An Improved Definition of Sewage Treatment Works Dry Weather Flow

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Abstract

Sewage treatment works dry weather flow (DWF) is currently defined in UK practice as the mean effluent flow during a 7-day period of dry weather, as defined by stringent rainfall limits. This definition of DWF has a number of shortcomings, including the rarity of qualifying dry periods in the UK. This paper details work carried out for UK Water Industry Research to develop an improved measure of DWF. Alternatives considered included variations on the current method, percentiles of daily flows (with and without rainfall conditions), and standard measures of central tendency such as the mean.

Methods were judged against criteria including continuity with the current method and applicability to real data. It was concluded that the alternative definition of DWF best satisfying the criteria is the 20th percentile of daily flows. It is recommended that this definition be applied in Environment Agency (EA) sewage treatment works compliance assessment with appropriate recognition of uncertainty. The EA is currently in discussion with sewerage companies on how to implement a new definition of DWF based on this approach.

Introduction

The need for a measure of DWF

In the United Kingdom a sewage treatment works (STW) is issued with a discharge consent in order to limit pollution of the watercourse receiving treated effluent. This consent includes a flow limit based on Dry Weather Flow. The reasoning is that in dry weather the flow volume of the receiving watercourse is at its lowest, resulting in reduced dilution of sewage effluent; also, sewage flow in dry weather is expected to be the closest representation of domestic and industrial sewage flows, without additional flows due to surface runoff.

The current definition of DWF

The current definition of DWF was first published in 1975 in the Institute of Water Pollution Control Glossary [1] and is quoted below from the Environment Agency (EA) standard consent conditions [2].

"the average daily flow to the treatment works during seven consecutive days without rain (excluding a period which includes public holidays) following seven days during which the rainfall did not exceed 0.25 millimetres on any one day".

Due to a lack of flow data, there has been no systematic assessment by the EA of DWF compliance at STWs. However, requirements have recently been imposed for STW flow monitoring and reporting, and it is expected that EA assessment of flow compliance will commence in 2006.

The current definition of DWF has a number of shortcomings however, and slightly varying definitions have been applied across the UK water industry. Problems and ambiguities include:

- The relative rarity of qualifying periods of dry weather in the UK. Analysis of 1,803 works-years of rainfall data has shown that 38% do not have a dry period satisfying the definition.
- Seasonal variation in sewer infiltration has the effect that the DWF is likely to vary depending on when in the year the dry period occurred. If a dry period occurs in winter, DWF is likely to be greater.
- The requirement for reliable rainfall data means it may not be possible to calculate DWF even if effluent flows have been well monitored and recorded. Also, rainfall data may have been obtained from a rain gauge distant from the STW. This is important because rainfall (especially summer storms) can be very localised; rain could fall in the STW drainage area without being recorded by the corresponding rain gauge.

- The current definition gives no guidance on combining measured dry period flows if there is more than one dry period at a STW in a given year.

- There are differing versions of the current definition, for example, some versions state that flows during a summer and a winter dry period must be obtained and averaged to give the final estimate of DWF for that year.

Given these problems, it was decided by the UK water industry that a new measure of DWF should be sought, and in 2004 UK Water Industry Research (UKWIR) commissioned a project to develop an improved method of estimating DWF. This paper details the work carried out under this project by Tynemarch Systems Engineering Ltd.

Selection of an improved method of calculating DWF

Process

The process for selection of an improved method of calculating DWF can be summarised as follows:

i) Define selection criteria.

ii) Identify alternative methods to be considered.

iii) Collate and validate data for testing alternative methods.

iv) Develop tools for assessment of alternative methods.

v) Assess the performance of various interpretations of the current method (considering ambiguities in, and differing versions of, the current definition). Select the best performing interpretation as a baseline against which other methods will be compared.

vi) Assess the performance of each alternative method against this baseline.

vii) Produce a shortlist of methods for more detailed assessment against the selection criteria.

viii) Identify a preferred definition.

Selection criteria

The selection criteria to be used were agreed on through discussion with the UKWIR Project Steering Group and include the five criteria listed below. Note that “assessment period” refers to the period of time for which a compliance assessment (and thus a measure of DWF) is required. This was assumed to be a 12-month period not necessarily corresponding to a calendar year.

- **Applicability** – For what proportion of assessment periods can a method be calculated? Can a method still be calculated if a proportion of data in the assessment period is missing or invalid? Is there a need for rare rainfall conditions (as with the current definition), or can a method be calculated without the need for rainfall data at all?

- **Repeatability** – For a STW at which flows are expected to be stable year-on-year (no significant changes in drainage area population or industry for example) does a method give a value of DWF that is consistent from year to year? The current method may not, because the timing of dry periods (summer or winter) can significantly affect results.

- **Continuity** – Does the new method give results consistent with those of the baseline method (i.e. the current definition)? A new method should give results whose mean is not significantly different from the mean DWF of the baseline method.

- **Simplicity** – Is the new method easy to understand, and can it be easily calculated (manually in a spreadsheet, and with potential for automated calculation)?

- **Ready for implementation** – Does the method require further development before it can be implemented?

Alternative methods to be considered

A number of broad groups of DWF definition were considered as introduced in this section. Within each group, large numbers of method variations were produced by changing parameters such as percentiles.

Interpretations of the current method

The current definition of DWF varies between sources; also, there are ambiguities not covered in any of the current definitions that must be defined before the method can be applied. Listed below are some of the parameters that may change depending on the interpretation of the current definition.

- Whether to exclude flows at weekends and/or public holidays.

- Restrictions on the use of winter dry periods, and requirements for both summer and winter dry periods.

- The approach to be applied when combining results from multiple dry periods in a year or season.

- With dry periods continuing for more than 7 days should the flow be averaged over the whole dry period, the first 7 days or the last 7 days?

- Whether to relax the definition and allow a 6-day dry period to be used if there is no qualifying 7-day dry period.

Various combinations of the above were tested in order to select a "best" interpretation of the current method against which alternatives could be compared.

Variations on the current method

All existing versions of the current method, and any interpretations obtained by varying the factors discussed above, are based on the average flow in a 7-day period of rainfall not exceeding 0mm, preceded by a 7-day period (the "antecedent period") with rainfall not exceeding 0.25mm on any day. These numbers can be regarded as four parameters, with variations on the current method being obtained by changing their values.

Rainfall-dependent percentile methods

This group of methods is based on the National Water Council "median flow in dry weather" definition [3]:

"Within a selected period during which it is desired to record the characteristic flow of sewage, the median value of the total volume of sewage received during a period of 24 hours should be determined for all days on which the rainfall was less than or equal to 1.0mm."

This can be generalised to "the Mth percentile of flows on dry days". In the NWC method, M = 50, and a dry day is one having rainfall no more than 1.0mm.

At least one UK water company has defined a dry day to be a day of zero rainfall preceded by at least one day of zero rainfall. This suggests a generalised definition of dry day as “day with rainfall less than N mm, preceded by P days with rainfall less than Q mm”.

Different methods of this type can thus be obtained by varying the percentile M and the parameters N, P and Q.

Rainfall-independent percentile methods

Simpler than the percentile of flows on dry days is a percentile of flows on all days, with no consideration of rainfall. The EA have considered the 5th percentile of daily flows (i.e. the flow that is exceeded on 95% of days).

In a drainage area with a large proportion of the flow to the STW being weekday-only trade effluent, weekday flows will nearly always exceed weekend flows. For such STWs, it would be the case that low percentiles of all flows are effectively a measure of the weekend flow, and may be a poor guide for setting flow consents. Thus, the percentile of flows on weekdays only has been considered as well as the percentile of all daily flows.

Moving average methods

At least one company has used a method referred to as MAM-7 (Mean Annual Minimum 7) or SDMF (seven-day minimum flow) [4] where the DWF is taken to be the minimum over a year, of the 7-day moving average of daily flows.

A generalisation of this method is “the Mth percentile of the N-day moving average flow”.

Further parameters must be considered in this method, relating to calculation of the N-day moving average if there are gaps in the data.

Standard measures of central tendency

The following measures of central tendency were considered:

- **Mean** – a standard calculation, although variations such as excluding weekend flows were also considered.
- **Geometric mean** – again, a standard calculation.
- **Mode** – the most frequently observed flow. For continuous variables (such as sewage flow) the mode cannot be calculated exactly, because the exact value of the sewage flow on each day is observed only once; however, methods exist for estimating the mode based on clustering of flow values. Various estimates of the mode can be obtained and compared with other methods of calculating DWF.

Data

A total of 4,447 works-years of sewage flow data and 3,123 works-years of associated rainfall data were received for 1,515 STWs belonging to nine water and sewerage companies. These data were subject to various validation tests.

Sewage flow data

Flow data were automatically checked for null, zero and negative values, and for periods of constant or near-constant flows indicating measurement errors. Flows that were very low relative to those typical of the STW were assumed to be erroneous. Additional manual validations were applied where it was observed that DWF estimates were unrealistic.

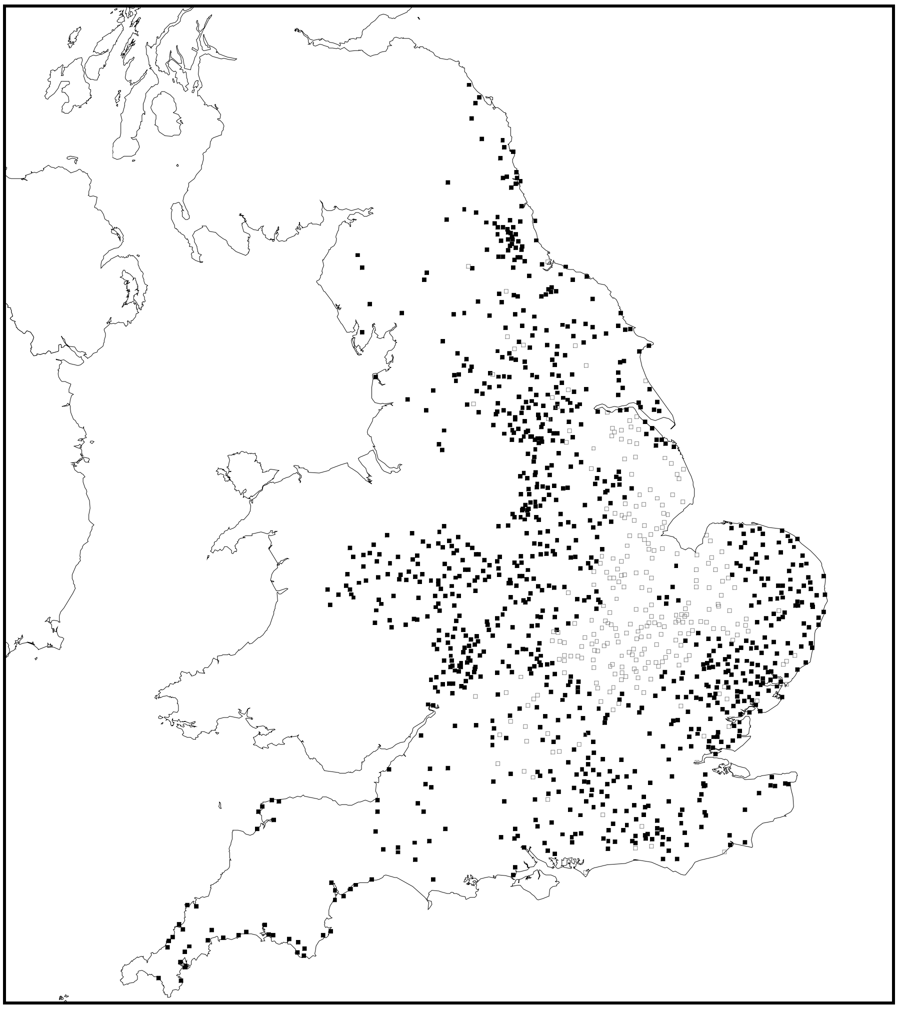
Rainfall data

Automatic checks of rainfall data involved first invalidating missing or negative values. Years where a rain gauge had a very high or very low proportion of rainy days were invalidated, as this indicated incomplete or interpolated data when a rain gauge was not read daily. Long periods of zero rainfall were inspected manually and if regarded as infeasible, were assumed to be missing data. As with flow data, additional manual validations were applied where unrealistic DWF estimates were observed. Finally, all summer dry periods were reviewed manually to check that sewage flows did not show behaviour consistent with localised rainfall within the STW catchment.

Data used

Only a very small proportion of the works-years of sewage flows and rainfall were free of invalid data. Restricting the analysis to these “perfect” data would involve discarding the majority of the data received, as well as being an unrealistic test of alternative methods. It was decided that works-years with at least 75% of the data valid would be passed forward for use in the analysis – this provides 3,266 works-years of flow data and 1,803 works-years of rainfall data. These data were derived from 1,302 STWs as illustrated in Figure 1.

Figure 1 - Geographical distribution of flow and rainfall data used in analysis



Key
■ = STWs with at least one 12-month period of combined flow and rainfall data used in the analysis.
□ = STWs with at least one 12-month period of flow data used in analysis, but no 12-month period of combined flow and rainfall data

Analysis tools

Producing DWF estimates

By changing method parameters, large numbers of methods (1,012 in total) were easily produced within each method type. In order to test these methods against the considerable quantities of effluent flow data provided, it was necessary to develop software to divide validated data into assessment periods and return DWF estimates. Manual checks were used to ensure calculations proceeded as intended.

Analysing the performance of methods

For each DWF estimation method, the DWF value, or an indication that a value could not be calculated, was produced for each works-year. Further software was used to combine the thousands of values to produce statistics for the methods quantifying their performance against the principal selection criteria. These statistics enabled large numbers of methods to be compared and a shortlist selected. Three such statistics are described below.

- **Success Rate** – This quantifies Applicability, and is the proportion of assessment periods with valid data, for which an estimate of DWF can be calculated.

- **Temporal Variability** – This quantifies Repeatability, and is a measure of the relative variation occurring in DWF estimates between different years at the same works. Temporal Variability is calculated by first normalising each DWF estimate by the mean DWF on that works, then pooling these values for all works and calculating their standard deviation.

- **GeoMean Ratio** – This quantifies Continuity. For each assessment period on a works where the new method and the baseline method both return a DWF estimate, the ratio between the estimates is calculated. GeoMean Ratio is the geometric mean of these ratios for every assessment period on every works. Values greater than 1 indicate that the new method overestimates DWF compared to the baseline method; values less than 1 indicate the new method underestimates DWF.

More detailed manual statistical analyses involving the use of (amongst others) scatterplots, correlation matrices, t-tests and ANOVAs, were used to judge these methods against further selection criteria. In particular, this was necessary to check for systematic biases, such as a method underestimating DWF (relative to the baseline) for large STWs, and overestimating it for small STWs.

Results of analysis

Findings are outlined here; more detailed results are contained in the UKWIR Project Report [5].

Selected baseline method

The current definition (as quoted in the Introduction) returns a DWF estimate for 62% of works-years with valid flow and rainfall data, and has a poor performance in terms of repeatability – DWF changes significantly from year to year at the same works.

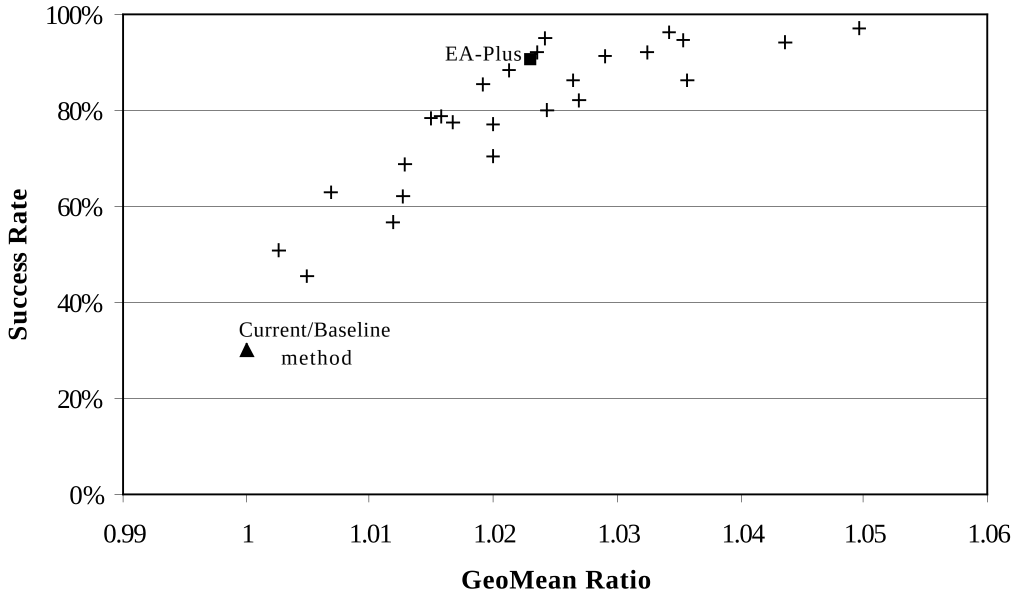
The best identified interpretation of the current method was one using summer dry periods only. DWF can be calculated for only 30% of valid works-years, but performance in terms of repeatability is improved. This method was used as the baseline method against which methods of other types could be compared where applicable.

Performance of other method types

- Starting with the baseline method and relaxing the rainfall requirements for a dry period, it was observed that much more applicable methods could be produced without changing the estimated DWF by more than a few percent. The best performing of these variations on the current method, referred to as “EA-Plus”, defines a dry period as “7 days of rainfall not exceeding 1 mm on any day, preceded by 3 days on which rainfall did not exceed 0.25 mm”. This method overestimates DWF by only 2% compared to the best interpretation of the current method, yet can be calculated for 90% of valid works-years with rainfall data. However, note that this method cannot be applied to the 45% of all valid works-years that lack accompanying rainfall data.

  Figure 2 compares variations on the current method. Methods with less strict rainfall requirements tend to have higher Success Rate but also greater GeoMean Ratio.

Figure 2 - Variations on the current method

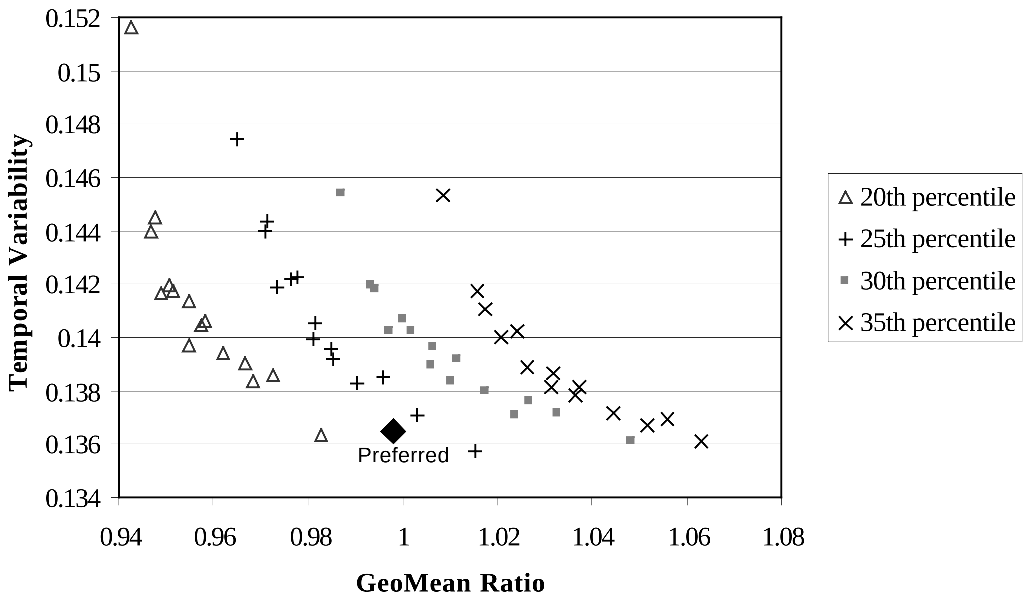


- Amongst rainfall-dependent percentile methods, it was found that the 25th percentile of flows on days with no more than 1 mm rainfall is in good agreement with the baseline method, and shows good repeatability (low Temporal Variability). This method can always be calculated provided the assessment period has adequate flow and rainfall data.

  The NWC method (median flow in dry weather) shows considerable disagreement with the current method; relative to the current method, it overestimates by 16%.

  Figure 3 shows some of the rainfall-dependent percentile methods including the preferred method of this type described above. For a given percentile, the methods with higher values of GeoMean Ratio tend to be those with less strict criteria for a dry day.

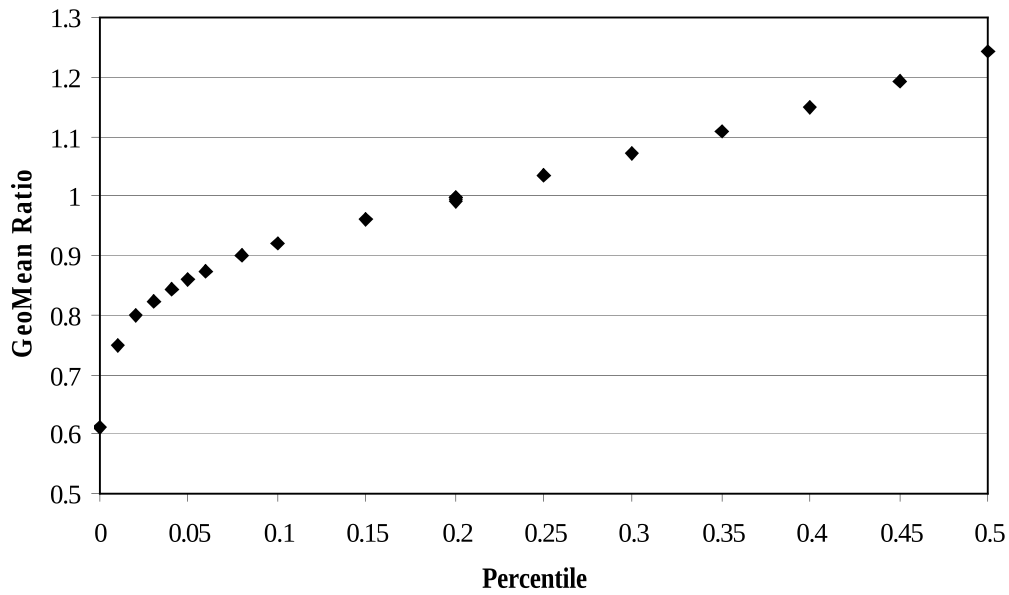
Figure 3 - Rainfall-dependent percentile methods



- Of the rainfall-independent percentile methods, the 20th percentile of all daily flows gives the closest agreement with the current method. The Temporal Variability is low compared to most percentiles, and lower than that of the current method. A DWF estimate is obtained as long as flow data are available, and without a need for rainfall data.

  The 20th percentile seems high in view of suggestions to use the 5th percentile of daily flows as a measure of DWF. However, applied to flow data available for this analysis, the 5th percentile was found to underestimate DWF by 14% compared to the current definition.

Figure 4 - Rainfall-independent percentile methods



- The preferred moving average method was the 15th percentile of the 7-day moving average of flows. This performs well in terms of Temporal Variability and continuity with the baseline method. Use of a 7-day moving average avoids effects caused by weekly flow patterns. Provided adequate flow data are available for a works-year, it is always possible to return a result.

  The MAM-7 method (the minimum 7-day moving average) underestimates DWF by 19% compared to the current method.

- The mean and geometric mean flows can be calculated for any assessment period with valid flow data, and show a low temporal variability. However, they overestimate DWF by around 40% and 30% respectively, and so would need to be used with a “correction factor”.

- The mode, estimated by clustering of effluent flow values, appears unreliable. It shows poor repeatability, and the GeoMean Ratio is heavily dependent on how the mode is estimated.

Comparing the best methods of each type against the selection criteria, and undertaking more detailed analysis such as checks for systematic bias, the 20th percentile of daily flows was identified as the most appropriate replacement for the current definition of DWF.

Implementation of new method

Following the results of the analysis undertaken for UKWIR and described in this paper, water companies and the EA are now discussing use of the 20^{th} percentile as the new measure of DWF. In implementing this approach, certain issues must be considered including the following:

- **The compliance testing window** – It is expected that flow compliance assessment will be based on flows over a calendar year or rolling 12-month period.
- **Completeness of the flow data used** – The 20^{th} percentile will still return a value even if only a very small proportion of data in a 1-year period are valid. Conditions must be set stating the minimum completeness of data for which the derived DWF can be regarded as meaningful.
- **Works exceeding DWF consents and changes to consents** – Applying the current method nearly a third of works exceed their DWF consent, and this figure is similar when applying the 20^{th} percentile. Further analysis suggests that many consent exceedences may result from inappropriate consent settings. Investigation will be needed to find out where this is the case, and to distinguish consent exceedences that reflect genuine breaches of environmental standards.
- **Recognition of uncertainty** – Estimating a percentile of the long-term flow distribution from a set of observed flows has an unavoidable uncertainty, and it is thus possible for a STW to be mistakenly judged as exceeding its consented flow. It is recommended that the compliance assessment includes recognition of this uncertainty through use of a confidence interval or equivalent approach.

Acknowledgements

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