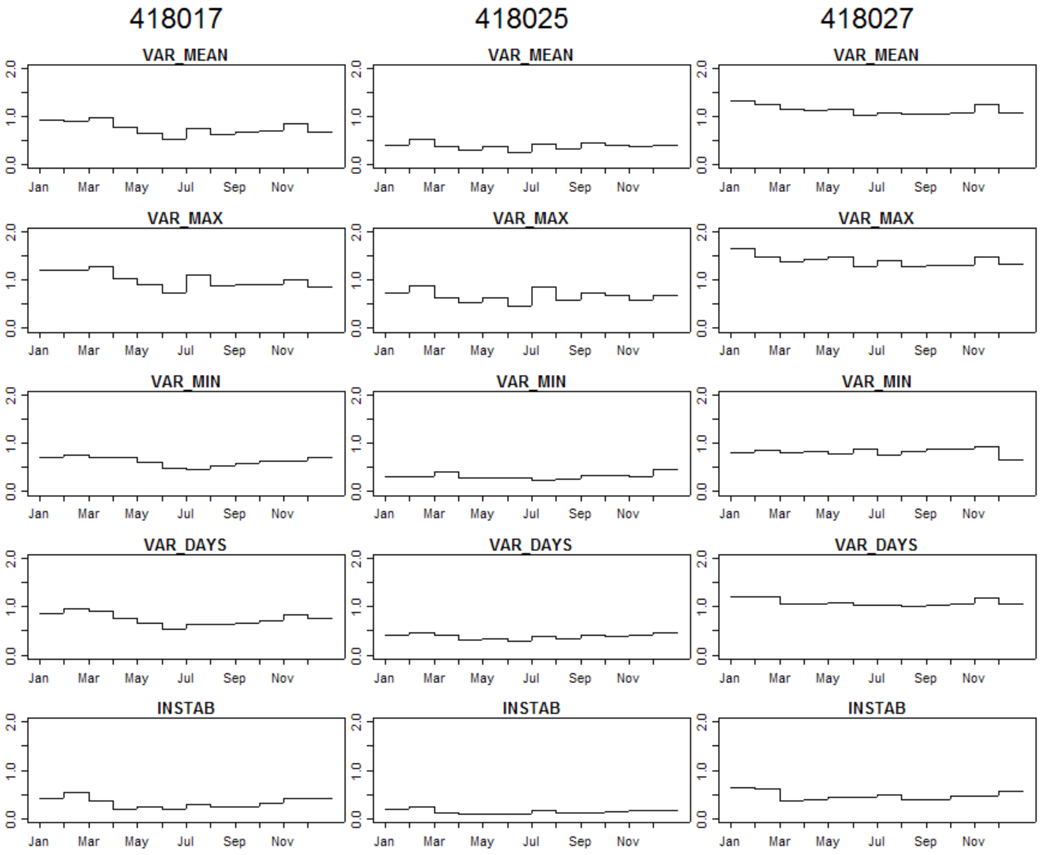

Figure 3: Monthly values of seasonal predictability for the three example sites. Each of the five distributions are shown: VAR_MEAN, VAR_MAX and VAR_MIN are the variability of monthly mean, maximum and minimum flows, respectively. VAR_DAYS is the variability of daily flow constrained to certain times of year. INSTAB is the mean variability within single months (instability).

Comparison of measures

Overall variability of daily flow was compared with average seasonal predictability according to each of the five distributions considered (i.e. the average over months of the values shown in Figure 3). Three of the five comparisons are shown in Figure 4. They show that while there is an obvious correspondence between variability and predictability, they are not entirely consistent. In some cases, sites in the middle of one measure may be near the extreme of the other measure. Rank correlations were used to quantify the consistency of measures: VAR_MAX was 0.85, VAR_MIN was 0.93 and INSTAB was 0.88. For the other distributions (not shown), VAR_MEAN had a rank correlation of 0.94, and VAR_DAYS was 0.98. Thus the mean value of VAR_DAYS is very similar to the overall variability of flow. This is not surprising since it does measure daily variability, but constrained to specific times of year.

It can also be seen in Figure 4 that INSTAB was the only measure in which site 418025 was clearly separate from the others (corresponding to low overall variability).

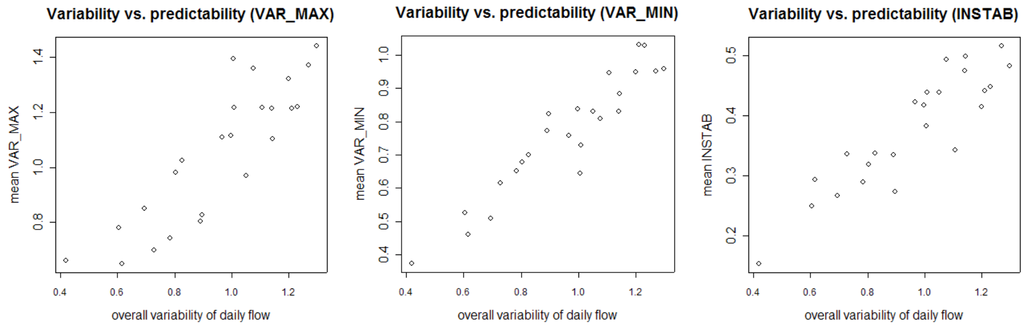

Figure 4: Comparison of overall variability and average seasonal predictability. The values were calculated from a common 20-year period at each of 24 sites (see Figure 1).

Figure 5 shows a pair-wise comparison of the five types of unpredictability. With respect to mean unpredictability, VAR_MEAN, VAR_MAX and VAR_DAYS are quite highly inter-correlated, while INSTAB is not highly correlated with any other measure. With respect to mean unpredictability, a similar pattern holds, but the correlations are generally lower. INSTAB is particularly uncorrelated with any other measure.

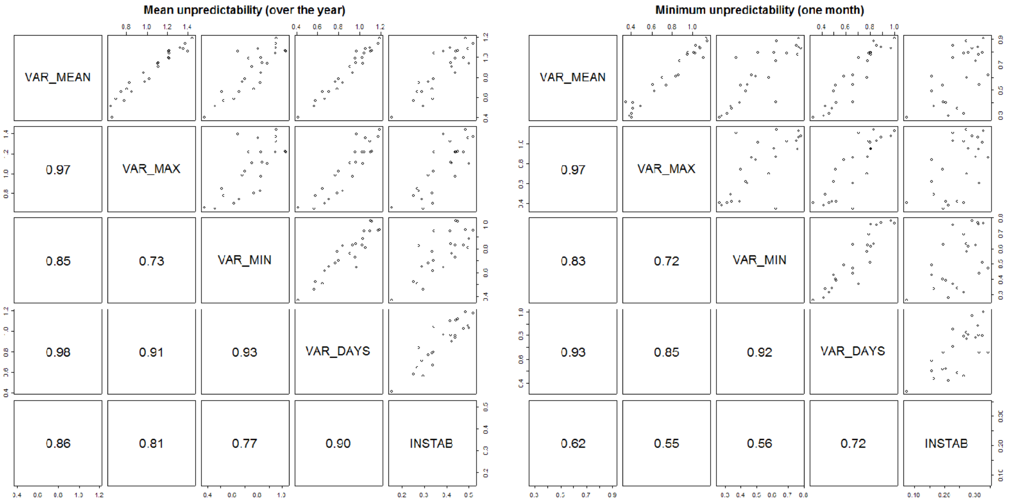

Figure 5: Comparison between the five types of unpredictability. The figure on the left compares mean unpredictability and the one on the right compares minimum unpredictability. The values were calculated from a common 20-year period at each of 24 sites (see Figure 1). Each scatterplot compares variables listed along the same column and row. Corresponding rank correlations are also shown.

In order to assess redundancy between the five measures, a Principal Components Analysis was undertaken (on the correlation matrix: i.e. variables were scaled). A separate analysis was applied to mean unpredictability and minimum unpredictability. The results are shown in Table 3. In both analyses, 99% of variance can be represented by three components: clearly there is redundancy in the original set. For mean unpredictability, one measure captures 90% of the variance, whereas minimum unpredictability requires two measures to reach the same level. The first principal component has roughly equal weightings, while the highest weights in second and third principal components apply to INSTAB and VAR_MIN.

Table 3: Results from Principal Components Analysis of the five types of unpredictability. Columns show the proportion of variance accounted for by each principal component. For instance, 90% of the variance of mean unpredictability can be represented by one measure (one principal component), and 82% of the variance of minimum unpredictability can be represented by one measure.

	PC1	PC2	PC3	PC4	PC5
Mean unpredictability	0.90	0.06	0.04	0	0
Minimum unpredictability	0.82	0.11	0.06	0.01	0

Finally, mean unpredictability was compared to minimum unpredictability (within each type of distribution). Three of the five comparisons are shown in Figure 6. Rank correlations were, for VAR_MAX 0.96, for VAR_MIN 0.84, and for INSTAB 0.80. In the latter cases, overall unpredictability is not a good indicator of temporarily predictable conditions.

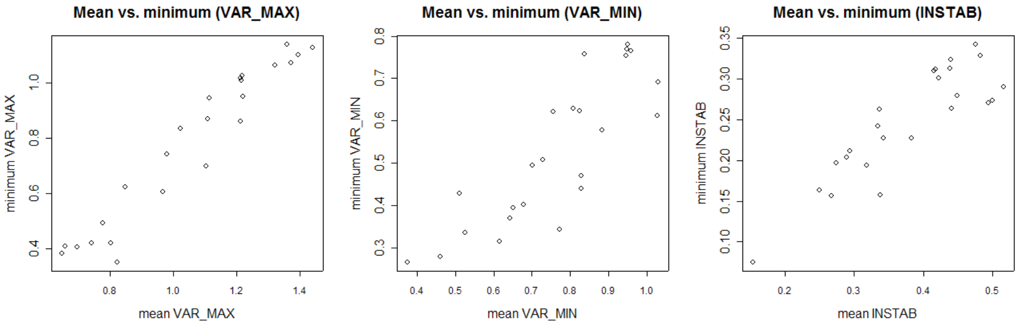

Figure 6: Comparison of mean unpredictability (over the year) and minimum unpredictability (i.e. the most predictable month). The values were calculated from a common 20-year period at each of 24 sites (see Figure 1).

Effect of temporal resolution on ranking of sites

The sensitivity of statistics was assessed to the number of intervals into which the year is divided. Interval lengths varied from several months to one week. The results were expressed as a rank correlation, revealing changes in the order of sites according to a given measure. This can be seen in Figure 7 for two cases: with respect to mean unpredictability, both were quite robust to changes in temporal resolution, remaining above 90% correlation with between 5-52 intervals. However, minimum unpredictability was more sensitive. VAR_MAX was less sensitive than INSTAB to temporal resolution.

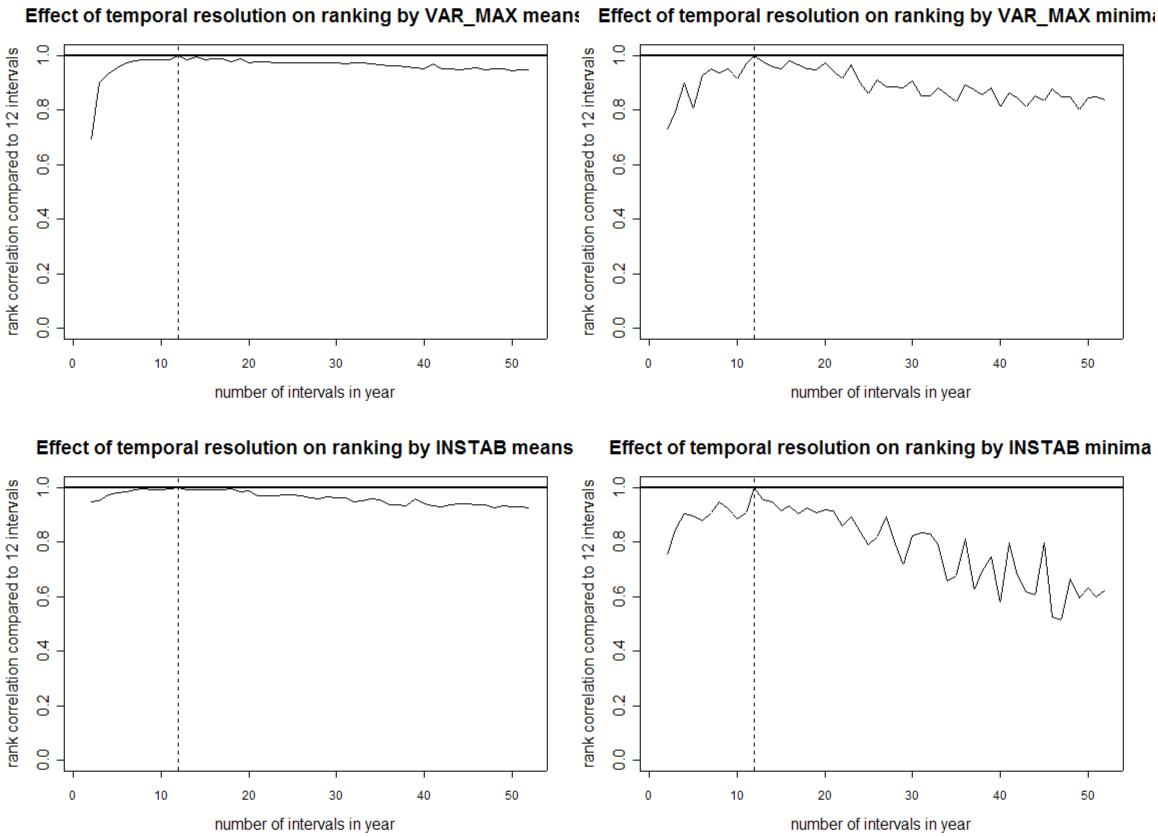

Figure 7: Effect of temporal resolution of the ranking of sites. The base case had 12 intervals in the year (months). This was changed to between 2 and 52 intervals, and the values of statistics compared to the base case by rank correlation.

Effect of record length on ranking of sites

The sensitivity of statistics was assessed to the length of record used in their calculation. The original 20-year period was contracted, one year at a time, down to 7 years. The results were expressed as a rank correlation, revealing changes in the order of sites according to a given measure. This can be seen in Figure 8 for two cases: with respect to mean unpredictability, VAR_MAX was robust down to about 14 years but still remained above 80% correlation, and INSTAB was robust in all cases. In contrast, VAR_MAX was quite strongly affected in terms of minimum unpredictability when the record was contracted to 14 years; INSTAB was again quite robust.

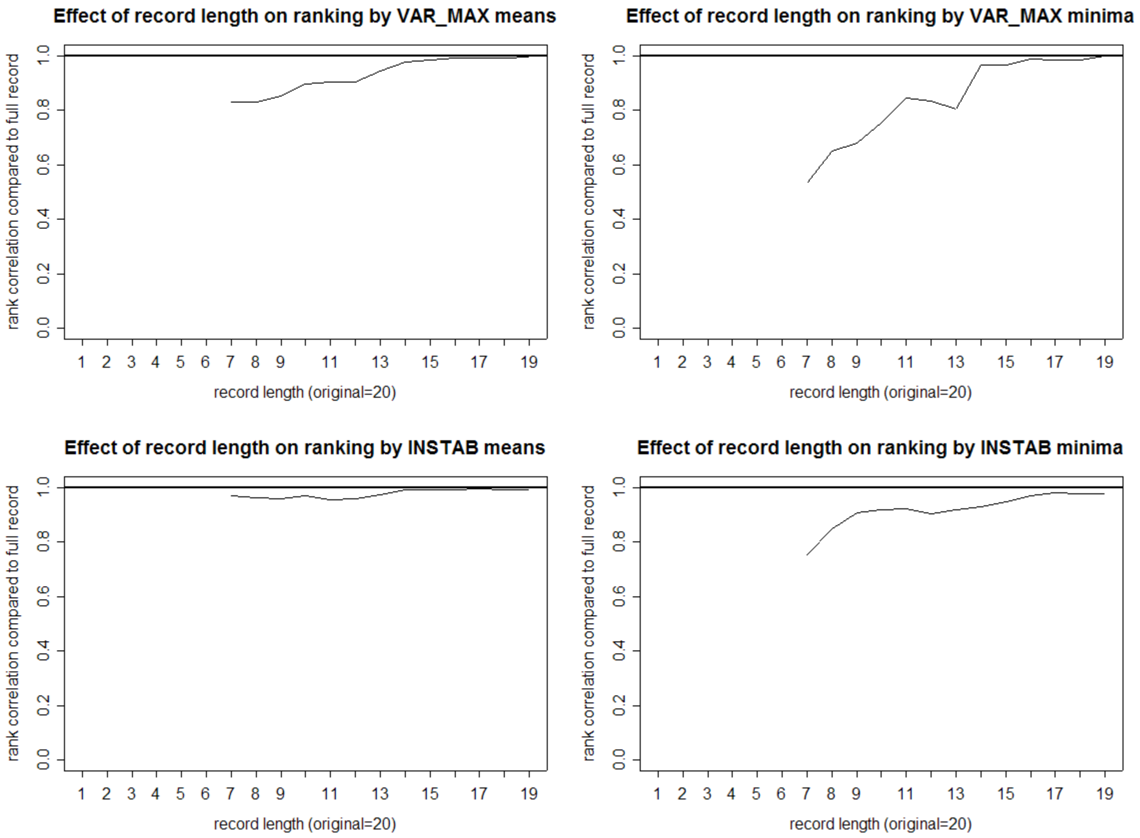

Figure 8: Effect of record length on the ranking of sites. The base case had 20 years of record. This was contracted down to 7 years, and the values of statistics compared to the base case by rank correlation.

It should be noted that contracting the period of record is a test that is specific to the years involved. It may reveal cases when a small number of years are overly influential on the results, but it is certainly not a definitive test of data requirements.

Discussion

This study has shown that seasonal predictability is not the same as overall variability. The two measures are inconsistent in many cases, in the sense that they can each rank rivers differently in a regional context. Ecological theory emphasises the importance of seasonal timing and predictability of flow conditions. Even so, many studies do not include any measure of it, or if they do, the robustness and appropriateness of the measure is rarely examined.

This study has also shown that the existence of temporarily predictable conditions is not well represented by measures of general predictability. These general measures are the most widely used, in the form of Colwell's (1974) index.

An examination of rank correlations, as well as a Principal Components Analysis, revealed that one or two measures are sufficient to capture 90% of the variance across sites (although this result may be specific to the study region). The seasonal predictability of monthly maxima (VAR_MAX) and monthly instability (INSTAB) are relatively unrelated and are conceptually attractive. Analogous measures were used by Pusey *et al* (1995), as variants of Colwell's index. The approach taken here is arguably more objective since discrete flow states are not required.

The measures assessed were found to be robust to changes in temporal resolution, particularly general predictability. Temporary predictability was also reasonably robust within a factor of two (finer or coarser). Reducing the period from 20 down to 15 years did not greatly affect the ranking of sites, although further changes did have some effect.

The findings in this study should be qualified in several respects. Firstly, only one measure of variability was used to calculate seasonal predictability (the definitions given allow any such measure to be used). Importantly, variability was calculated from log-transformed flow. Different results should be expected when assessing untransformed flow data.

Another limitation is that the study region is within a specific climatic region, so that the flow regimes are not necessarily representative of those in other regions. Furthermore, some of the rivers assessed here were spatially nested or adjacent, or otherwise did not have independent flow regimes. The data set therefore does not have the statistical power that would be suggested by its sample size.

The assessment of sensitivity to record length undertaken here was a specific test, and certainly does not allow a definitive statement about data requirements. The common period was simply contracted from one end, which may reveal a strong influence of those later years. A more general test could assess the robustness of results to omitting single years of record: a "jackknife" assessment (Efron and Gong, 1983). Furthermore, this study did not examine the length of record which may be required to adequately characterise a river flow regime. Rather, the focus was on comparing specific conditions in a common period.

Conclusions

This study has emphasised the information contained in seasonally-specific patterns of variability. Such patterns may be obscured by measures of overall variability. However, ecological theory suggests that they may be important to in-stream and floodplain organisms. Furthermore, the existence of temporarily predictable conditions is not necessarily consistent with measures of general predictability (averaged over the year).

The robustness and possible redundancy of measures was assessed in this study. The feasibility and appropriateness of assessing seasonal flow predictability was thus demonstrated.

A framework such as that described here could usefully inform future hydroecological studies and promote the use of more robust and powerful measures of seasonality.

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