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LOW FLOW ESTIMATION IN ARTIFICIALLY INFLUENCED CATCHMENTS TRAINING COURSE

Report 3

Estimating Artificially Influenced Low Flow Statistics

Preface

This Manual describes procedures for adjusting natural low flow statistics at ungauged sites where significant human activities influence the flow characteristics. Reference should be made to Report No. 1 for details of how to derive the natural low flow statistics and Report No. 2 for details of how to define the cumulative impact of artificial influence above a site. Report No. 4 describes the Micro LOW FLOWS V2.1 Software package which has been developed to automatically estimate and adjust low flow statistics at ungauged locations.

Contents

1. Introduction

The estimation of low flow statistics is a major component in the determination of minimum acceptable flows, the issue of abstraction licences and discharge consents and the setting of compensation releases from reservoirs. Four methods of low flow estimation are commonly applied by the UK water industry.

1. Calculation of low flow statistics from continuous gauged flow data series.

2. Direct measurement of low flows at "ungauged" sites by an occasional programme of "spot" current meter measurements.

3. Estimation of time series of river flows using catchment-specific hydrological models.

4. Estimation of low flow statistics by multivariate models which relate low flows to catchment characteristics.

Where continuous flow data are available at the design site of interest method 1 is the most accurate and preferred technique. However, design information is generally required at ungauged locations and method 2, or more commonly, flow estimation procedures (methods 3 or 4) must be used.

The project Low Flow Estimation in Artificially Influenced Catchments (NRA Report R&D report 274, Bullock et al, 1994) addressed the problem of assessing artificial influences on low flows and developed practical design techniques for low flow estimation in artificially-influenced catchments within the Micro LOW FLOWS software.

1.1 THE IMPACT OF ARTIFICIAL INFLUENCES ON LOW FLOWS

In natural rivers, the magnitude of low river flows are determined by climatic and runoff generation processes, amongst which effective rainfall, groundwater recharge and aquifer properties exert a dominant function (Gustard et al., 1992). However, as a result of the development of rivers and catchments for water resource purposes, few rivers now possess natural river flow regimes.

The early development of river regulation began in the late 18th Century initially for navigation requirements and later to meet the growing demands of population centres. In upland areas small rivers were impounded to create reservoirs to store winter high flows to supplement summer low flows. The rate of large dam-building accelerated after 1950. The demands of the electricity industry, requiring water for cooling, and agriculture for irrigation have continued to grow. Since 1965 the emphasis in water management has been on direct river management, with reservoirs, abstractions, water treatment and inter-basin transfers providing for the integrated management of water resources.

As a consequence of this level of water development, many rivers in England and Wales exhibit artificially influenced river flow regimes and few rivers display natural flow characteristics.

The impact of man's development of water is most severe during periods of low flows when absolute volumes of water transfers represent a significantly higher proportion of the natural flow regime. As a broad indication of the extent of artificial influences upon low flows, fewer than 20% of the gauged flow regimes, represent 'natural' conditions.

In addition, many artificial influences may operate seasonally, for example abstractions for spray irrigation. As a consequence it is necessary to consider estimation of low flow statistics on a monthly basis.

1.2 SUMMARY OF OVERALL METHOD

The objective of the project was to estimate low flow statistics at ungauged sites in artificially influenced catchments, considering abstractions from surface and groundwater sources, discharges to surface water and compensation flows from impounding reservoirs. The overall methodology at an ungauged site can be summarised as follows:

1. Estimation of key natural low flow statistics at the ungauged site; specifically mean flow, monthly mean flow, monthly flow duration curves and mean monthly minima.

2. Identification of all artificial influences upstream of the ungauged site.

3. Quantification for all individual artificial influences upstream of actual values of monthly abstraction rates, discharge returns and reservoir compensation flows.

4. Simulation using the Theis analytical solution of the reduction in streamflow associated with abstractions from groundwater sources according to source and aquifer properties.

5. Construction of a monthly artificial influence profile at the ungauged site which represents the net impact of all upstream artificial influences.

6. Combination of the estimated natural monthly low flow statistics with the monthly artificial influence profile to estimate artificially influenced monthly low flow statistics.

7. Aggregation of monthly artificially influenced low flow statistics to produce annual artificially influenced low flow statistics for design purposes, notably mean flow, flow duration curves and low flow frequency statistics.

8. Estimation of natural and artificially influenced low flow statistics at numerous locations along a river to construct residual flow diagrams.

The overall methodology has been incorporated within Micro LOW FLOWS (Version 2.1) for automated application, although the methods could also be applied manually.

1.3 LOW FLOW ESTIMATION MANUALS

This Manual is the third in the series which describes the estimation of artificially influenced low flow statistics in ungauged catchments, based on combination of estimated natural monthly low flow statistics and cumulative monthly influence profiles, with application of the Theis solution for groundwater abstractions. Report No.1 described procedures for estimating natural low flow statistics on a monthly timescale. Methods for developing monthly influence profiles were described in Report No. 2. The implementation of the above estimation procedures within Micro LOW FLOWS is described in Report No.4.

Within this manual, Section 2 summaries the estimation of artificially influenced low flow statistics, Section 3 describes the methods for adjusting the low flow statistics and Section 4 describes the implementation of these techniques within Micro LOW FLOWS.

To help explain the estimation techniques in this report worked examples have been included in Appendix A using data for the Pang catchment. Syndicate exercises are provided for the Roman catchment to allow the reader to work through the procedures.

2. Estimation of Artificially Influenced Low Flow Statistics

Methods have been developed for the estimation of natural annual low flow statistics at ungauged sites; these are published in Gustard et al., 1992 and are presented in the course Introduction to Low Flow Hydrology. Methods for estimating low flow statistics in artificially influenced catchments are based on the estimation of monthly low flow statistics and monthly influence profiles which reflect the seasonal variability of the magnitude and sensitivity of flows to artificial influences.

The overall methodology for the estimation of artificially influenced low flow statistics at an ungauged site comprises four principal steps, as follows:

1. Estimation of natural low flow statistics at the ungauged site, specifically mean flow, monthly mean flow, twelve monthly flow duration curves and twelve mean monthly minima using the techniques described in Report 1 of this course;

2. Construction of a cumulative monthly artificial influence profile at the ungauged site which represents the nett impact of all upstream artificial influences. This involves:

    (i) identification of all artificial influences upstream of the ungauged site;

    (ii) quantification of actual or predicted values of mean monthly abstraction rates, discharges and reservoir releases. In the case of groundwater abstractions this involves estimating the reduction in streamflow by the application of the Theis analytical solution according to source and aquifer properties (Refer to Report 2);

3. Combination of the estimated natural low flow statistics with the monthly artificial influence profile to estimate artificially influenced monthly low flow statistics (Refer to Report 2);

4. Aggregation of monthly artificially influenced statistics to produce annual artificially influenced low flow statistics for design purposes (Refer to Report 2).

This report describes the methods for adjusting the natural low flow statistics once the requisite natural monthly flow statistics and cumulative influence profiles have been estimated.

3. Adjusting natural low flow statistics

Once the natural low flow statistics have been derived and the upstream artificial influence profile has been identified, adjustment can be made to the natural monthly low flow statistics. Once the monthly flow statistics have been adjusted to reflect the impact of upstream influences these adjusted monthly statistics can be recombined to estimate the annual artificially influenced statistics presented by Micro LOW FLOWS V2.1. The adjustment procedure for individual statistics is now presented in more detail.

3.1 MEAN FLOWS

The estimation of artificially influenced Mean Monthly Flows (MMF) and the subsequent recombining of these flows to yield an influenced annual mean flow consists of three steps:

1. The cumulative monthly influence profiles for upstream influences at the site are applied to the corresponding estimated values of MMF to calculate twelve values of artificially influenced monthly mean flows;

2. Depending on the sign of the artificial influences adjustments (which may vary between months), the MMF for each month may be reduced (if abstractions or impounding reservoirs dominate) or increased (if discharges dominate);

3. The artificially influenced annual mean flow is calculated as the average of the twelve adjusted monthly flows, weighted by the number of days in each month.

The adjustment procedure applied to the monthly mean flows is described in more detail below.

Consider a catchment with (m) abstraction licences, (m) discharge consents and one impounding reservoir. Each abstraction licence and discharge consent may have (n) sites associated with it, where (n) has a maximum value of 20. Furthermore, it can be assumed that some of these sites may be located downstream (DS) of the reservoir site and some may be located upstream of the impoundment (UI). Considering the kth month within the year, the estimated natural monthly mean flow (NAT_kMF_{RS}) at the reservoir site is subtracted from the estimated natural monthly mean flow at the design site (NAT_kMF_{DS}) and the monthly reservoir release (RR_k) is added to the NAT_kMF_{DS}, i.e The reservoir influence algorithm for the adjustment of monthly mean flow is:

$$INF_kMF_{DS} = NAT_kMF_{DS} - NAT_kMF_{RS} + RR_k$$

When abstractions and discharges downstream of the impoundment are included, the overall artificial influence algorithm for monthly mean flow becomes:

$$INF_kMF_{DS} = (NAT_kMF_{DS} - NAT_kMF_{RS}) + RR_k + (DIS_{kDS} - DIS_{kUI}) - (ABS_{kDS} - ABS_{kUI})$$

where: DIS_{kDS} = the sum of all discharges above the design site,
DIS_{kUI} = the sum of those discharges above the reservoir site.
ABS_{kDS} = the sum of all abstractions above the design site,
ABS_{kUI} = the sum of those abstractions above the reservoir site.

In general DIS_K at a site is indexed by:

$$\sum_{j=1}^{m}\sum_{i=1}^{n} \text{SCAMTH(i,k) if actual discharge data exist}$$

$$\text{or } \sum_{j=1}^{m}\sum_{i=1}^{n} \text{SCPMTH(i,k) if predicted discharge data are used}$$

where: SCAMTH (i,k) = actual monthly discharges for month (k) at site (i)
SCPMTH (i,k) = predicted monthly discharges for month (k) at site (i)
and there are (m) discharge consents each with (n) sites.

and ABS_k , at a site is indexed by:

$$\sum_{j=1}^{m}\sum_{i=1}^{n} \text{SACTMTH(i,k) if actual abstraction data exist}$$

$$\text{or } \sum_{j=1}^{m}\sum_{i=1}^{n} \text{SPRETMTH(i,k) if predicted abstraction data are used}$$

where: SACTMTH (i,k) = actual monthly abstraction quantities for site (i) in month (k)
SPREMTH (i,k) = predicted monthly abstraction quantities for site (i) in month (k)
and there are (m) abstraction licences each with (n) sites.

The artificially influence annual mean flow is then calculated as the weighted mean of the twelve values of INF_kMF_{DS} (where k = 1 to 12).

However, in the case of a catchment containing an impounding reservoir, influences above the reservoir site are excluded and the monthly reservoir release profiles (RR_k) replace the natural or artificial flow regime at the reservoir site.

3.2 FLOW DURATION CURVE

The estimation of 12 monthly flow duration curves, scaled by MMF and fitted to the annual flow duration curve, is a pre-requisite to estimating the impact of the artificial influence profile, at a site, on the annual flow duration curve. The estimation of the artificially influence annual flow duration curve consists of three steps:

1. The 360 flow values (expressed in $m^3\ s^{-1}$) are adjusted by the monthly artificial influence profile, ie. the 30 flow values constituting the monthly FDC for each month are adjusted by the nett artificial influence for that month;

2. The flow values are then ranked in order of magnitude and an exceedance probability, P_n, for each flow is calculated based on the rank, given by the equation:

$$P_n = X_n \times \frac{100}{360}$$

where X_n is the rank of the nth largest flow value;

3. The annual artificially influenced flow duration curve is the resultant distribution derived by plotting the flows against the corresponding percentile

The adjustment of the individual monthly flow duration curves is now presented in more detail considering the same catchment configuration as for the estimation of artificially influenced MMFs.

The estimated natural monthly flow duration curve is represented by 30 flows at equal probability intervals at both the design site (NAT_kFDC_{DS}) and the reservoir site (NAT_kFDC_{RS}). The reservoir release in month (k) is represented by RR_k as before. The reservoir influence algorithm for adjustment of monthly (k) flow duration curve is:

$$INF_kFDC_{DS} = NAT_kFDC_{DS} - NAT_kFDC_{RS} + RR_k$$

Further adjustments are made for abstractions and discharges downstream of the impoundment. The overall artificial influence algorithm for the monthly flow duration curve in month (k) is given by:

$$INF_kFDC_{DS} = (NAT_kFDC_{DS} - NAT_kFDC_{RS}) + RR_k + (DIS_{kDS} - DIS_{kUI}) - (ABS_{kDS} - ABS_{kUI})$$

3.3 MONTHLY MINIMA

1. Estimates of MMM(7) are combined with the monthly artificial influence profile; in other words, the MMM(7) for each month is adjusted by the nett artificial influence for that month in an identical way to the adjustment of Monthly Mean Flows.

2. In certain circumstances, this may result in negative flow values for certain months which should be set to equal zero. The output of this activity is 12 values of artificially influenced MMM(7).

3. If an estimate of MAM(7) is required, then in the absence of more complex solutions involving time series simulations, MAM(7) should be assumed to equal the lowest of all 12 values of artificially influenced MMM(7). In all circumstances, adoption of this assumption will overestimate the true value of MAM(7) (because in time series MAM(7) represents the mean of minima occurring in different months, which must by definition be less than the mean of minima selected from the same month).

4. Micro LOW FLOWS Implementation

Micro LOW FLOWS V2.1 generates estimates of low flow statistics (natural and artificial) of two general types:

i) as estimates pertaining to a single stretch of river, termed single stretch estimates;

ii) as residual flow diagrams which graphically represent the accumulation of flow estimates along the profile of a river.

4.1 SINGLE STRETCH ESTIMATES

Micro LOW FLOWS allows, in principle, natural and artificially influenced low flow statistics to be estimated at over 150 000 individual stretches of river in England and Wales, as defined by the river network digitised from 1:50 000 topographic maps. Micro LOW FLOWS is set up on a regional basis as defined by the administrative Regions of the National Rivers Authority, and the number of river stretches varies between these Regions.

Micro LOW FLOWS generates estimates of the following low flow statistics and measures:

NATURAL	ARTIFICIAL
Mean flow (MF) (in $m^3 s^{-1}$)	Mean flow (MF) (in $m^3 s^{-1}$)
Flow duration curve (as % of MF)	Flow duration curve (as % of influenced MF)
Q95 (in $m^3 s^{-1}$ and as % of MF)	Q95 (in $m^3 s^{-1}$ and as % of influenced MF)
Other percentiles (in $m^3 s^{-1}$)	Other percentiles (in $m^3 s^{-1}$)
MAM(7) (in $m^3 s^{-1}$ and as % of MF)	MAM(7) (in $m^3 s^{-1}$ and as % of influenced MF)
MAM(D) (in $m^3 s^{-1}$)	MMM(7) (in $m^3 s^{-1}$)
Low flow frequency curve (in $m^3 s^{-1}$)	

Natural and artificially influenced estimates of mean flow, flow duration curve, Q95 (and other percentiles) and MAM(7) are presented simultaneously on screen and hardcopy outputs. Micro LOW FLOWS has full capabilities of generating tabular and graphical outputs to designated peripheral devices. In addition, monthly artificial influence profiles are displayed numerically on screen. In all cases, estimates and profiles correspond to the downstream end of river stretches.

4.2 RESIDUAL FLOW DIAGRAMS

A residual flow diagram represents a hydrological "snapshot" of the total quantity of water in a river or stream for any location on the river for a chosen flow condition. The diagram illustrates the relative composition of flow at any point in terms of natural and artificial components.

Origins of the residual flow diagrams remain untraced. However, the framework of the residual flow diagram was implemented by the Mersey and Weaver River Authority as part of the Periodical Survey undertaken in 1969 following the Water Resources Act, 1963. It was recognised that in many rivers, the artificial component of the flow overwhelmed the natural flow component during periods of dry weather, thereby influencing quality planning. A method of flow dissection was developed such that the artificial and natural components could be represented graphically as the residual flow diagram. An idealised residual flow diagram is illustrated in Figure 4.1 whereby flows, both natural and artificial, are accumulated as distance from the source increases and the residual flow is calculated as the distance (in flow units) between the natural and artificial flow components on the diagram.

The principal structure of the residual flow diagram comprises a vertical axis which represents the line of the principal channel. Distance from source, or any other starting point, is measured downwards from the top of the axis. The horizontal axis represents the total flow of the river (measured in Ml d^{-1} or $m^3\ s^{-1}$). The flow is separated into two components: the natural flow component is on the left of the vertical axis; the artificial component spans the full width of the axis with net gains (positive) on the right of the vertical axis and net losses (negative) on the left. The units used for the abstractions and discharges will be the same as for the natural flows. The residual flow is calculated as the sum of the natural and artificial flow components.

The natural flow component can be represented by a choice of natural flow statistics, for example the mean flow, a flow with a chosen flow percentile, e.g. Q95 or a minimum flow for a given duration or return period e.g. MAM(7). However, rarely was it possible to modify the artificial component to represent water use activity under low flow as opposed to average conditions.

The structure and presentation of the residual flow diagram has been modified for implementation within Micro LOW FLOWS, in which the horizontal axis represents positive or negative flow contributions. The natural and residual flows are always positive or zero and the artificial flow component may be positive (discharges) or negative (abstractions). The graphical presentation of the residual flow diagram within Micro LOW FLOWS is illustrated in Figure 4.2.

Residual flow diagrams may be constructed within Micro LOW FLOWS for different low flow statistics, and are constructed as follows, using the example of the Q95 statistics.

1. Natural Q95 is estimated for each river stretch;

2. Artificially influenced Q95 is estimated for each river stretch. This is termed the residual flow Q95;

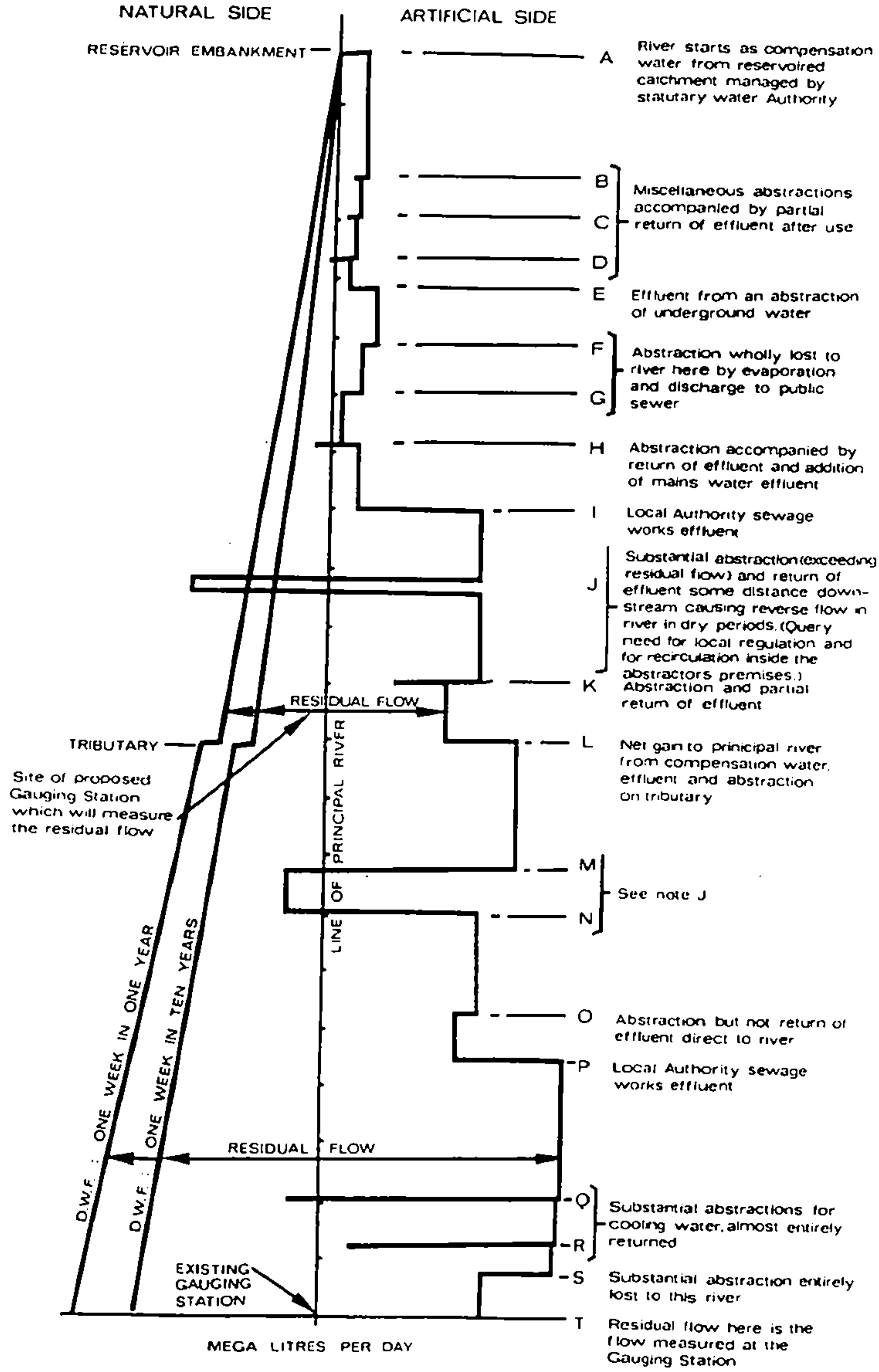

Figure 4.1 *Idealised residual flow diagram (from Mersey & Weaver River Authority, 1969)*

3. Artificial component = residual flow Q95 - natural Q95.

Hence, the artificial flow component is positive where the residual flow Q95 exceeds the natural Q95 (in the case of discharge impacts being greater than abstraction impacts upstream) and negative when residual flow Q95 is less than the natural Q95 (that is where abstraction impacts are greater than discharge impacts upstream). Clearly, the artificial component can be zero when there are no upstream influences or the impacts of the influences balance to zero;

4. Plot natural Q95, residual flow Q95 and artificial component against distance downstream.

It should be noted that this method of construction differs from the traditional method discussed above. As illustrate in Figure 4.1 the traditional method would equate to

Residual flow Q95 = natural Q95 + artificial components

on the basis that the artificial component for a ***given flow condition*** can be quantified. However, this is rarely ever the case and represented a major limitation of this type of diagram. The modified residual flow diagram construction method in this report estimates the residual flow Q95 directly. The artificial component is calculated as a by-product and will vary between different flow conditions.

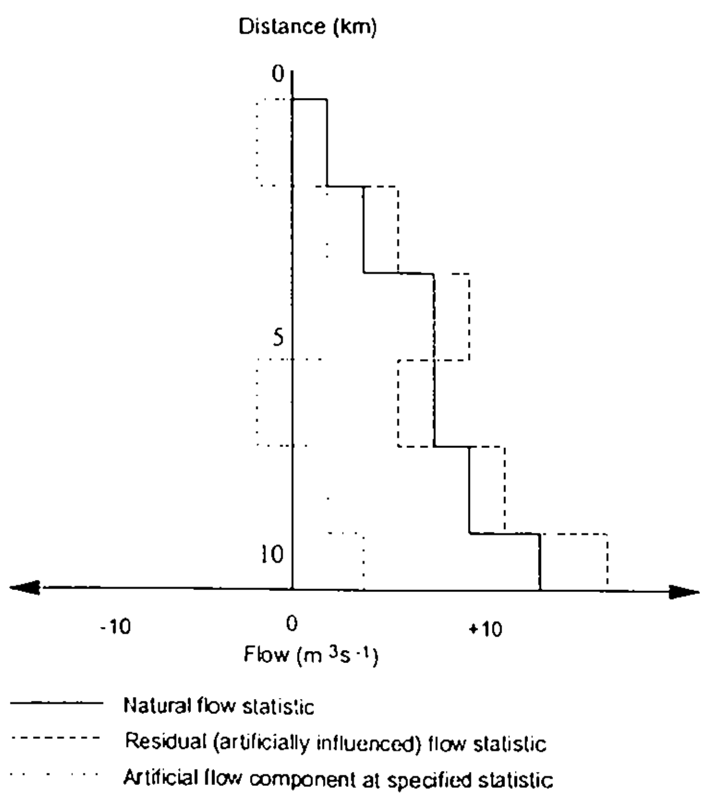

Figure 4.2 Residual flow diagram within Micro LOW FLOWS

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APPENDIX A

LOW FLOW ESTIMATION IN ARTIFICIALLY INFLUENCED CATCHMENTS TRAINING COURSE

SYNDICATE EXERCISE

ESTIMATION OF THE ARTIFICIALLY INFLUENCED FLOW DURATION CURVE

Estimation of the Artificially Influenced Flow Duration Curve

The objective of this exercise is to estimate an artificially influenced flow duration curve. This exercise combines the results of Syndicate Exercises on the Estimation of Natural Low Flow Statistics and Construction of Monthly Influence Profiles.

The general procedure will be as follows:

1. For each month, adjust the 30 daily flows by the nett artificial influence (Tables 1a-b and 2a-b).

2. Combine the influenced flow values in each month which represents 360 values (Tables 3a and 3b).

3. The distribution of the artificially influenced flows will be different to the natural flows, therefore it is necessary to rank artificially influenced flows as before. (Tables 4a and 4b).

4. Plot the natural and artificially influenced annual flow duration curves.

1. ESTIMATION OF ARTIFICIALLY INFLUENCED MONTHLY FLOW DURATION CURVE

Using the following tables, collate data on both the natural monthly flow duration curve and the monthly influence profile for the months of April and August. For the Pang catchment, an April influence of -0.15 m^3s^{-1} and an August influence of -0.25m^3s^{-1} are assumed. For the Roman, use the nett total of Abstractions A, B and STW C. Estimate the artificially influenced flow by combining the nett monthly influence and the natural flow estimates for each percentile.

Draw two sets of flow duration curves for the River Roman, one set for April and one set for August, which illustrate both the natural and the artificially influenced flow duration curves.

Table 1a *River Pang: April*

(a) %ile	(b) natural flow	(c) nett mthly influence	(d) artificial flow
2	2.7	-0.15	2.55
5.3	2.17	-0.15	2.02
8.7	1.99	-0.15	1.84
12	1.78	-0.15	1.63
15.4	1.62	-0.15	1.47
18.7	1.54	-0.15	1.39
22	1.43	-0.15	1.28
25.4	1.37	-0.15	1.22
28.7	1.29	-0.15	1.14
32.1	1.22	-0.15	1.07
35.4	1.15	-0.15	1.00
38.8	1.09	-0.15	0.94
42.1	1.06	-0.15	0.91
45.5	1.02	-0.15	0.87
48.2	0.98	-0.15	0.83
52.2	0.95	-0.15	0.80
55.5	0.91	-0.15	0.76
58.8	0.89	-0.15	0.74
62.2	0.86	-0.15	0.71
65.5	0.84	-0.15	0.69
68.9	0.79	-0.15	0.64
72.2	0.78	-0.15	0.63
75.6	0.75	-0.15	0.60
79	0.71	-0.15	0.56
82.3	0.68	-0.15	0.53
85.6	0.64	-0.15	0.49
89	0.6	-0.15	0.45
92.3	0.55	-0.15	0.40
95.6	0.5	-0.15	0.25
99	0.37	-0.15	0.22

Table 1b *River Pang: August*

(a) %ile	(b) natural flow	(c) nett mthly influence	(d) artificial flow
2	1.13	-0.25	0.88
5.3	0.92	-0.25	0.67
8.7	0.82	-0.25	0.57
12	0.74	-0.25	0.49
15.4	0.69	-0.25	0.44
18.7	0.65	-0.25	0.4
22	0.62	-0.25	0.37
25.4	0.59	-0.25	0.34
28.7	0.56	-0.25	0.31
32.1	0.53	-0.25	0.28
35.4	0.52	-0.25	0.27
38.8	0.49	-0.25	0.24
42.1	0.48	-0.25	0.23
45.5	0.46	-0.25	0.21
48.8	0.44	-0.25	0.19
52.2	0.42	-0.25	0.17
55.5	0.4	-0.25	0.15
58.8	0.39	-0.25	0.14
62.2	0.37	-0.25	0.12
65.5	0.36	-0.25	0.11
68.9	0.34	-0.25	0.09
72.2	0.33	-0.25	0.08
75.6	0.32	-0.25	0.07
79	0.3	-0.25	0.05
82.3	0.29	-0.25	0.04
85.6	0.27	-0.25	0.02
89	0.24	-0.25	-0.01(assume 0.00)
92.3	0.23	-0.25	-0.02(assume 0.00)
95.6	0.19	-0.25	-0.06(assume 0.00)
99	0.18	-0.25	-0.07(assume 0.00)

Notes 1. Natural flows and percentiles are read from Table 14a of Syndicate Exercise 1 NB these are the adjusted flows

2. The nett influence is identified from previous page

3. Artificially influenced flow = col (b) + col (c)

Table 2a *River Roman: April*

(a) %ile	(b) natural flow	(c) nett mthly influence	(d) artificial flow
2.0			
5.3			
8.7			
12.0			
15.4			
18.7			
22.0			
25.4			
28.7			
32.1			
35.4			
38.8			
42.1			
45.5			
48.2			
52.2			
55.5			
58.8			
62.2			
65.5			
68.9			
72.2			
75.6			
79.0			
82.3			
85.6			
89.0			
92.3			
95.6			
99.0			

Table 2b *River Roman: August*

(a) %ile	(b) natural flow	(c) nett mthly influence	(d) artificial flow
2.0			
5.3			
8.7			
12.0			
15.4			
18.7			
22.0			
25.4			
28.7			
32.1			
35.4			
38.8			
42.1			
45.5			
48.8			
52.2			
55.5			
58.8			
62.2			
65.5			
68.9			
72.2			
75.6			
79.0			
82.3			
85.6			
89.0			
92.3			
95.6			
99.0			

Notes 1. Natural flows and percentiles are read from Table 14b of Syndicate Exercise NB these are the adjusted flows

2. The nett influence is identified from Table 7 of Syndicate Exercise 2

3. Artificially influenced flow = col (b) + col (c)

Draw two sets of flow duration curves for the River Roman, one set for April and one set for August, which illustrate both the natural and the artificially influenced flow duration curves.

2. COMPILATION OF THE ARTIFICIALLY INFLUENCED FLOWS

Example for Pang assuming the monthly influences given below:

Table 3a River Pang

Rank	%ile	Estim. Annual FDC	Mth Flag	Mthly Nett Influence	A.I Flow	Rank	%ile	Estim. Annual FDC	Mth Flag	Mthly Nett Influence	A.I Flow
303	84.17	0.40	9	-0.18	0.22	332	92.22	0.31	5	-0.18	0.13
304	84.44	0.40	3	0.00	0.40	333	92.50	0.30	8	-0.25	0.05
305	84.72	0.39	7	-0.27	0.12	334	92.78	0.30	7	-0.27	0.03
306	85.00	0.39	6	-0.25	0.14	335	93.06	0.30	9	-0.18	0.12
307	85.28	0.39	8	-0.25	0.14	336	93.33	0.29	6	-0.25	0.04
308	85.56	0.38	9	-0.18	0.20	337	93.61	0.29	8	-0.25	0.04
309	85.83	0.38	7	-0.27	0.11	338	93.89	0.28	10	0.00	0.28
310	86.11	0.38	10	0.00	0.38	339	94.17	0.28	7	-0.27	0.01
311	86.39	0.38	12	0.00	0.38	340	94.44	0.28	9	-0.18	0.10
312	86.67	0.37	8	-0.25	0.12	341	94.72	0.27	8	-0.25	0.02
313	86.94	0.37	4	-0.15	0.22	342	95.00	0.27	12	0.00	0.27
314	87.22	0.37	9	-0.18	0.19	343	95.28	0.26	10	-0.00	0.26
315	87.50	0.36	7	-0.27	0.09	344	95.56	0.26	7	-0.27	0.00
316	87.78	0.36	8	-0.25	0.11	345	95.83	0.25	11	0.00	0.25
317	88.06	0.36	6	-0.25	0.11	346	96.11	0.25	9	-0.18	0.07
318	88.33	0.35	10	0.00	0.35	347	96.39	0.24	8	-0.25	0.00
319	88.61	0.35	9	-0.18	0.17	348	96.67	0.24	7	-0.27	0.00
320	88.89	0.35	7	-0.27	0.08	349	96.94	0.23	10	0.00	0.23
321	89.17	0.34	8	-0.25	0.09	350	97.22	0.23	8	-0.25	0.00
322	89.44	0.34	11	0.00	0.34	351	97.50	0.22	9	-0.18	0.04
323	89.72	0.34	9	-0.18	0.16	352	97.78	0.22	6	-0.25	0.00
324	90.00	0.33	7	-0.27	0.06	353	98.06	0.21	7	-0.25	0.00
325	90.28	0.33	10	0.00	0.33	354	98.33	0.20	10	0.00	0.20
326	90.56	0.33	8	-0.25	0.08	355	98.61	0.19	8	-0.25	0.00

Jan	$0.00m^3s^{-1}$	Apr	$-0.15m^3s^{-1}$	Jul	$-0.27m^3s^{-1}$	Oct	$0.00m^3s^{-1}$
Feb	$0.00m^3s^{-1}$	May	$-0.18m^3s^{-1}$	Aug	$-0.25m^3s^{-1}$	Nov	$0.00m^3s^{-1}$
Mar	$0.00m^3s^{-1}$	Jun	$-0.25m^3s^{-1}$	Sep	$-0.18m^3s^{-1}$	Dec	$0.00m^3s^{-1}$

The following Table presents the low flow end of the natural annual flow duration curve for the River Roman. Complete the two empty columns.

Table 3b *River Roman*

Rank	%ile	Estim. Annual FDC	Mth Flag	Mthly Nett Influence	A.I Flow	Rank	%ile	Estim. Annual FDC	Mth Flag	Mthly Nett Influence	A.I Flow
303	84.17	.03	8			332	92.22	.02	8		
304	84.44	.03	7			333	92.50	.02	7		
305	84.72	.03	6			334	92.78	.02	6		
306	85.00	.03	9			335	93.06	.02	7		
307	85.28	.03	10			336	93.33	.02	8		
308	85.56	.03	7			337	93.61	.02	9		
309	85.83	.03	8			338	93.89	.02	10		
310	86.11	.03	6			339	94.17	.02	7		
311	86.39	.02	7			340	94.44	.02	8		
312	86.67	.02	9			341	94.72	.02	6		
313	86.94	.02	8			342	95.00	.02	7		
314	87.22	.02	10			343	95.28	.01	9		
315	87.50	.02	6			344	95.56	.01	8		
316	87.78	.02	7			345	95.83	.01	7		
317	88.06	.02	11			346	96.11	.01	10		
318	88.33	.02	8			347	96.39	.01	6		
319	88.61	.02	9			348	96.67	.01	8		
320	88.89	.02	7			349	96.94	.01	9		
321	89.17	.02	6			350	97.22	.01	7		
322	89.44	.02	10			351	97.50	.01	8		
323	89.72	.02	8			352	97.78	.01	7		
324	90.00	.02	7			353	98.06	.01	8		
325	90.28	.02	9			354	98.33	.01	6		
326	90.56	.02	5			355	98.61	.01	7		
327	90.83	.02	8			356	98.89	.01	10		
328	91.11	.02	6			357	99.17	.01	8		
329	91.39	.02	7			358	99.44	.01	9		
330	91.67	.02	10			359	99.72	.01	7		
331	91.94	.02	9			360	100.00	.01	8		

3. ESTIMATION OF THE ARTIFICIALLY INFLUENCED ANNUAL FLOW DURATION CURVE

Having collated the adjusted flows, for each month, it is necessary to rank the artificially influenced flows. Table 4a shows the lowest 30 flows for the Pang. Complete Table 4b for the Roman.

Table 4a *Pang*

Rank	Percentile	Articially Influenced Flow
331	91.94	0.11
332	92.22	0.11
333	92.50	0.11
334	92.78	0.1
335	93.06	0.09
336	93.33	0.09
337	93.61	0.08
338	93.89	0.08
339	94.17	0.07
340	94.44	0.07
341	94.72	0.07
342	95.00	0.06
343	95.28	0.05
344	95.56	0.05
345	95.83	0.04
346	96.11	0.04
347	96.39	0.04
348	96.67	0.03
349	96.94	0.02
350	97.22	0.01
351	97.50	0.00
352	97.78	0.00
353	98.06	0.00
354	98.33	0.00
355	98.61	0.00
356	98.89	0.00
357	99.17	0.00
358	99.44	0.00
359	99.72	0.00
360	100.0	0.00

Table 4b *Roman*

Rank	Percentile	Artificially Influenced Flow
331	91.94	
332	92.22	
333	92.50	
334	92.78	
335	93.06	
336	93.33	
337	93.61	
338	93.89	
339	94.17	
340	94.44	
341	94.72	
342	95.00	
343	95.28	
344	95.56	
345	95.83	
346	96.11	
347	96.39	
348	96.67	
349	96.94	
350	97.22	
351	97.50	
352	97.78	
353	98.06	
354	98.33	
355	98.61	
356	98.89	
357	99.17	
358	99.44	
359	99.72	
360	100.0	

Draw the lower portion of the natural and artificially influenced annual flow duration curve for the River Roman (plot only the lowest 30 flow values). Comment on the differences.