

BRITISH HYDROLOGICAL SOCIETY

An Introduction to Operational Control Rules using the 10-Component Method

by

ALLAN LAMBERT

BHS Occasional Paper No. 1

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Preface

Most large complex water resources systems (WRSs) already use control rules, often derived after extensive research by specialist groups or consultants. Clearly, the wider use of practical control rules for all types and sizes of WRS can be expected to confer extra benefits and help to reduce the chances of avoidable mismanagement. However, in the Author's experience, many operations personnel responsible for management of WRSs are either:

i) unaware how control rules can assist operations management;
or ii) regard the derivation or modification of control rules as a specialist function, too complex for them to understand or contribute to.

During the 1984 drought in parts of the U.K., many systems without control rules experienced significant - and perhaps avoidable - problems because of the restricted use of this valuable management aid.

Practical control rules are generally a blend of hydrology, environmental science, engineering, judgement, experience, psychology and politics. If they are to be effective, their derivation needs to be an iterative process in which the invaluable experience of system operators (past and present) must somehow be incorporated. Ideally the system operators need a basic understanding of the principles involved, an objective which is often impossible to achieve if the principles are based on complex mathematical and statistical methods.

Experience in designing the complex control rules for the multi-purpose, multi-reservoir systems in North Wales and North-East England in the early 1970s demonstrated that practical control rules can, in many cases, be built up from a series of components which are individually quite simple to use and understand. This introductory guide attempts to explain these components, with examples, so that user-friendly practical control rules can be designed, used, and modified as necessary, by non-specialists.

Ten general components have been defined. Depending upon the problem, the constraints and the objectives, the appropriate components are selected, developed and combined, then presented in simple (often graphical) formats. Some of the components will be familiar (e.g. recession curves) while others, such as refill curves, were developed to remedy perceived deficiencies in existing methods.

The 10 Component method has been applied to the operational management of almost all of Welsh Water's many and varied WRSs - large and small - in North Wales; and to a multipurpose reservoir in the Caribbean. Many of the individual components are in general use elsewhere within the U.K. and internationally.

However, as no two sets of control rules are identical because each situation represents a unique combination of characteristics, constraints and objectives, there is a perceived need to develop the confidence and expertise of those who wish to use the 10 Component method.

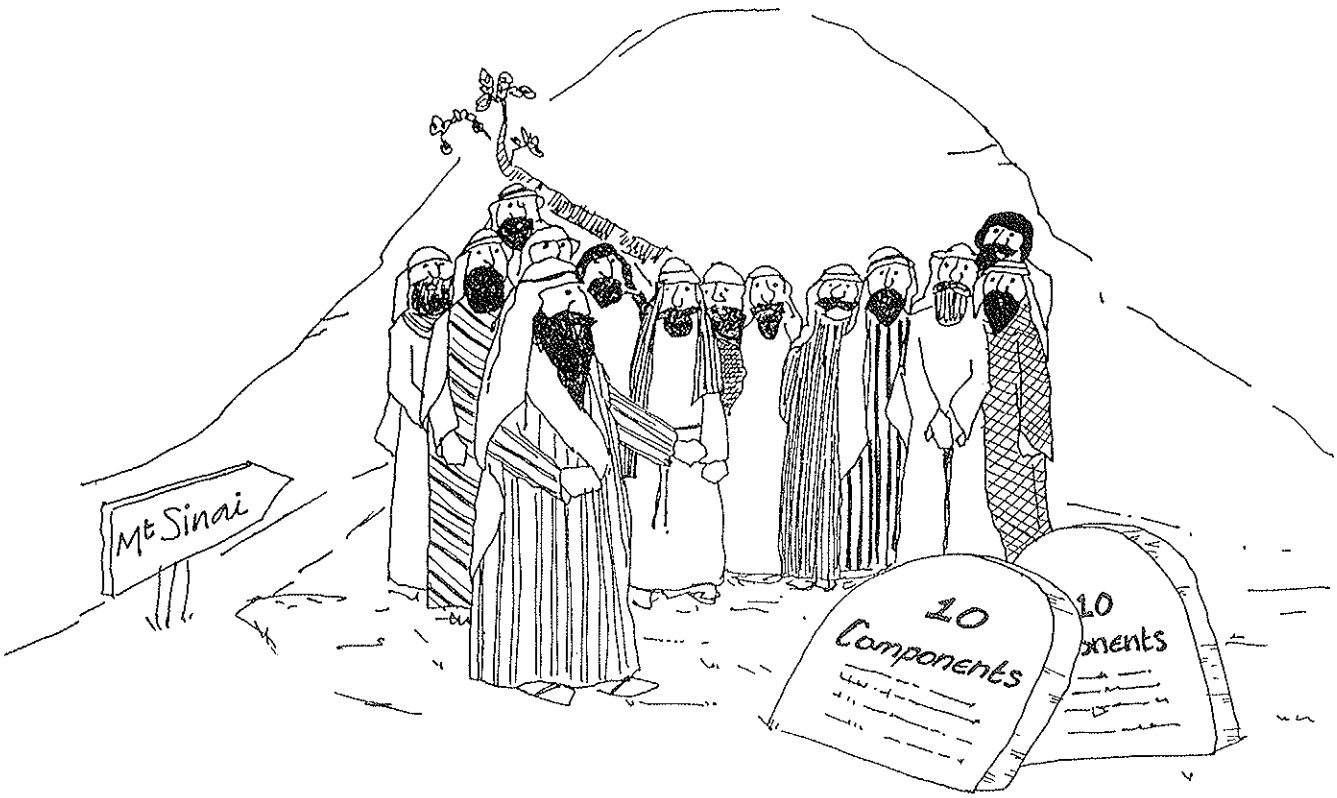
This guide therefore has two objectives:

i) to provide a basic framework and terminology;
ii) to encourage others to derive and use simple practical control rules.

Although the 10 Component method has many applications, it cannot solve all control rules problems; for example, multi-year drawdown sequences and major hydro-power generation will generally require more sophisticated analytical techniques. To those who might criticise the 10 component method as being too simplistic, or even naive, the response would be

* it works in many cases
* it helps operators to understand their systems
* it incorporates real operational constraints
* it is practical, rather than theoretical.

It should be seen as complementary to the more sophisticated techniques, and a means by which control rules can be 'popularised' so that the present mystique which surrounds them can be removed once and for all.



GOOD NEWS CHAPS, — IT'S GOT TO BE DOUBLE-SPACING
SO THERE'S ONLY ROOM FOR TEN !!

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The Author has worked for U.K. Water Authorities and their predecessors for over 25 years in Water Resources and Water Supply Operations, and also acts as a Consultant for the World Meteorological Organization. He is currently Special Projects Manager in Welsh Water's Northern Division.

Chapter 1 Introduction

River basin agencies such as Water Authorities inevitably influence most river-based activities as they operate their water resources systems. Although one prime function, e.g. water supply, usually has economic precedence, other river interests should reasonably expect a high standard of resource management, which will limit the adverse effect of hydrological extremes (drought and flood) whilst taking a positive attitude towards provision of incidental benefits to minority users whenever circumstances permit.

Each individual system represents a combination of engineering, hydrology, demands and economics which is unique for the particular stage of development of the resources. It requires an effective decision support system which

ensures the prime objectives are met;

maximises incidental benefits;

can be modified at short notice to cope with unpredictable events;

can be used, understood and refined by operational staff;

uses available data, however minimal.

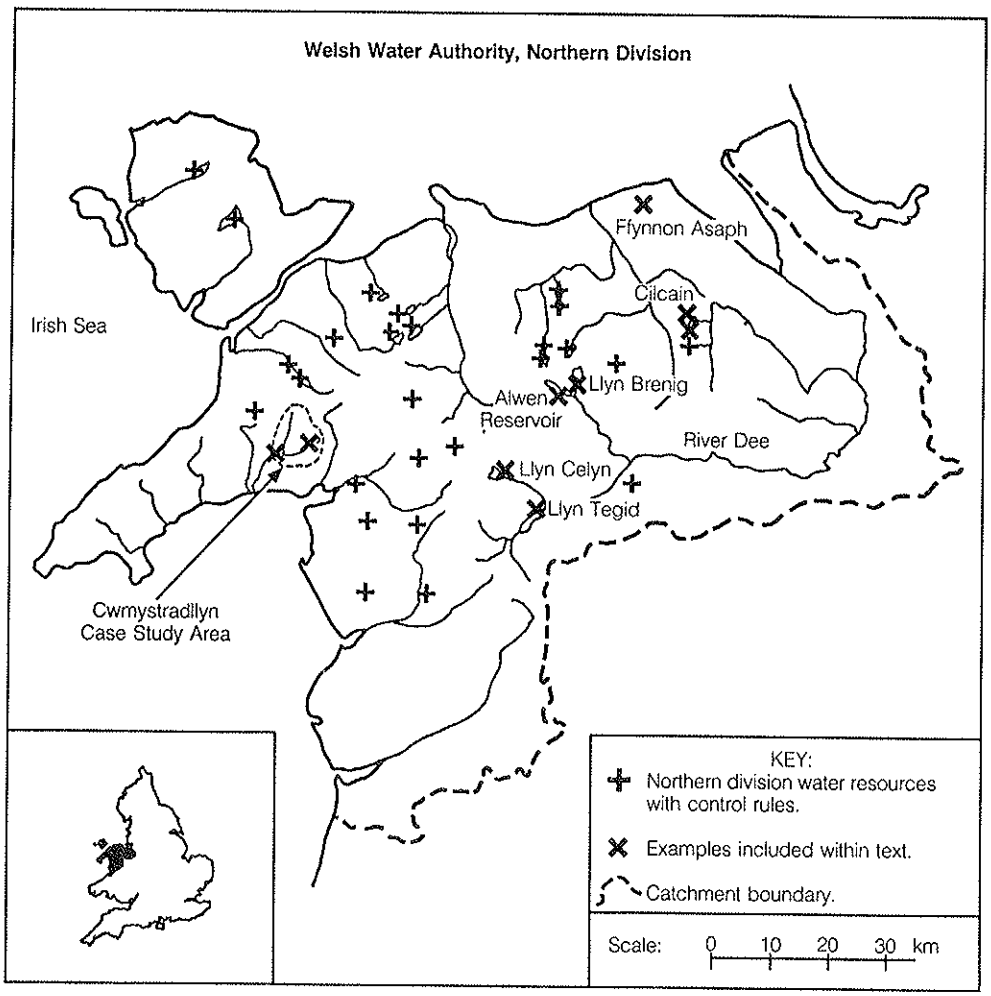
Although drawdown and refill management in droughts, and flood control, are obvious major aspects of the operational control of Water Resources Systems, there are many other useful features which can be included in the design of practical Operational Control Rules (OCRs).

Experience in North Wales has shown that flexible OCRs can be designed for most situations by separating the problem into some combination of appropriate selected components from the following list.

(1) DEMANDS
(2) RESOURCES
(3) DRAWDOWN CURVES
(4) REFILL CURVES
(5) ZONES, BANDWIDTHS and ACTION LINES
(6) AGGREGATED STORAGE
(7) SEGREGATED STORAGE
(8) DECISION DIAGRAMS
(9) RECESSION CURVES
(10) OPERATIONAL ECONOMICS.

When individual components are combined to form an OCR, the result can appear complex and intimidating to operators; the use of relatively simple individual components enhances understanding and assists explanation. The prime objective of the design process is to allow operational decisions to be made by non-specialists, by continual plotting of one or more simple parameters (such as reservoir level, demand, river flow) on a seasonal control rules graph.

The techniques have been used successfully for almost all Water Authority resources systems, large and small, in North Wales (see map). This includes the three large reservoirs which are used (Ref 1) for multi-purpose regulation of the River Dee involving water supply, flood mitigation, safeguarding migratory fish, recreation and hydro-power generation. The technique has also been used for an initial control rules formulation on a Caribbean reservoir used for flood control, hydro-power and irrigation (Ref. 2), and for initial control rules on major reservoirs in the Northumbrian Water Authority area.



The principal benefits arising from use of the techniques are:

identification and documentation of practical constraints;
effective use of resources within these constraints;
pre-planning of contingency conservation measures, conditional upon levels/storages/flows achieving particular values;
provision of incidental benefits when possible;
rapid identification of times when resources must be operated to maximise security of supply, rather than to minimise operating costs;

highlighting of changes in operational practice, or limited additional engineering works, which would improve security of supply or economic performance.

An understanding of the features and uses of each individual component is necessary, and in Chapter 2 each of them is briefly described, using general or individual examples, so that the reader may become familiar with the general concepts. Many of these examples are selected from the Dee system, or the Cwmystradllyn system which forms the main case study in Chapter 5. The general layout of the Dee Reservoirs - Tegid, Celyn, Alwen and Brenig - is shown on the map opposite; that of the Cwmystradllyn system can be found on p.27 or p.32.

Control rules are particularly useful for resources systems which are, or could be, used in a multipurpose manner, and such aspects are briefly discussed in Chapter 3, with particular reference to the possibilities of multipurpose use of reservoirs in the U.K. during the Autumn/early winter in most years. Other topics include opportunities for more flexible compensation water provisions, for recreational activities, and for use of Control Rules in the 'Operating Agreements' between the interested parties following the intended privatisation of English and Welsh Water Authorities in late 1989.

In Chapter 4, the suggested procedures for Blending, Proving, Monitoring and regular Revision of Control Rules are outlined. However, because every system has its own unique features, in an introductory guide such as this it is very difficult to outline general criteria for the selection and blending of the appropriate components in particular cases. This design skill only comes with practice, and by consideration of case studies (the more the better). There is only space for one complete case study in this guide (Chapter 5 and Appendices A1 to A5), but those with the time and interest to read it through should obtain an understanding of the blending process, and the management benefits which can be achieved.

Appendix B1 gives details of how refill curves (one of the most frequently used components) are calculated from long-term runoff data; refill curves derived from rainfall data are covered in Appendix A5. Appendix B2 describes how and why the control rules for a large regulating reservoir needed to be modified following construction of a new reservoir within its catchment area.

These are only a selection from many diverse examples, which prove conclusively that substantial progress can be made on operational control rules using relatively simple techniques, often with little hydrometric data. All too often the excuse is made that 'we need more data' when, in truth, sufficient information is already available to produce usable results and substantially improved management. If this introductory guide encourages others to achieve confidence and expertise in this field, it will have achieved its objective. The Author would be pleased to provide further guidance and assistance on request, through individual contacts or workshops for groups of students.

Chapter 2 The Ten Components

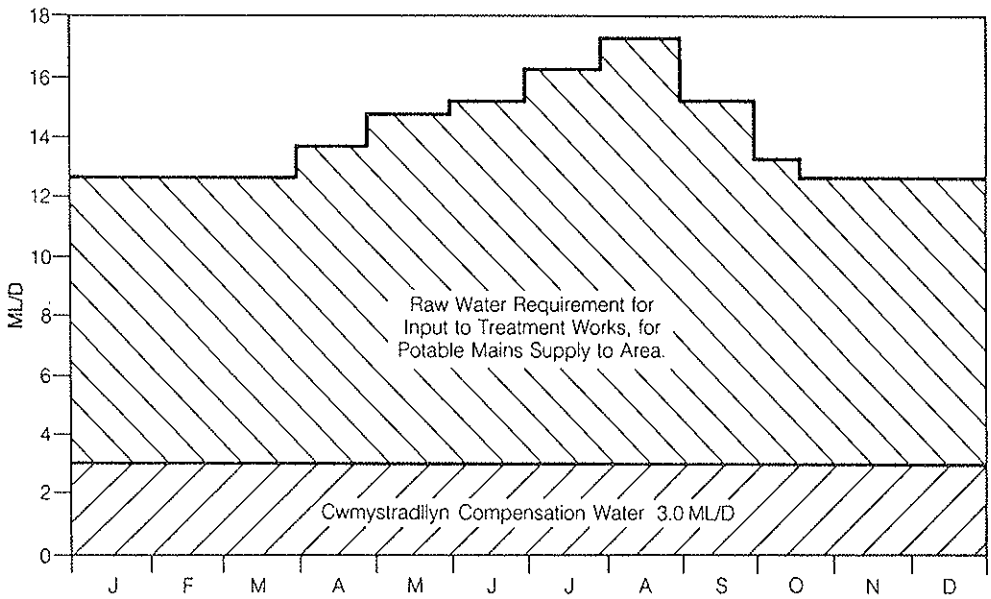
(1) DEMANDS

It is usually necessary to specify the seasonal demand variation relating to the prime objective, e.g. water supply. It is often appropriate to split demands into:

BD	Basic demands (must be met at all times)
CD	Conditional demands (subject to predetermined circumstances)
RD	Random demands (must be met, but timing not pre-specified)
OD	Opportunistic demands (subject to surplus availability)

For example, in Appendix A.1 the various seasonal demands on Cwmystradllyn, a direct supply/river regulating reservoir in north-west Wales are listed and categorised, with the simplifying assumptions explained. The basic demands - compensation water and water supply - are shown in Fig. 1.1 below, and demonstrate the effect of summer tourism on seasonal water supply in this rural area.

Figure 1.1 Basic demands on Cwmystradllyn Reservoir, Lleyn Peninsula



Whilst Fig. 1.1 shows the gross basic demands on storage, the net basic demand on storage, after allowing for minimum inflows, is also used for derivation of some control rules.

Conditional, Random and Opportunistic demands will usually be incorporated as annotations to the control rules, after their initial derivation from basic demands.

Conditional demands are those which can be satisfied only if the resources are considered sufficient when the demands arise. For example, at Cwmystradllyn there is an allocation for

fisheries freshet releases (the river is used by migratory sea-trout) of 136 Ml in August and September, provided that the reservoir exceeds a particular level.

An example of Random demand is the allocation of 159 Ml for fisheries freshet releases at Cwmystradllyn, for release at any time during April to October. In this case, the storage must be reserved until the release is requested by fisheries specialists, and the timing cannot therefore be pre-defined in any particular year.

As most water resources systems are designed to meet some specified basic demand in a drought sequence of some specified severity (e.g. 1 in 30 yrs to 1 in 100 years), it follows that in the majority of years there will be a surplus of resources. Monitoring of storage (using control rules) will clearly indicate when there is a surplus of resources, which can then be used to meet Opportunistic demands - for example, enhanced releases for hydro-power generation.

During a control rules study and derivation for an existing system, it is not unusual to find that

a) if control rules exist at all, they relate to demands and objectives which are not totally relevant to present circumstances; for example, they may be based on the design demand of the system, whereas current basic demands are often less than the design demand.

or b) what initially seems to be classifiable as one type of demand (BD, CD, RD or OD), can in fact be changed to another type (e.g. BD to OD, or CD) to improve the management of the system. For example, compensation water can be reduced (if a drought order is obtained when reservoir levels are low) or increased (when reservoir levels are high).

Because Control Rules design is an iterative process with the decisions, and hence the demands, being influenced by the Control Rules used, it is generally appropriate to start the process using only the most essential of the Basic Demands.

(2) RESOURCES

Although river flows can generally be measured continuously at or near the intended point of interest, it is often extremely difficult to measure directly the natural inflows into reservoirs, as tributary gauging stations rarely cover the whole catchment area. Average rates of reservoir inflows over defined time periods can, however, be inferred from measurements of reservoir drawoff and changes in storage, a method which implicitly allows for evaporative losses from the reservoir surface; this method was used to derive the average design drought summer inflows to Cwmystradllyn (based on 1984).

For Reservoir Control Rules purposes, one of the most important measurements is the continual monitoring of reservoir storage and its variation. This requires a reliable stage-storage relationship and regular level measurements to adequate discrimination and a consistent datum. Surprisingly, these simple criteria are often not realised. Periodic re-surveys of reservoirs are essential, as they often show usable capacity to be significantly different (usually less) than historic surveys or inherited stage-storage tables/graphs indicate.

There are many ways in which reservoir level and storage can be expressed. Choices should be based on ease of use and interpretation, e.g.

Level: units above/below spillway;
relative to sea level;
above lowest drawoff;
relative to some arbitrary rounded figure representing spillway level (e.g. 10 metres).

Storage: total storage;
usable storage above lowest drawoff;
equivalent runoff (mm) needed to refill to spillway;
A wide variety of units are used, e.g. Ml, tcm, cumec-days, million gallons, acre-ft.

Appendix A.2 shows the level and storage data for Cwmystradllyn reservoir, in a calendar year format suitable for incorporation into graphical control rules. On the left-side vertical axis, the level (relative to an arbitrary datum, with overflow at 15.00 metres) is shown to arithmetic scale, for ease of data plotting, when control curves are in use. On the right-side vertical axis, the storage is shown to a non-linear scale, in units of Megalitres (Ml), with the readily accessible 'gravity' storage; also shown is the emergency reserve storage below normal drawoff level which would require temporary pumping. The storages are also expressed in mm runoff needed for refill, and per cent full. Knowing the catchment area, mm runoff and Ml inflow become interchangeable (1 mm on 1 sq km yields 1 Ml).

Maximum drawoff rates and hydro-electric power production efficiency will generally reduce as reservoir levels fall; as with other basic data, the relationships need to be defined *before* a drought occurs. Drawoff pipe levels can easily be plotted on Control Rules graphs, as in Appendix A2, where they can be used for rapid assessment of drawoff level options in relation to current storage.

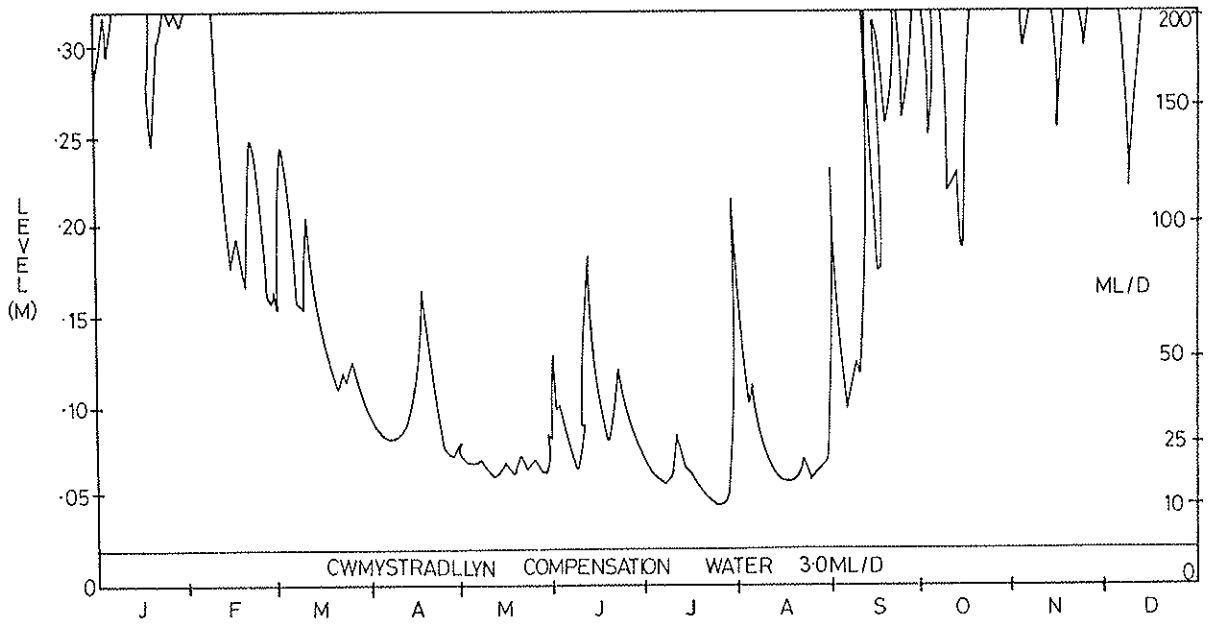
Depth measurements over a wide reservoir spillway are almost always too inaccurate for reliable calculation of overflows: a downstream gauging station is a sensible investment in most cases. When the high cost of *providing* storage is considered, it is false economy not to invest in reliable measurement of drawoffs, discharges and river flows.

Resources data will usually include measured or naturalised river flows, runoffs and rainfall from the resources systems under review, or data transposed from other catchments. Evapotranspiration estimates will sometimes be needed. However, the lack of historical hydrological data is not a valid excuse to defer preparation of operational control rules. Rainfall and runoff data are only used explicitly for three of the 10 Components (drawdown, refill and recessions). Calculations based initially on best estimates can be refined as better data become available in the future.

Reliable hydrometric data for most water resources systems are usually quite limited. The 1984 drought, extended into the Autumn, provides the basis of the single summer design drought for Cwmystradllyn, which is used to assess minimum summer inflows to the reservoir and river flows at the Dolbenmaen river abstraction point. Fig. 2.1 shows the reconstructed hydrograph of 1984 daily mean flows on the Afon Dwyfor at Dolbenmaen gauging weir, assuming only compensation water is released from Cwmystradllyn. Fig. 5.2 (p.29) and Appendix A3 show how much useful information for control rules can be derived from this single flow sequence, measured at a purpose-built Crump weir for high accuracy.

It is generally worth attempting to generate (usually by correlation) an approximate sequence of daily inflows/river flows for the historic classical droughts in a region (e.g. 1929, 1933/34, 1937/38, 1959, 1975/76 and 1984 in North Wales). Where the reliability of any generated data set is inadequate for initial control rules derivation, it can still be valuable in testing whatever control rules have been derived.

Figure 2.1 Reconstructed Daily Flows at Dolbenmaen Weir, 1984 Drought



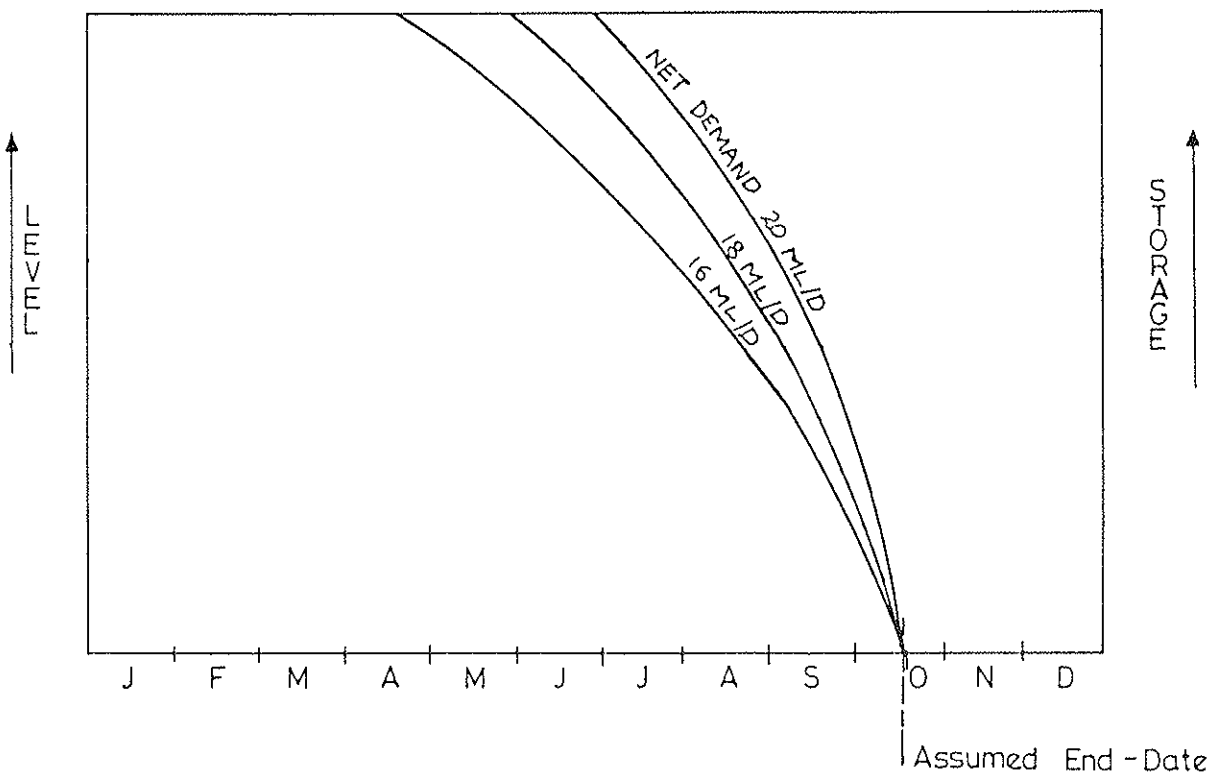
(3) DRAWDOWN CURVES

Operational Control Rules should seek to answer the actual questions asked in the real world. The question most often asked during 'drawdown' periods relates to whether the resources can be made to last until the drought ends. Thus the judgement of drought end-date clearly affects almost all the strategic and tactical decisions made. Because actual failure of water supplies is not a permissible political option in the U.K., the drought end-date is usually assumed to be the latest ever known from hydrometric records. Often a factor of safety is added if there is no emergency reserve of storage available.

Different types of resources in the same region will have different drought end-dates, depending on their speed of response to significant rainfall. Direct river abstractions (regulated or unregulated) will generally respond rapidly to rainfall and experience earlier end-dates than medium-sized direct supply reservoirs; the latter may continue to fall for up to a month after winter rainfall has commenced, until soil moisture deficits have substantially been filled. Groundwater resources, which depend on deep infiltration for recharge, may continue to diminish for many months after winter rainfall has commenced.

The general form of drawdown curves is shown in Fig. 3.1. To use drawdown curves operationally, simply plot the level/storage for the given date on a graph such as Fig. 3.1: if the point lies to the right of the drawdown curve, there is no resource problem for that calendar year, provided that the specified net demands are not exceeded and that any drought does not last later than the assumed end-date. Obviously, the higher the net demand, the steeper the drawdown curve.

Figure 3.1 General Form of Drawdown Curves



Drawdown curves are determined by calculating the storage required at, say, the beginning of each calendar month, to satisfy the net demands on reservoir storage until the assumed end-date of the drought. The calculations, which are worked backwards from the end-date until the available storage is reached, are normally based on demands during a minimum runoff sequence. The majority of reservoir systems in North Wales are of sufficient size, in relation to catchment area and runoff, that they are 'single-season critical'; i.e. they would fail during a single summer's drought. For these systems, the minimum runoff sequence used for control rules design is that of the 1984 drought (April to August) extended on the assumption that significant rainfall recommences in mid-October.

It is therefore necessary to distinguish between

HYDROLOGICAL YIELD - a theoretical concept, which assumes complete fore-knowledge of the magnitude, timing and duration of the drought event, in particular its actual end-date.

and

OPERATIONAL YIELD - a practical concept which must be based on an assumed end-date of the drought event, with the duration dependent upon the actual start-date and the assumed end-date.

For a single-reservoir system, Operational yield will generally be less than Hydrological yield, because the assumed duration of the drought for Operational yield will be greater. This is perhaps one of the reasons why some resource systems appear to require emergency conservation measures more frequently than their original design frequency (usually based on hydrological yield, using an historic or synthesised drought of specified severity). However, experience shows that conjunctive use of resources, and other operational management activities arising from use of control rules, can usually overcome the apparent difference between Operational yield and Hydrological yield.

Appendix A.4 shows the drawdown curve for Cwmystradllyn, using the basic demands of compensation water and supply requirement described in Appendix A.1, with an assumed inflow of 1.5 Ml/day. Because it is the *net* demand which determines the rate of reservoir drawdown, very accurate estimates of minimum inflow are only needed when there is a small difference between basic demand and inflow. In the Cwmystradllyn Case Study, the basic demands in summer are about 10 times the estimated minimum inflow (in 1984), so that a 20% error in estimating inflow would give the same overall error as a 2% error in estimating demand. It is therefore acceptable to use an assumed steady minimum inflow of 0.3 mm/day (1.5 Ml/day) for the whole of the period from 1st April to the assumed drought end-date of 17th October (based on the latest recorded end-date of a drought in North Wales, that of 1959).

(4) REFILL CURVES

When a drought ends the question most often asked is "When will the reservoirs refill?"

Many reservoirs - particularly multi-purpose ones - need to be managed when they are refilling as well as when they are being drawn down. Refill curves provide a very flexible technique which enables tactical decisions to be taken continually during general periods of refill within a range of overall strategies and objectives. Regular plotting of reservoir level/storage against the refill curves during rapidly changing situations identifies shortage or excess, enabling appropriate actions to be initiated.

Refill curves require probability analysis of seasonal runoff data (typically October to April in Wales) to derive cumulative inflows, which are then incorporated with basic demands and storage data. The alternative methods of presentation, both using seasonal graphs of storage, as shown in Figs. 4.1 and 4.2, are:

Type (i): different refill chances for a given basic demand, or
Type (ii): different demands for a given refill probability.

The technique (Ref. 1) was first introduced in 1974 on Llyn Celyn, a large regulating reservoir on the Dee system, to identify when excess water was available for flood storage or hydro-electric power generation. Appendix B.1 shows the method of calculation when a long series of monthly runoff data is available: for Llyn Celyn, Type (i) refill curves are appropriate, because the basic demand (compensation water) is very small and not amenable to significant reduction. A cruder method of calculation, based on quarterly rainfall, is used when only limited hydrometric data are available. This is the case at Cwmystradllyn, where type (ii) refill curves are appropriate, because the rule curves will be used to guide decisions about reducing (when necessary) the winter demands on the reservoir. The calculations, which use minimum estimated winter inflows, are shown in Appendix A.5.

Refill curves have some other very useful applications in multi-purpose systems in the U.K.; for example

- identifying years when additional releases can be made (even though reservoirs are still substantially drawn down) for hydro-power generation, or to improve river conditions for migrating fish;

- creation of additional short-term seasonal flood control storage;

- deciding when to continue, stop or recommence abstraction from lowland sources with high marginal costs used conjunctively with cheaper upland sources.

Control rules incorporating refill curves will clearly define those reservoirs which have poor refill characteristics and will allow preplanned extra refill (and/or demand reduction) measures to be implemented as necessary if the reservoir level remains consistently below the appropriate refill curve. It is particularly important for their design to seek out, from whatever data sources are available, estimates of rainfall or runoff for the driest refill periods since hydrological records began: generally (for North Wales) the winters of 1928/29 and 1933/34.

As there are many combinations of refill probability and demand, it is usual to carry out calculations for a wide range of combinations, using computer-based spreadsheets. However, because of the mass of choices which result from such work, it is most important to have

Figure 4.1 Type (i) Refill Curves - different refill probabilities for a given basic demand, e.g. Llyn Celyn (App. B.1)

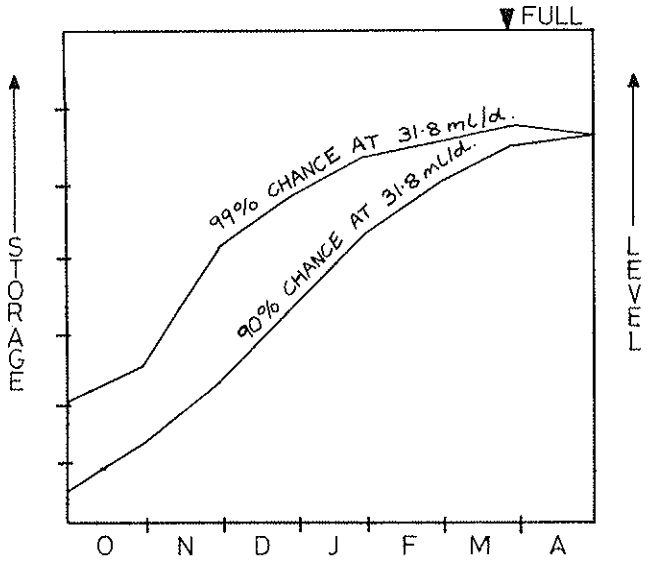
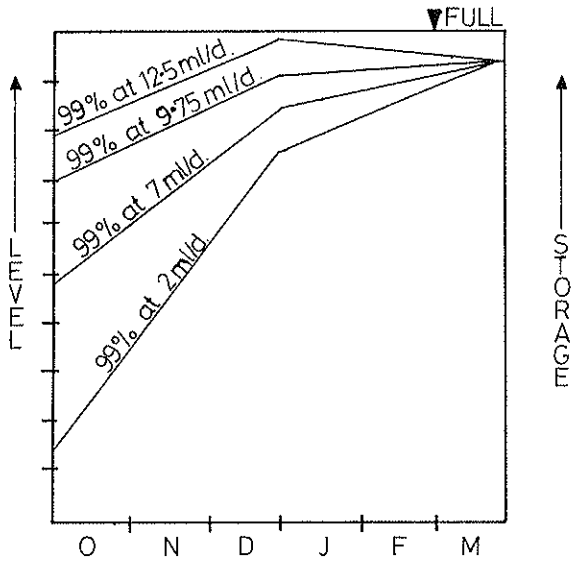


Figure 4.2 Type (ii) Refill Curves - different demands for a given refill chance e.g. Cwmystradllyn (App. A.5)



clear objectives as to how and why one wishes to use the refill curves for operational decisions.

Some of the problems experienced in the U.K. drought of 1984 could be attributed to the choice of sources in resources systems used conjunctively, e.g. the overdrawing of cheap but irreplaceable upland gravity storage near the end of the preceding refill period (February to April), whilst lowland river intakes and boreholes with surplus resources but higher marginal operating costs in power and chemicals were under-used. However, such problems were easily avoided for those reservoir systems which had appropriate OCRs formulated *prior* to 1984. It is evident that effective drought management in the U.K. depends upon the correct decisions being taken well *before* the public and the media become aware that a potential drought problem exists.

A quick calculation will usually show if refill is likely to be a problem in dry winters. For example, the average basic demand on Cwmystradllyn in October to March is 12.5 Ml/d, equivalent to 2.45 mm/day runoff, or 446 mm runoff in total. Winter rainfall also needs to satisfy evapotranspiration losses of some 95 mm and recharge a typical soil moisture deficit of 50 mm at the beginning of October. Thus a winter rainfall of at least 446 + 95 + 50 = 591 mm is needed before any refill of reservoir storage (equivalent to 625 mm at maximum drawdown, see Appendix A4) can take place. A correlation of the average annual rainfalls at Cwmystradllyn and Cwm Dyli, a 66 year record, indicates a minimum winter rainfall of only 709 mm (in the 1933/34 drought), and only a 40% chance of more than 1216 mm winter rainfall. These simple calculations clearly demonstrate that there is a real danger of Cwmystradllyn not refilling in dry winters after drought summers, and that control rules must incorporate timely guidance on appropriate water conservation measures during the seasonal winter refill.

(5) ZONES, BANDWIDTHS AND ACTION LINES

On a seasonal reservoir control rules graph, a ZONE is fixed by reference to upper and lower storage limits, and usually start/finish calendar dates. A ZONE is generally specified with a single conditional purpose in mind, i.e.

if level ***or*** storage is in ZONE X
then operate in a specified manner.

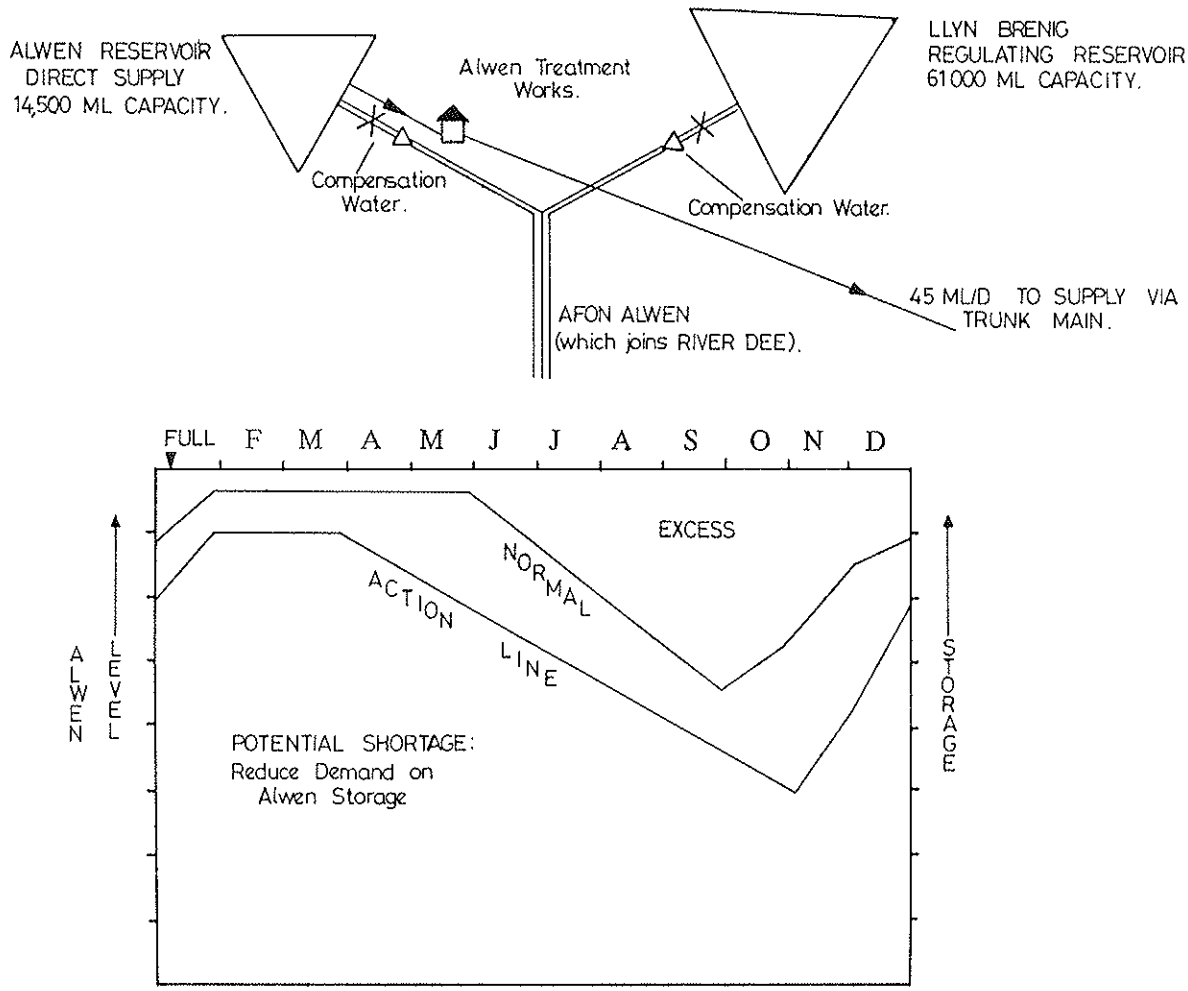
There can be many ZONES in a control rules graph, but generally they form two groups - 'normal' and 'abnormal' operation. 'Normal' operation implies no shortage or excess of water for the time of year; 'abnormal' can relate to *either* shortage *or* excess. Fig. 5.1 shows a simple example where 'ZONES' are used on the Alwen direct supply reservoir (Dee system) for various beneficial purposes.

A BANDWIDTH is a particular type of ZONE limited by upper and lower lines which are often parallel. It is particularly useful for defining control rules for 'normal' operation of the lower of two reservoirs in series, where the lower reservoir storage/discharges can be easily modified by increase or decrease of releases from the upper reservoir should 'abnormal' conditions occur in the lower reservoir. Appendix B.2 describes the BANDWIDTH operation of Llyn Tegid, downstream from Llyn Celyn on the Dee Regulation System, where the BANDWIDTH is used to enhance system yield (by catching summer spates) and balance short term variations in Llyn Celyn hydro-power releases (which can be timed for maximum operational economy). The BANDWIDTH lower limit is also designed to assist summer water-based recreation (mainly sailing) on this important recreational asset in the Snowdonia National Park. Appendix B.2 also demonstrates the fundamental change which is often needed to a particular control rule when a new element - in this case Llyn Celyn - is introduced into a water resources system.

Control rules can be thought of as the 'Highway Code' of water resources management, drawn up to meet most foreseeable situations but deliberately allowing the operator maximum local discretion in making decisions. For example, a reservoir level might be falling from a 'normal' into a 'shortage' ZONE (implying some operational action), but the operator knows that some rain (or snowmelt) is imminent, and sensibly defers any action for a few days. However, in some cases it is necessary to define an ACTION LINE (usually the boundary of a ZONE or BANDWIDTH). If the level/storage/demand/flow crosses this line, a particular action *must* take place within a defined timescale, for example commencement/cessation of flood control releases.

There are two main pitfalls to be avoided in the design of ZONES/BANDWIDTHS/ACTION LINES. The first is the almost irresistible temptation to fill the control rules graph with *too many* lines, thus wasting scarce manpower resources in frequent superficial resource management activities. The second is the problem of 'hunting', a situation which occurs when a zone limit line is drawn at the same slope as the usual rate of reservoir drawdown; in such cases the level may marginally oscillate between zones on a week-to-week basis, causing frequent changes in operational policy which almost immediately generate changes back to the original policy.

Figure 5.1 Alwen Reservoir Control Rules: Zones and Action Line



Notes:

1. The hydrological yield of Alwen reservoir in the 18-month 1933/34 drought was only 34 Ml/day. However, it is usually operated at 45 Ml/d when in the NORMAL or EXCESS zones, as this upland water has low production and distribution costs.

2. When the Alwen reservoir level falls through the ACTION LINE, into the potential shortage zone, the demand on Alwen is reduced by:
Stage (1): reduction of Alwen compensation water, with consequent increase of Llyn Brenig compensation water,
Stage (2): reduction of supply from Alwen by conjunctive use of more expensive sources.

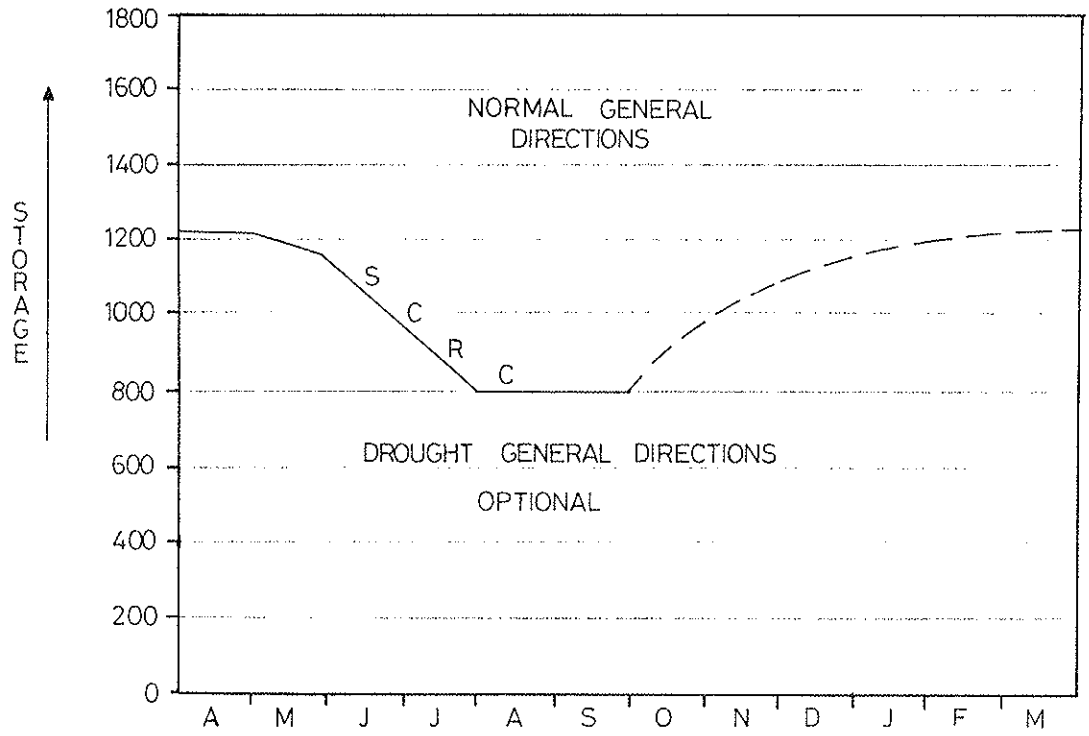
3. When in the EXCESS zone, extra releases can be made from Alwen for hydropower generation, and to enable Brenig compensation water to be reduced when Llyn Brenig is refilling.

(6) AGGREGATED STORAGE

For a single reservoir operating in isolation, one control rules graph of storage is usually all that is possible, or necessary. Where two or more reservoirs operate conjunctively, in series or in parallel, and some decision-making (e.g. overall drought strategy) needs to be based on the total storage in all the reservoirs, it is appropriate to have one or more control rules based on aggregated storage, in addition to the individual control rules for each reservoir. For example, on the regulated River Dee, a Control Rule (Fig. 6.1) based on the aggregated storage of the two principal reservoirs (Llyn Celyn and Llyn Brenig) is used to aid the important decisions on when to switch between 'Normal' and 'Drought' methods of operating the system and its components.

It should be noted that refill curves for more than one reservoir should not generally be combined into an aggregated refill curve, as the superficial interpretation of such a curve can give misleading results. It is preferable to derive and use refill curves for individual reservoirs.

Figure 6.1 Dee Regulation System Conservation Rule Curve (SCRC) (based on aggregated storage of Llyn Celyn and Llyn Brenig)



Note: When combined storage falls below the SCRC, the Dee Consultative Committee may decide to implement Drought General Directions. The SCRC is not, therefore, an ACTION LINE.

(7) SEGREGATED STORAGE

Where reservoirs operate conjunctively, whether in series or in parallel, decisions must be taken regularly on the proportion of drawoff taken from each reservoir. The calculations necessary to guide such decisions may sometimes be very complex (e.g. where a reservoir has a multi-year refill period, as with Llyn Brenig on the Dee Regulation System) and will depend upon such factors as

reservoir drawdown in relation to refill characteristics,

balancing of tributary flows where regulating reservoirs operate on different tributaries of the same river,

limitations on maximum drawoff capacity,

water quality considerations.

However complex the derivation, the results should be presented in a simple form for operational purposes, and can be classified as SEGREGATED STORAGE control rules.

In a multi-reservoir system, a useful first step in the control rules derivation is to list the catchment area, surface area, usable capacity and average runoff for each reservoir and to calculate the ratio of usable capacity to average runoff in days. Table 7.1 shows these data for the four major Dee reservoirs which are used conjunctively (Ref. 1). The capacity/runoff ratio shows the wide diversity of speed of refill, and where there is such diversity it is generally not too difficult to decide which reservoir to use at any time, by reference to the individual (segregated storage) control rules for each of the reservoirs, once their winter refill curves have been derived.

Table 7.1 Dee Regulations: facts and figures

Reservoir	Catchment Area (km^2)	Surface Area (ha)	Usable Capacity ($m^3 \times 10^6$)	Average Runoff m^3s^{-1}	Average mm yr^{-1}	Capacity/Runoff Days
Llyn Celyn	60	325	81	3.1	1590	302
Llyn Tegid	262	400	18	11.5	1380	18
Llyn Brenig	22	370	60	0.62	884	1120
Alwen Res.	26	150	15	0.73	899	238

The only additional rule curve needed for the Dee system is one (not reproduced here) which identifies how to share overall major regulation releases between Llyn Celyn and Llyn Brenig, in order to minimise Llyn Brenig overflows, and balance the Dee tributary inflows at the end of a major drought.

When setting up segregated storage control rules for multi-reservoir systems, it is often necessary to use the technique of decision diagrams to provide clear user-friendly directives to operations personnel. An example is shown in the following section.

(8) DECISION DIAGRAMS

The format of DECISION DIAGRAMS will be familiar to people with computer programming experience. The technique demands a logical approach on the part of the systems designer, and is particularly appropriate when day-to-day decision making is delegated to non-technical personnel. The small but previously troublesome Cilcain direct supply reservoirs system in North Wales was run satisfactorily during the 1984 drought by manual operatives, using the Control Rules and Decision Diagram shown below and opposite.

Figure 8.1 Cilcain Supply System

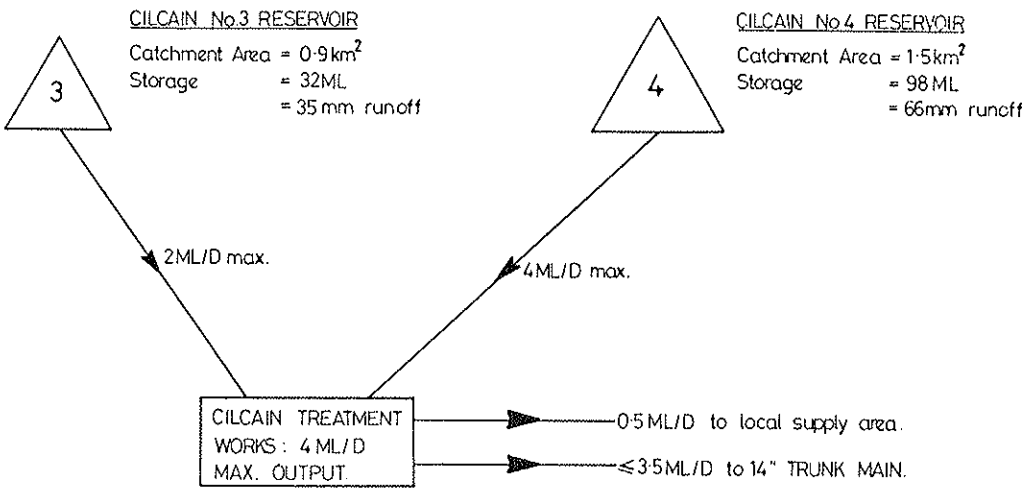


Figure 8.2 Control Rules used in 1984 Drought

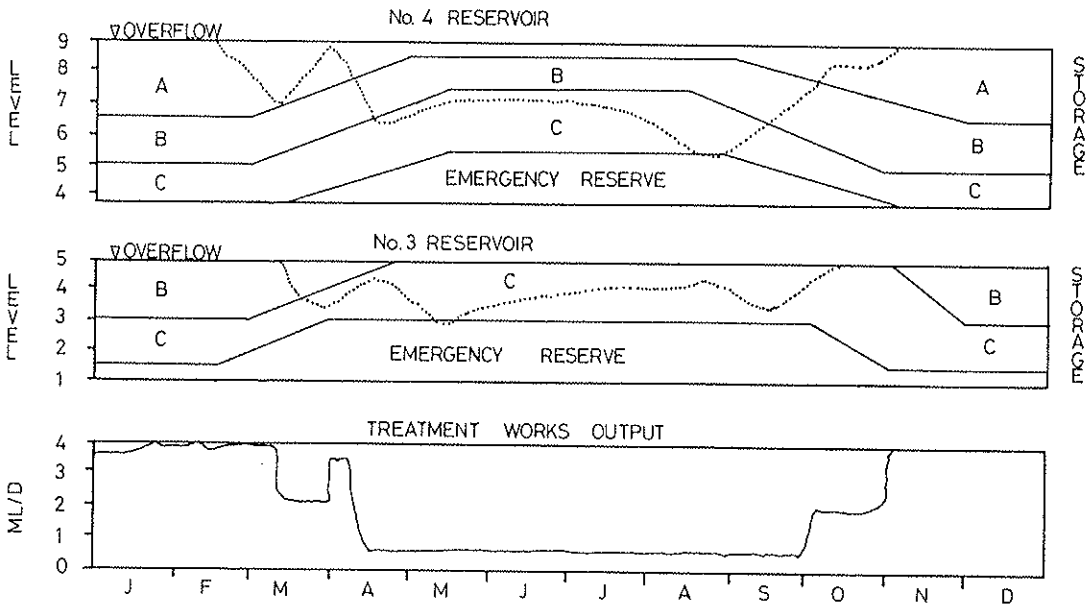
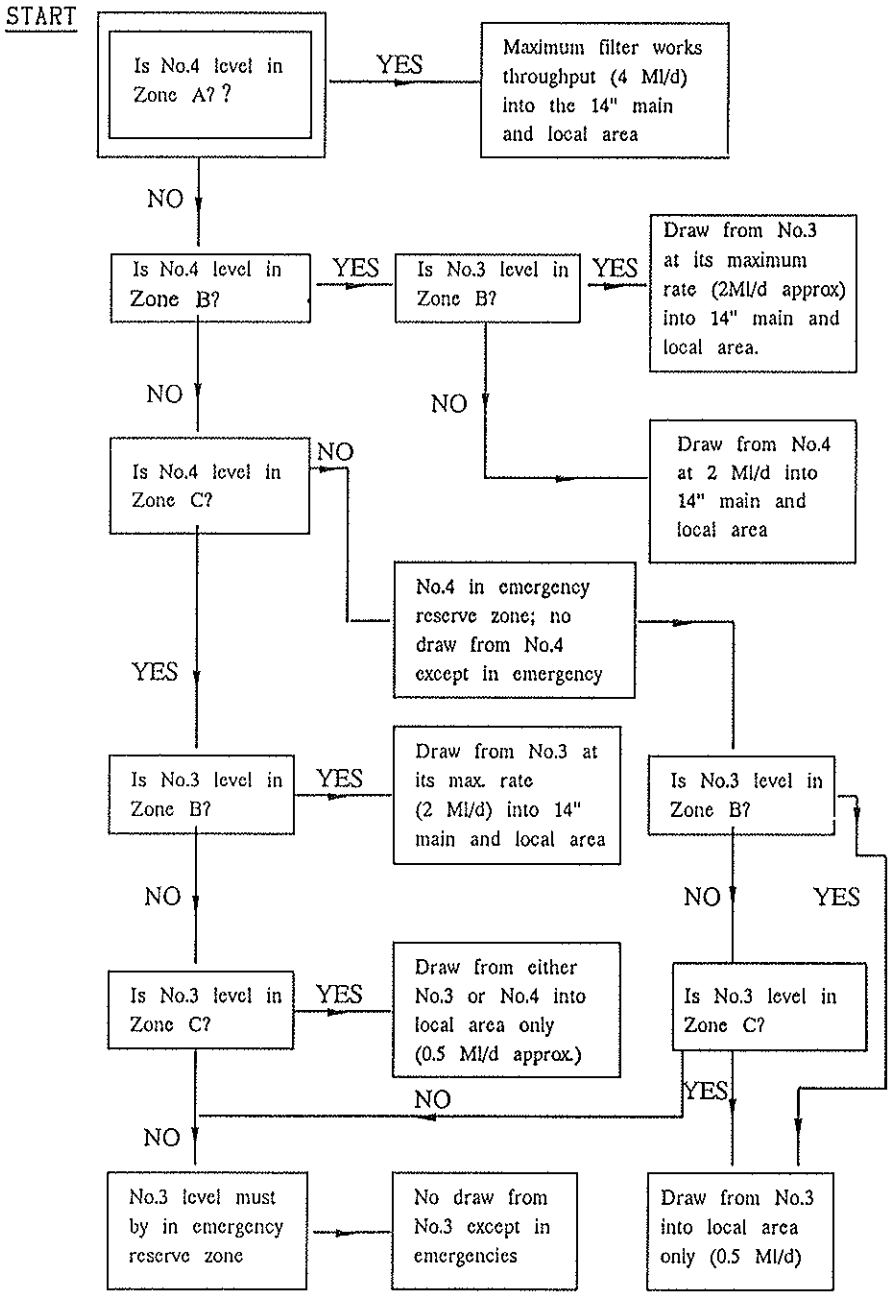


Figure 8.3 Cilcain Reservoirs Decision Diagram for Choice of Sources, 1984



The overall objectives of these control rules are, in order of priority,

(i) to guarantee the 0.5 Ml/d supply to the local area, which cannot be served from any other source,
(ii) to maintain an emergency reserve for temporary supply to the trunk main in the event of failure of the trunk main from Alwen reservoir,
(iii) to maximise the output from Cilcain to the trunk main, for economic reasons relating to marginal supply costs and bulk supply charges.

(9) RECESSION CURVES

Recession curves - i.e. the natural rates at which river flows decrease in the absence of effective rainfall - are very familiar to hydrologists. Although implicitly used in some flood forecasting methods and for routine determination of low-flow release requirements on regulated rivers, they have not been used extensively for other simple operational applications, e.g.

> forecasting the earliest date when a particular rate of river flow (which will have operational consequences) may be reached;
>
> forecasting, for direct river abstractions, the minimum flows to be expected at some future times if no rainfall occurs.

Recession curves are useful early warning systems which are particularly relevant for direct river abstractions, or abstractions from reservoirs which are so small in relation to river flow (storage equivalent to only a few mm runoff) that they are effectively direct river abstractions. In such cases, applications for Drought Orders and plans for emergency works must often be initiated *before* natural river flow has fallen to the critical value, and recession curves based on reliable river flow measurements are used, as part of control rules, for such management decisions on several small resource systems in North Wales.

Where several sources are operated conjunctively, it is operationally useful to know that river flows/reservoir inflows will be sufficient to maintain present operating strategy for some period ahead, e.g. one, two or three weeks; this allows operations personnel to concentrate on other matters during this period. Simple graphical control rules based on comparison of current flow rates against standard recession curves will achieve this objective.

A simple example of recession curves in control rules is shown in Figs. 9.1 and 9.2. A deep-seated spring from the Carboniferous Limestone is the main component of base-flow in the Afon Ffyddion. Abstractions from this stream, near the spring, are one of the cheapest of several sources used conjunctively to supply the North Wales holiday resort of Prestatyn. The recession of base-flow in spring and summer of a dry year follows a predictable pattern, but its start-date varies depending upon the previous winter's rainfall. By matching the early part of the recession in any year to the master curve derived in 1976, a reliable forecast of the minimum abstractable water for the rest of the summer can be made (after taking account of abstraction licence conditions which safeguard residual flows over Dyserth Waterfall, a popular tourist attraction).

Figure 9.1 Flynnon Asaph Supply System

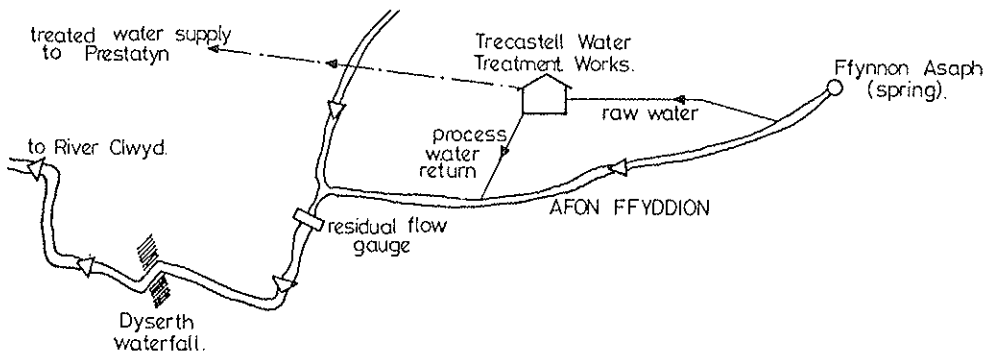
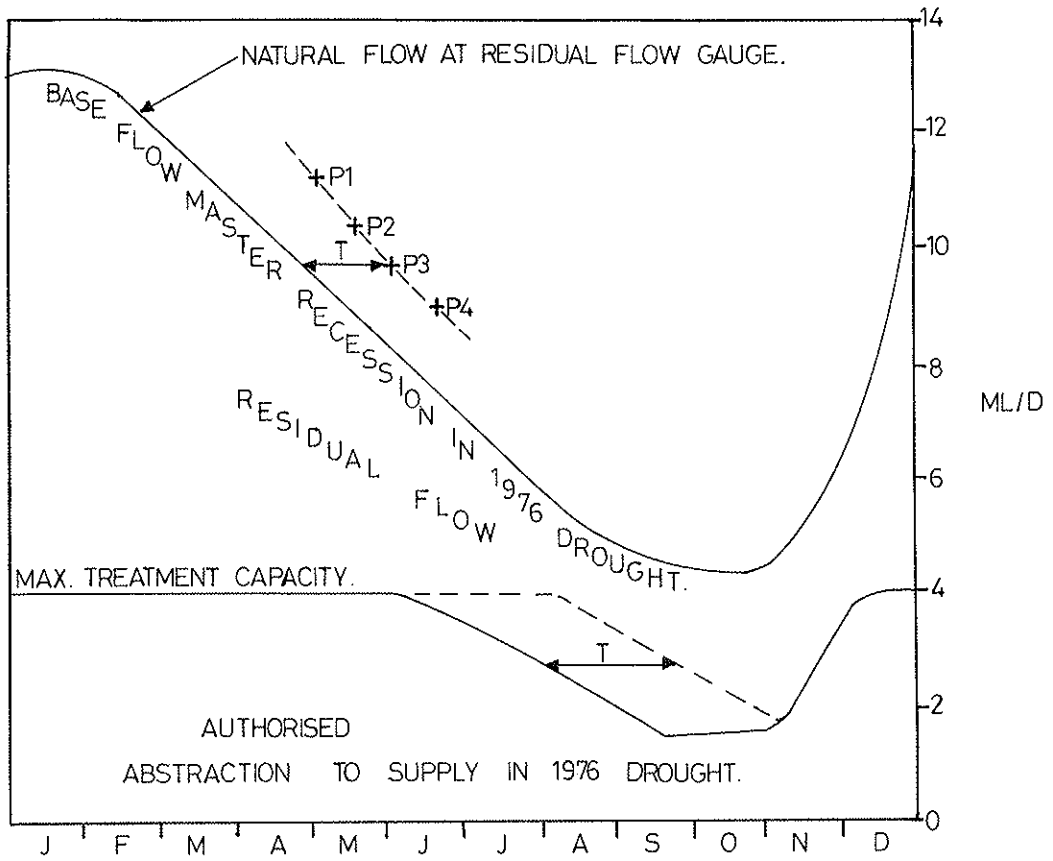


Figure 9.2 Flynnon Asaph: Master Recession Control Rule



To use the control rule, actual base flow is plotted once per week (P_1 etc.) each spring; time-shift (T days) is determined from comparison with master recession; using T, forecast of permitted minimum abstraction to supply is adjusted.

On fast-response river systems, recession curves are also very useful operationally but on a shorter time-scale than for groundwater systems. On the Afon Dwyfor (Cwmystradllyn) system, the recessions of natural river flow experienced in the 1984 drought (Fig. 2.1) can easily be used by operations personnel to forecast, on a day-to-day basis, the minimum time before river flows will fall to specified, seasonally varying 'hands-off' flows, when river regulation releases must commence (see Appendix A3 for further details).

(10) OPERATIONAL ECONOMICS

Relatively unsophisticated control rules of the type described are clearly most applicable when the economic considerations are straightforward, i.e. where there is a principal use for which operational costs can be derived, and the benefits of other opportunistic uses can also be roughly assessed. Where hydro-power is the main use (not usually the case for U.K. Water Authorities) more sophisticated approaches will generally be necessary.

For water supply, the most useful comparative measure of operating cost is often the short-term marginal cost of producing and distributing potable water, expressed in £/Ml. Marginal treatment costs (power + chemicals) range from £3/Ml for upland reservoirs and boreholes to £15/Ml for lowland river abstractions, and potable water pumping costs frequently reach £30/Ml for lowland or borehole sources. Bulk supply costs for potable water from neighbouring water undertakings often exceed £100/Ml. For facilities which are operated seasonally (e.g. Dolbenmaen Water Treatment Works) there is also a substantial fixed cost saving (mainly wages/overtime) for each week during which the station can be kept shut down in the winter period.

When control rules are derived using current basic demands, it will usually be evident that

(i) there is a deficiency of resources related to basic demands

or (ii) resources are approximately equal to basic demands

or (iii) resources are more than sufficient for basic demands (usually for a recently constructed scheme).

In cases (i) and (ii) there are frequently more economical options than expensive new capital works. Basic demands can be reduced at critical times of year as indicated by the control curves. Demands on storage can be minimised by

- reducing losses from raw water mains,
- minimising process water losses at water treatment works, by recirculation or change in compensation water measurement point,
- reducing leakage in distribution systems,
- introduction of seasonally variable compensation water conditions,
- providing links (raw or treated water) for conjunctive use with nearby resources systems with different hydrological characteristics.

In case (iii), there is usually the possibility of more flexible use of the resources, often in a multipurpose manner which will result in economic benefits. For example, at Llyn Celyn the recalculation of Probable Maximum Flood in the early 1970s indicated that the existing bellmouth spillway could become 'gorged'; as an alternative to installing additional spillway capacity, the control rules for Llyn Celyn and Llyn Brenig were modified to allow more of the Llyn Celyn PMF hydrograph to be absorbed into Llyn Celyn flood storage, thereby deferring the need for the capital works for many years.

Because the particular circumstances of an individual resource or group of resources tend to be unique at any particular time, the incidental economic benefits to be gained from control rules are generally site-specific. Thus, for example, the discharges from Cwmystradllyn made specifically for a Mill downstream on the Dwyfor, have been changed by agreement from a *statutory* to an *optional* basis, with appropriate compensation payments. As another example, the sharing of releases from Llyn Celyn and Llyn Brenig on the Dee regulation system have

been modified in the early summer to enhance the Llyn Celyn hydro-power income without adverse effects on other interests.

It is not unusual for newly-derived control rules to highlight a relatively minor capital expenditure improvement or change in abstraction licence conditions which will allow objectives to be achieved. In other cases, net present value calculations show that it is economically preferable, where demands are only rising slowly, to continue to run high cost sources intermittently to maintain adequate operational yields, rather than to invest in major new capital works.

One other important feature of operational economics is the scale of potential savings for a particular system, as it affects the amount of time (and hence cost) which it is justifiable to spend on derivation of control rules. For big multipurpose systems, annual savings can easily exceed £10,000, and hence most already have control rules. For small systems, which may cost only £10,000 per annum to operate, a quick, cheap method of deriving control rules is all that can be justified economically – which is why the 10-component method has proved so useful in North Wales.

Chapter 3 Multipurpose Aspects of Control Rules

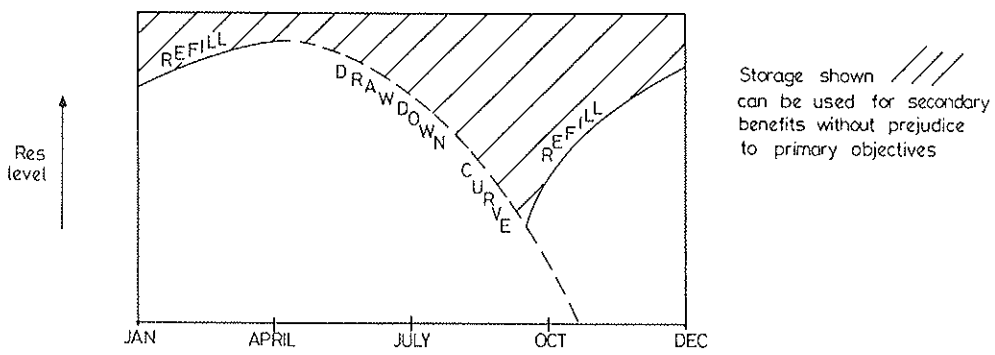
The majority of U.K. reservoirs were constructed as part of single-purpose local water supply systems, prior to the formation of multi-purpose water authorities in 1974. Control rules derived for these sources in isolation generally indicate scope for using the reservoirs regularly or conditionally in wider contexts such as:

- seasonal flood control;
- hydro-power generation;
- enhanced seasonal discharges for fisheries;
- additional releases (from boreholes and reservoirs) for dilution of effluents pending completion of sewage treatment works improvements;
- intermittent release for dilution and flushing of random pollution events;
- maintenance of specified reservoir levels for particular seasonal recreational activities.

The philosophy of conjunctive use of different sources, both surface and groundwater, has been practised extensively since 1974, with clear economic advantages: it provides even more opportunity for such secondary benefits.

One of the best periods for such secondary benefits in Wales is the earlier part (October-January) of the refill period, when the refill curves often identify a significant upper portion of reservoir storage. The excess can safely be used, subject to possible constraints on the quality and temperature of water discharged, for other purposes (often mutually compatible); for example

- short term flood detention;
- extra releases for migrating fish;
- hydro-power generation during peak demand period.



Good working relationships between different interests can take years to establish, but progress can be speeded up if river basin agencies demonstrate their constructive intentions by deeds as well as words. For example, special facilities to an international standard have been developed for canoe slalom and white-water canoeing on the River Tryweryn, part of the Dee system, which regularly carries hydropower/regulation releases from Llyn Celyn down into Llyn Tegid.

For fisheries, special additional releases are made to protect the grilse (young salmon) returning up the Dee estuary in July, and during the autumn extra opportunistic releases are made in most years to assist migratory fish moving upstream to spawn in several North Wales rivers.

Experience has shown that simplified rule curves are an excellent means of explaining the general problems of resource management to everyone - technical or not - with an interest or involvement in management of water resources and rivers. This is opening up the possibility of a more flexible seasonal approach to statutory compensation water discharges and residual flows (particularly in February to May) which can better safeguard the interests of all river users.

Hill and Mawdsley (Ref 3) cite some of the few examples in the UK where recreational interests are specifically included in Control Rules. It is no coincidence that these examples are drawn from the Welsh and Northumbrian Water Authorities, where the 10-component method has been used for Control Rules derivations. Stokes (Ref 4) gives several detailed examples of how recreational interests have been incorporated into Control Rules in Wales.

In North Wales, with over 80 separate sources, many of which are used conjunctively, most control rules are designed for delegated decision-making on a daily or weekly basis at Area and Unit operations offices. Specific levels, flows, consumptions and demands are transmitted to Divisional HQ each Wednesday where they are used for general monitoring of the more important control rules, preparation of Divisional reports to Regional HQ (Brecon) when required, production of weekly supply and demand data, and comparison with overall consumption targets. Only if an Area or District office has failed to follow an important aspect of a control rule without prior consultation would Divisional HQ seek an explanation of the circumstances.

When programming engineering or maintenance works which necessitate preplanned drawdown of reservoir storage, it is extremely useful to examine the control rules and schedule the work at times which minimise the risk of conflict with basic objectives. On most occasions, it is advisable to draw up special temporary rule curves for the duration of such work.

Current Government proposals to divide the existing functions of water authorities in the U.K., with the creation of a National Rivers Authority, envisage the use of 'Operating Agreements' between the NRA and the public utility companies for the operation of water resources systems. It seems reasonable to suppose that such 'Operating Agreements' will not work effectively unless they incorporate practical operational control rules, and provision for their periodic review.

Chapter 4 Blending, Proving, Monitoring and Revision of Control rules

With the exception of single source reservoir systems, which will have drawdown and refill curves blended into a single graph, it is not possible to specify firm guidelines as to the number and format of control rules for any particular system. However, this should be seen as an opportunity rather than as a disadvantage, since the designer is not constrained to a small range of options previously used elsewhere.

Formulation of control rules by the 10-component method is an iterative process consisting of the following main steps:

(a) defining the specific and general objectives;

(b) identifying those components which are relevant to the problem;

(c) collation of readily available data (hydrology, demands, costs etc); identification of obvious operational constraints;

(d) desk study formulation of first draft;

(e) discussion of first draft with operations personnel who run system, identifying less obvious constraints and local knowledge, including any formal or informal basis used for decisions; attempting to generate interest and commitment on their part; formulation of second draft;

(f) brief appraisal of application of second draft using available data (often limited to less than 10 years) in a simple simulation study.

(g) User-friendly formulation for 1st year's trial operation;

(h) Trial operation, encouraging regular informal discussions and ad hoc variations suggested to overcome unforeseen circumstances and constraints not initially identified;

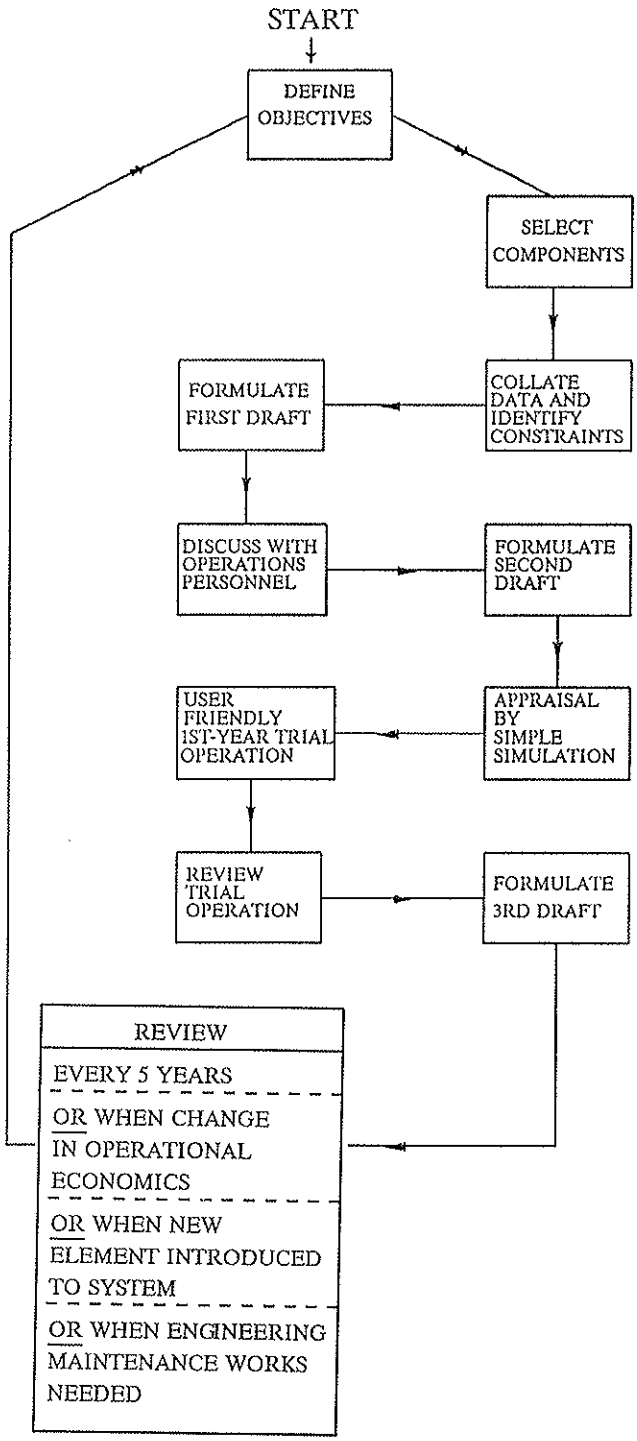
(i) review of trial operation;

(j) issue of 3rd draft formulation;

(k) subsequent review of control rules every five years
or following a significant change in operational economics
or following introduction of a new element to the system.

By the time stage (g) is reached, it should have become clear whether the system generally needs to be operated to maximise output or to minimise operating costs. In some cases the control rules will show that modifications to the system are necessary if it is to meet even the basic objectives. This

was in fact the case with Cwmystradllyn, where the Statutory Provisions in 1984 had no effective facility for reducing the discharge for the Mill as a flexible conservation measure. Accordingly, revised Abstraction Licences incorporating this and other flexible facilities were sought early in 1988 after extensive consultation with river interests: the Cwmystradllyn Rules Curves are now based on the conditions in these new licences, which were approved by the Welsh Office in Autumn 1988.



Chapter 5. Cwmystradllyn Case Study

Cwmystradllyn Reservoir (see plan) is the principal source of water supply for the Lleyn peninsula, a popular summer holiday area in North Wales, with a resident population of approximately 30 000. Tourism and farming are the main economic activities. The dam, on the headwaters of the Afon Dwyfor, impounds 2910 Ml of readily accessible storage, with an additional emergency storage reserve accessible by temporary pumping from the original natural post-glacial lake. The catchment area is 5.1 km^2.

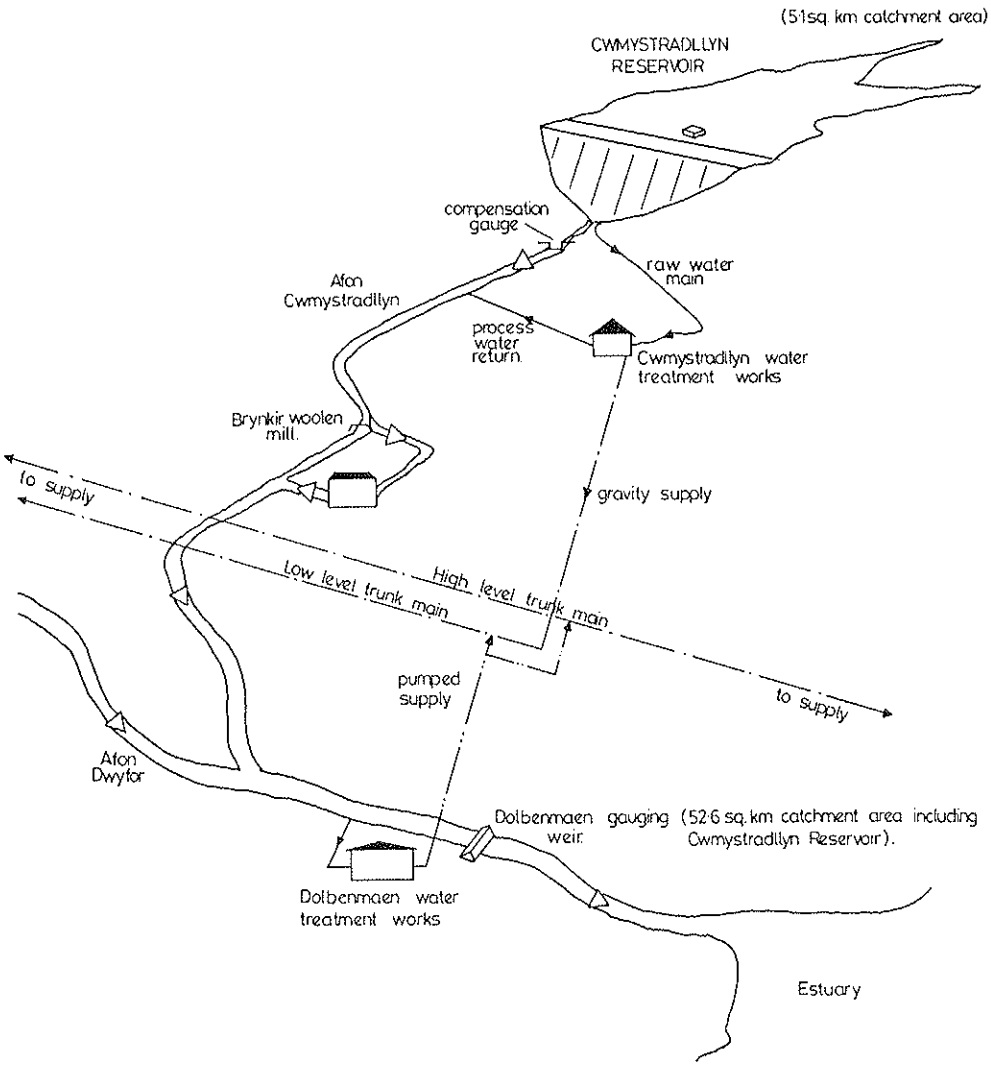
By the late 1970s, rising demands had outstripped the yield of the original direct supply reservoir and Cwmystradllyn treatment works built in the 1950's. Additional resources were provided by raising the dam to its present capacity and creating a river abstraction and new treatment works on the Afon Dwyfor at Dolbenmaen: this allowed Cwmystradllyn to be used in the dual roles of direct supply and river regulation. The relationships between compensation/regulation discharges and Dolbenmaen abstractions, fixed following a Public Enquiry in an attempt to compromise between different interests, were extremely complex. This was prior to any operational experience of running the new system. There were no control rules specified for the system operation.

No real problems were experienced until 1984 when a significant drought occurred and very severe restrictions on compensation water, residual flows and non-essential mains water supplies had to be imposed from mid May onwards, using the powers of the Drought Act 1976. The immediate response after 1984 was to assume that the resources were inadequate, and a new £1m scheme to link the supply area with an existing direct-supply reservoir to the north was actively considered.

However, derivation of draft control rules using the 10 Component method early in 1985, showed that if the resources could be managed more flexibly, – in particular if the component of compensation water discharged for a Mill could become optional rather than a statutory requirement – then, combined with a range of other measures (including simplification of the licence conditions), all interests could be safeguarded (and even enhanced) by improved management of the existing resources.

Between 1985 and 1988, there were extensive consultations with the major riparian interests (fishery and mill) and voluntary agreement was reached by late 1987 on a package of measures which included benefits for all concerned. These measures were incorporated in amended Abstraction Licence Applications, which were advertised and approved in 1988. The following Control Rules, derived using these new methods of operation, show that the system is capable of operating effectively even in a drought as severe as 1984. The Control Rules have also highlighted a previously unidentified problem: that of ensuring refill during dry winters. This will be particularly important whenever an 18-month drought, similar to those in 1887/88 and in 1933/34, recurs, as it surely will at some time.

The two main control rules are shown in Fig. 5.1 (based on Cwmystradllyn



level/storage, see p.28) and Fig. 5.2 (based on river level/flow at Dolbenmaen gauging weir, see p.29). Both figures are incorporated in the 'Dwyfor General Directions' (Ref 5), an operational manual which describes the necessary actions more fully. All critical decisions can be based on plotting the current reservoir level and demand on Fig. 5.1 or the river level at Dolbenmaen on Fig. 5.2

To understand how these control rules are derived, it is necessary to study the following Appendices:

A1	Seasonal Demands: split into categories
A2	Basic resources: the formats for the RH and LH axes of Fig. 5.1.
A3	Dolbenmaen Weir Flows, 1984: used to assess times when regulation releases may be required in design drought.
A4	Drawdown Curve: April to October
A5	Winter Refill Curves

Fig. 5.1 is 'blended' from the individual components; this process is difficult to describe in detail because it is partly subjective, but the following observations may help the reader to understand the process:

(i) The vertical scales for storage are drawn on from Appendix A.2 and the design supply requirements are added to the base of the graph.

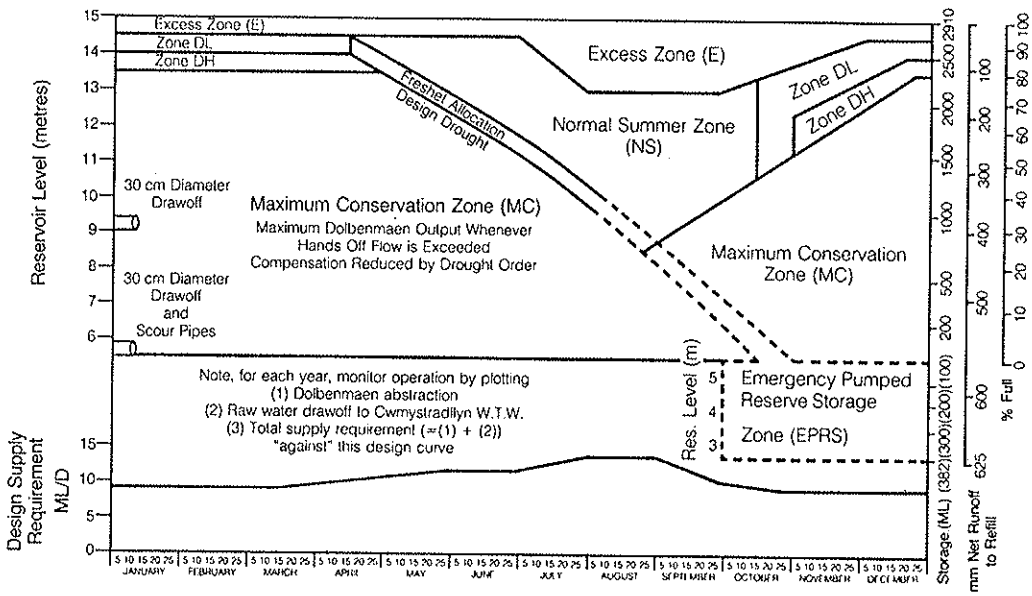
(ii) The drawdown curve (Appendix A.4) is added and the random fisheries freshet demand of 159 Ml (mentioned in Appendix A.1) is added to it.

(iii) The winter refill curves from Appendix A.5 corresponding to basic demands of 12.5, 9.75 and 7.0 Ml/d are pencilled in and are used (with some subjective minor modification) to delineate the Excess Zone (E), Zone DL (Dolbenmaen pumping to low-level mains system), and Zone DH (Dolbenmaen pumping to high-level mains system).

(iv) Section 2 of Appendix A.5 mentions the necessity of initiating conservation measures for winter refill before the autumn for low reservoir levels: the delineation between the Normal Summer Zone (NS) and the Maximum Conservation Zone (MC) in late summer is subjectively drawn by extending the 7 Ml/d winter refill curve back into September.

(v) The Excess Zone (E), defined by the 12.5 Ml/d refill curve between October and March, is drawn subjectively between April and September. When reservoir level is within this zone in August/September, the conditional fishery freshet release of 136

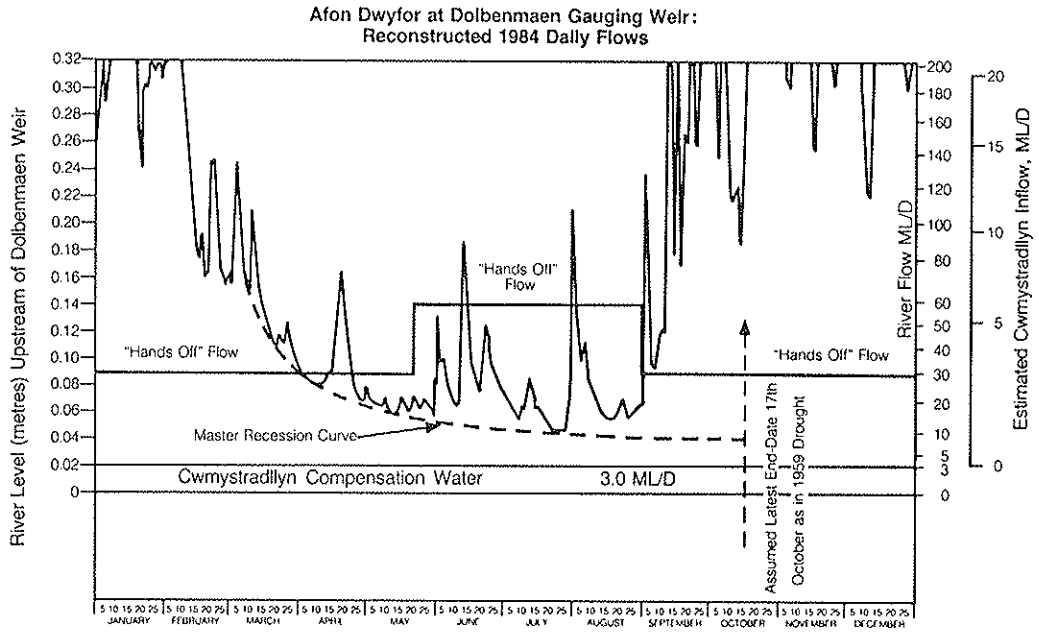
Figure 5.1 Cwmystradllyn Reservoir Control Rules, 1988



Ml (mentioned in Appendix A.1) can be made. The arrangements for conditional and opportunistic Mill releases are quite complex but depend largely upon levels being in the Excess Zone.

(vi) Figure 5.2 is derived from Appendix A.3, with some modifications. A master recession curve is drawn through the base points of the 1984 daily flows, and is extended to 17 October (the assumed latest end-date for the design drought). A second 'flow' scale is added to the RH vertical axis to indicate the probable inflow to Cwmystradllyn for various Dolbenmaen river levels; this is calculated on the assumptions that Cwmystradllyn is not overflowing and that there is a uniform contribution of flow per km^2 of catchment area. It is a simple yet useful device: for example, with a normal demand on Cwmystradllyn in February/March of 16.5 Ml/d (including the Mill release), it can be estimated that reservoir inflow will equal this drawoff rate when the river gauge falls to about 0.28 metres (9 February in 1984): within a day or so, the reservoir level will start to fall below the spillway, which is what happened in 1984.

Figure 5.2 Afon Dwyfor at Dolbenmaen Gauging Weir: Control Rules Graph



The general characteristics of the system are readily derived from a study of these two figures.

(i) The master recession curve (Fig. 5.2) clearly shows that, in the design summer drought, Dolbenmaen flow will be below

'Hands-off' level for almost the whole period between 1 April and mid-October. During this period therefore, whatever is abstracted at Dolbenmaen must be released from Cwmystradllyn reservoir. The drawdown curve in Fig. 5.1 shows there is just enough storage to meet basic demands in the design drought if the reservoir is full on 1 April. So what water resources benefits can the Dolbenmaen facility produce?

(ii) The main water resources benefit of Dolbenmaen is, quite clearly, to safeguard the refill of Cwmystradllyn in dry winters by reducing demands on Cwmystradllyn when necessary. The refill curves have shown how vulnerable the chances of refill are in the 2 summers + 1 winter droughts such as 1933/34 and 1887/88). By simply plotting weekly reservoir levels on Fig. 5.1, reservoir operators will know if and how Dolbenmaen use is to be continued after mid-October (when it is normally shut down, as the supply requirements fall to within the capacity of the Cwmystradllyn treatment works);

(iii) In the single summer design drought, Cwmystradllyn level will start to fall below its spillway in early February and, unless the demand on storage is reduced, there will be a substantial deficiency by 1 April (as occurred in 1984). Again, weekly plotting of reservoir levels on Fig. 5.1 will notify operators when, and to what extent, to start up Dolbenmaen, to take the resources benefit of abstracting from the Dwyfor in February and March when it is above the 'Hands-off' flow, so reducing demands on Cwmystradllyn storage and safeguarding attainment of the required level on 1 April.

The control rules derived are not necessarily optimal in a strictly theoretical sense, but they are practical. Following their derivation, it was accepted by the senior management of Welsh Water that Cwmystradllyn is a resources system which must be operated at the present time on the basis of safeguarding supplies rather than minimising operational costs, since both objectives are incompatible at present demands. Because of the substantial capital investment (at least £1m) needed to enhance the water resources of the Lleyn Peninsula, the most economic management option, now being applied, is

management of resources using the control rules, thus incurring occasional extra operational costs at Dolbenmaen;

plus careful monitoring of population trends;

plus an active leakage control policy to reduce overall demands to below their present level.

plus reduction of process water losses at Cwmystradllyn treatment works by recirculation when appropriate.

Appendix A.1

CWMYSTRADLLYN RESERVOIR SEASONAL DEMANDS (following granting of revised licences in 1988)

1. Basic Demands

Riparian Compensation Water

3.0 Ml/d continuous discharge to the Afon Dwyfor downstream of the reservoir is required as compensation flow. This can only be reduced or suspended by a Drought Order.

Domestic/Commercial Potable Mains Water Supply

The monthly average potable supply (1987 data) varies between 9.5 Ml/d (winter) and 14 Ml/d (summer) - see Appendix A.4 for details. Up to 10.5 Ml/d can be provided via Cwmystradllyn Water Treatment Works (WTW), which draws raw water direct from the reservoir and supplies by gravity into the high level and low level trunk mains. Dolbenmaen WTW provides more expensive pumped supplementary supply with output up to 8 Ml/d when required; it draws water from the Afon Dwyfor and, after treatment, pumps it into the mains (normally the low level network). When the river flow downstream of Dolbenmaen gauging weir falls below a specified 'Hands-off' flow (seasonally variable), daily regulation releases (equal to the Dolbenmaen daily abstraction) must be made from the reservoir to the Afon Dwyfor.

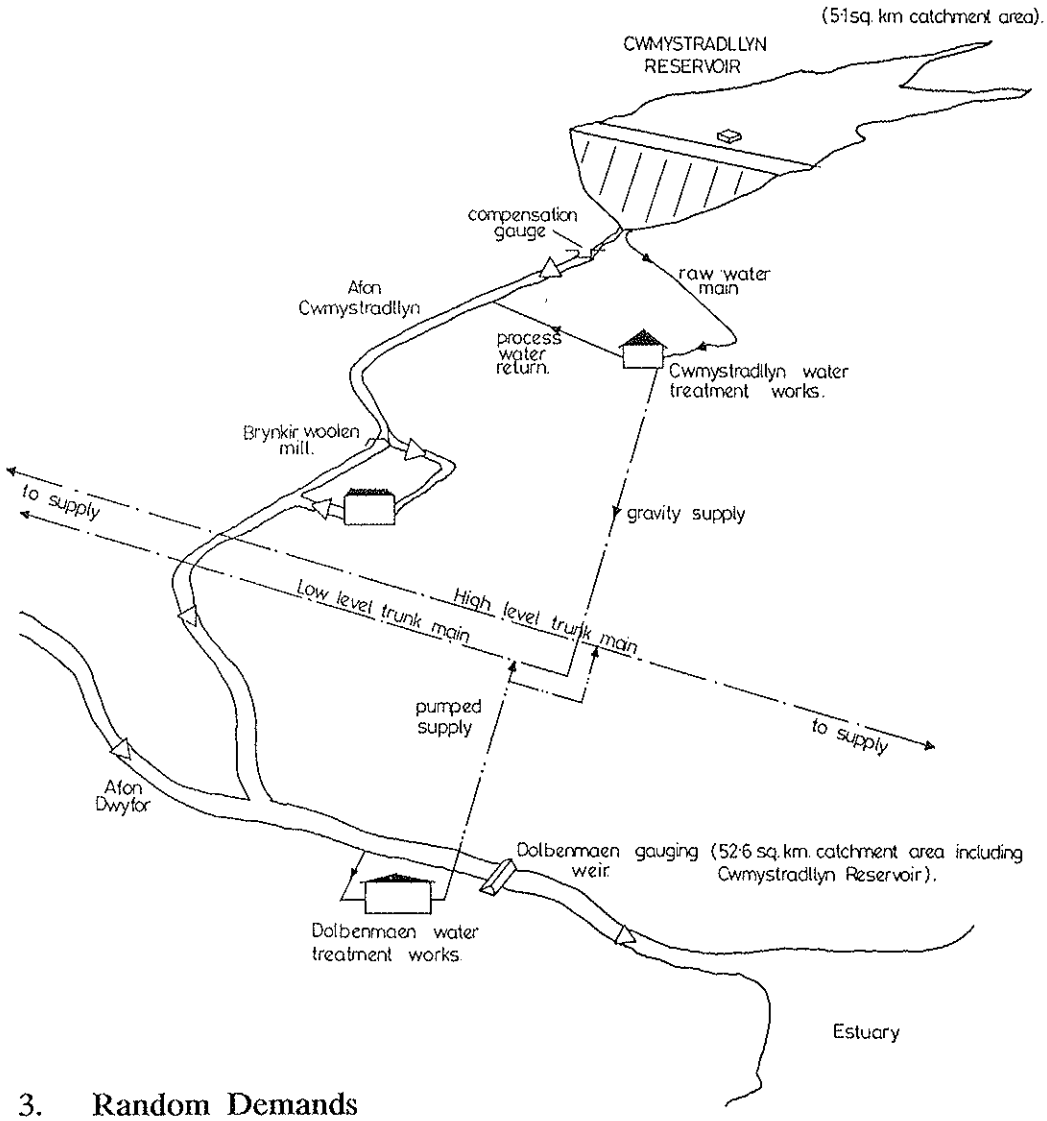
For the initial control rules derivation, the following simplifying assumption is made: between 1 April and the end of the single-summer design drought the gross supply demand on Cwmystradllyn storage is equal to the overall potable demand. This presupposes that:

> support of Dolbenmaen abstractions by Cwmystradllyn regulation releases is necessary throughout the summer in a design drought, and regulation losses in transit are negligible;
>
> leakage losses on raw water mains, and process water discharges to waste at the WTWs, are also negligible.

2. Conditional Demands

3.5 Ml/day (for nine hours on weekdays only) is released from the reservoir to the Afon Cwmystradllyn for on-site power generation at Brynkir Woolen Mill's water turbine and water wheel. This release can be reduced or suspended by agreement between Welsh Water and the Mill, it is treated as a conditional (not basic) demand.

Also, 136 Ml storage is reserved in Cwmystradllyn for provision of fishery freshets in August/September, provided that the reservoir storage exceeds 2070 Ml.



3. Random Demands

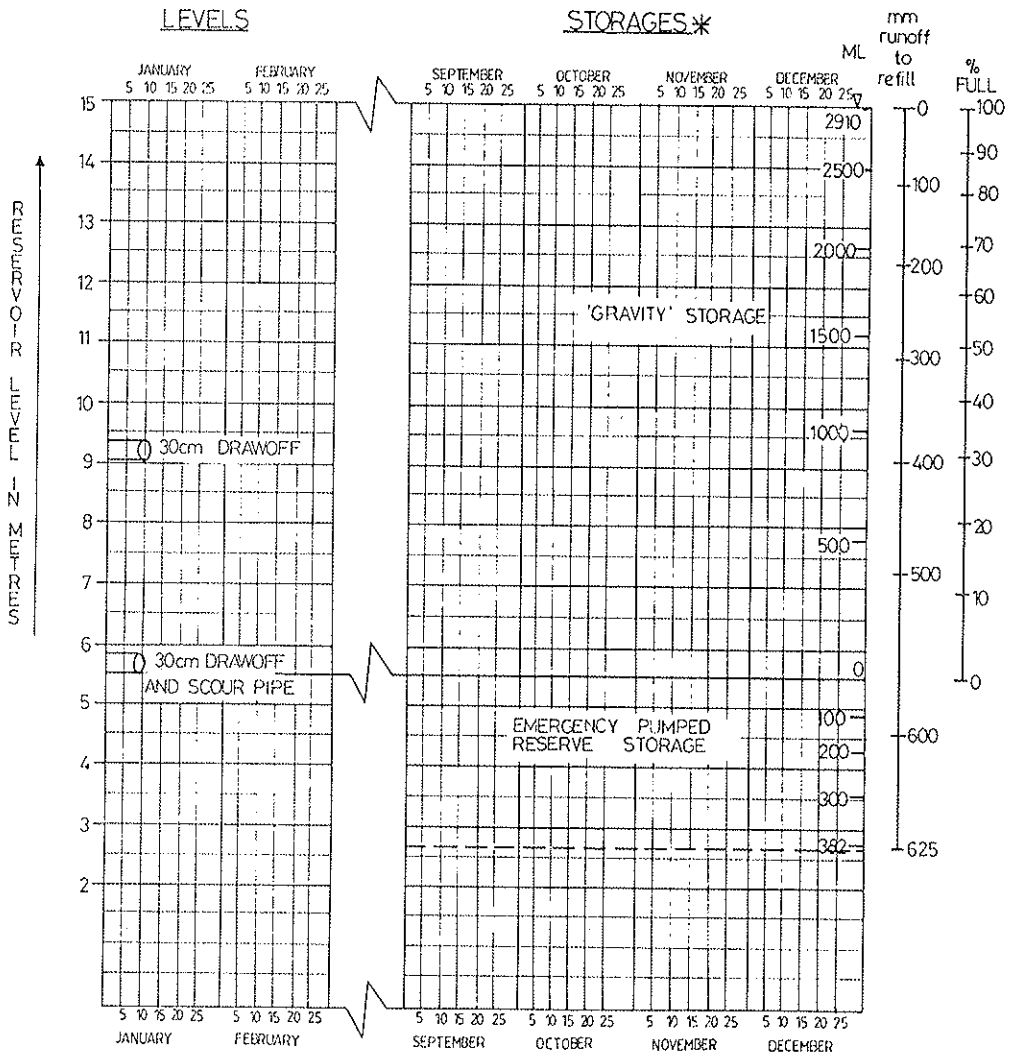
159 Ml storage is required for fisheries freshets between 1 April and 1 November each year; the exact timing of need cannot be specified in advance.

4. Opportunistic Demands

The weekday release for Brynkir Mill can be increased to 4.0 Ml/d when Cwmystradllyn reservoir has 'a temporary surplus of stored water' (to be defined by the Control Rules which are being designed, i.e. the 'Excess Zone' of Fig. 5.1).

Appendix A.2

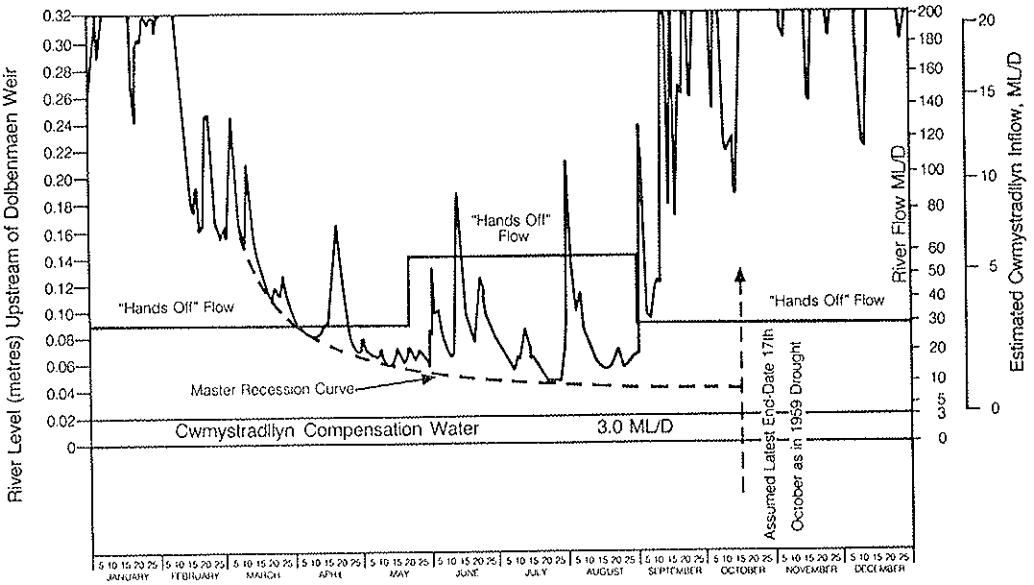
CWMYSTRADLLYN RESERVOIR: BASIC RESOURCES (STORAGE) DATA IN CALENDAR YEAR CONTROL RULES FORMAT



* 1mm runoff on the 5·1 Km^2 CATCHMENT AREA YIELDS 1 ML

Appendix A.3

AFON DWYFOR AT DOLBENMAEN GAUGING WEIR: CONTROL RULE GRAPH



The reconstructed 1984 daily flow sequence has been enhanced by adding

- a master recession curve
- an assumed latest drought end-date, based on the 1959 event.
- a further scale on the right hand vertical axis, which allows inflows to Cwmystradllyn reservoir to be estimated approximately, given the level at Dolbenmaen weir.

The graph also shows the seasonally varying 'hands-off' flow at Dolbenmaen weir. When river flow falls below this 'hands-off' flow, abstractions to Dolbenmaen treatment works must be supported by equivalent releases from Cwmystradllyn storage, so that the mean daily flows downstream of Dolbenmaen weir are not adversely affected. When the river flow exceeds 'hands-off' flow, abstractions to Dolbenmaen can be made from natural river flows without support from Cwmystradllyn.

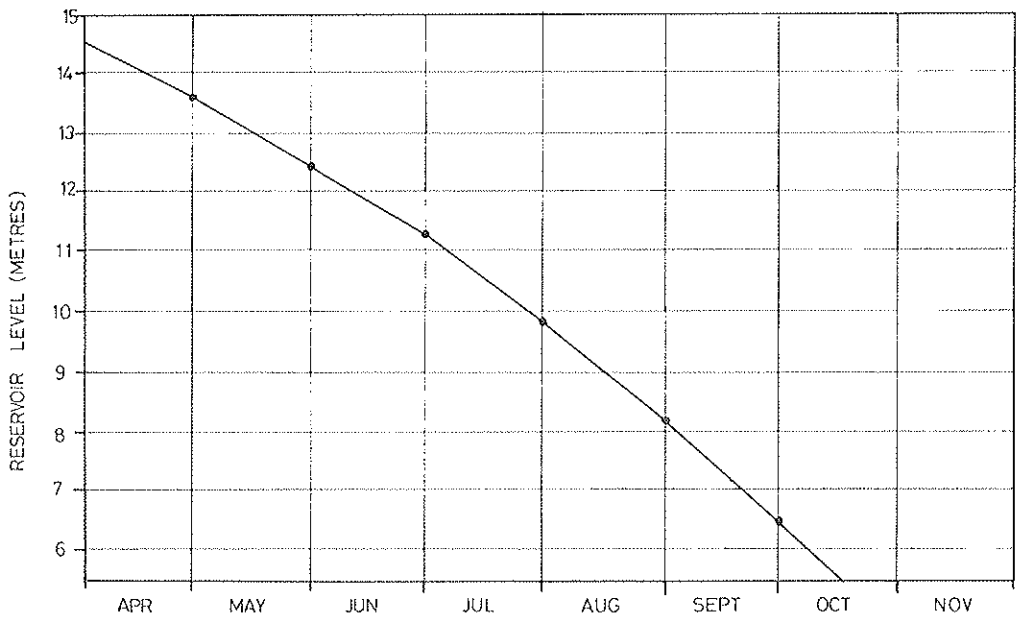
It will be observed that in a drought lasting from early April until mid-October, there are very few days when Dolbenmaen abstractions can be made without supporting releases from Cwmystradllyn. However, during the winter, unsupported Dolbenmaen abstractions can generally be made from natural river flows, thereby reducing demands on Cwmystradllyn storage.

Appendix A.4

DERIVATION OF CWMYSTRADLLYN DRAWDOWN CURVE

Period	Basic demands in Ml/d Comp + Supply - Inflow	Net Demand in Ml	Storage Required Date	Ml	Level
1-17 Oct.	3.0 + 10.0 - 1.5 =	11.5 x 17 = 196	1 Oct	196	6.48 m
Sept	3.0 + 12.0 - 1.5 =	13.5 x 30 = 405	1 Sept	601	8.14 m
Aug	3.0 + 14.0 - 1.5 =	15.5 x 31 = 481	1 Aug	1082	9.87 m
July	3.0 + 13.0 - 1.5 =	14.5 x 31 = 450	1 July	1532	11.28 m
June	3.0 + 12.0 - 1.5 =	13.5 x 30 = 405	1 June	1937	12.47 m
May	3.0 + 11.5 - 1.5 =	13.0 x 31 = 403	1 May	2340	13.56 m
April	3.0 + 10.5 - 1.5 =	12.0 x 30 = 360	1 Apr	2700	14.49 m

NOTES:
1. Average Supply demand mid-October to March = 9.5 Ml/d.
2. Because of reserve pumped storage, assume gravity storage is empty on 17 October, and no safety factor is needed.



Appendix A.5

CALCULATION OF WINTER REFILL CURVES FOR CWMYSTRADLLYN BASED ON RAINFALL DATA

1. Hydrological Data

Precipitation: Estimated monthly precipitation figures at Cwmystradllyn for the period 1921-81 were derived from the Cwm Dyli raingauge, using the ratio of annual average rainfalls (0.63 x Cwm Dyli). The driest January-March (1929, 234 mm) and the driest October-March (1933/34, 709 mm) were selected from the data; based on other long-term records in North Wales, each of these dry spells has a return period of the order of 1 in 100 years.

Evapotranspiration: estimated as 95 mm October-March inclusive
50 mm January-March inclusive

Soil Moisture Deficit: estimated as 50 mm on 1 October
Zero on 1 January

Calculated minimum runoff: from 5.1 sq. km. catchment area

Oct-March: (709 - 95 - 50) = 564 mm
(x 5.1 sq. km.) = 2876 Ml
= 15.8 Ml/d

Jan-March: (234 - 50 - 0) = 184 mm
(x 5.1 sq. km.) = 938 Ml
= 10.4 Ml/d

2. Refill Curves

Refill curves are derived using a 1 April target storage of 2700 Ml (see Appendix A.4), and remembering that the maximum storage (reservoir full) is 2910 Ml.

Normal Demand Refill Curve

The winter basic demand is 12.5 Ml/d (3 Ml/d compensation water and 9.5 Ml/d to supply), i.e. 1125 Ml for January-March and 2275 Ml for October-March.

January-March minimum inflow is 938 Ml, so 1 January storage must exceed

2700 + (1125 - 938) = 2887 Ml (15 metres approximately)

and October-March minimum inflow is 2876 Ml, so 1 October storage must exceed

2700 + (2275 - 2876) = 2099 Ml (13 m approximately)

if refill to 2700 on 1 April is to be assured.

So, using this information, a rule curve can be drawn (p.38) which will approximately define excess storage (above the rule curve). When the level is below the rule curve, Cwmystradllyn storage should be conserved by operating the more expensive Dolbenmaen abstraction (provided of course that the river flow exceeds the 'Hands-off' flow and the Dolbenmaen abstraction does not have to be supported by regulation releases from Cwmystradllyn). Operational experience shows that during short, cold, dry spells in winter, Cwmystradllyn level often falls to as much as 0.5 m below the spillway, before recovering when milder weather returns. Accordingly, on practical grounds, Dolbenmaen is not restarted in December-March unless the Cwmystradllyn level falls below 14.5 metres; the rule curves have been modified to incorporate this important practical point.

Minimum drawoff rate in driest winter after design drought

If storage is 196 Ml on 1 October (see Appendix A.4), and minimum winter inflow is 2876 Ml, then only (196 + 2876 - 2700) = 372 Ml is available for drawoff in the driest winter if refill to 2700 Ml is to be assured: this represents only 2 Ml/d drawoff (less than the compensation water). This clearly demonstrates that substantial conservation measures may be needed *prior* to October in a dry summer to safeguard refill during the winter, and the final control rules will need to incorporate such measures.

For January-March, at 2 Ml/d drawoff, the storage on 1 January could be

(2700 - [938 - (90 x 2.0)]) = 1942 Ml (12.48 m)

for refill to 2700 Ml to be assured.

Intermediate drawoff rates in driest winter

From mid-October to late March, the supply requirement can normally be met from the Cwmystradllyn Water Treatment Works. Dolbenmaen can be temporarily closed down, unless it is needed to meet short-term demand peaks (caused by bursts during the thaw after severe cold weather) or unless it is considered necessary to operate the river abstraction as a means of conserving Cwmystradllyn storage.

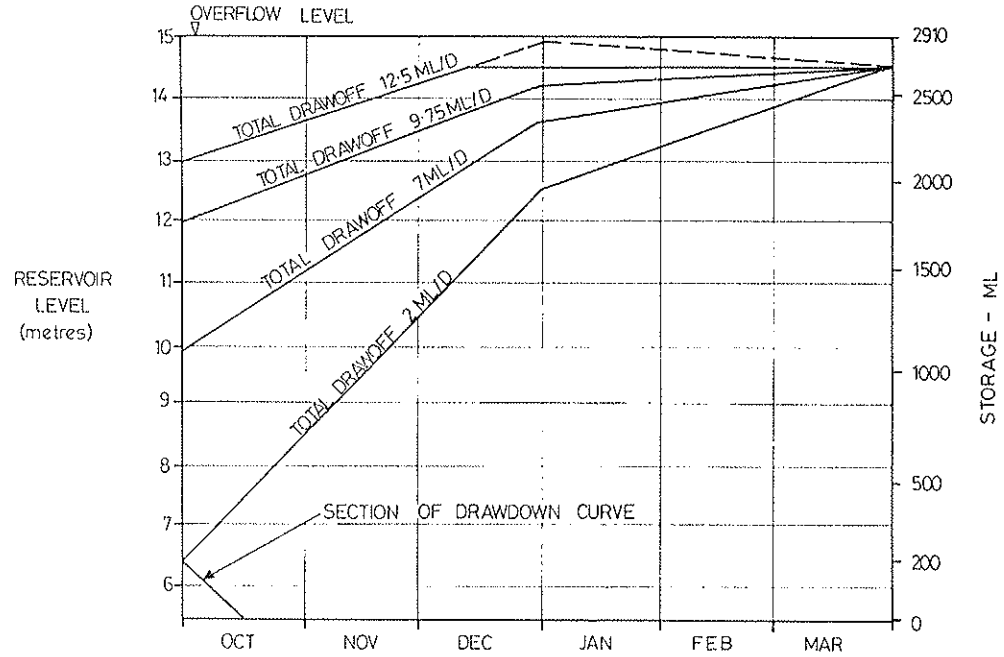
When it is operating in late autumn or early spring, Dolbenmaen usually pumps about 2.75 Ml/d into the low-level mains system, thus reducing the basic winter demand on Cwmystradllyn to about 9.75 Ml/d. It would therefore

be appropriate to calculate a winter rule curve for this demand, and also for a demand of about 7 Ml/d (which assumes that Dolbenmaen is pumping 5.5 Ml/d into both the high-level and low-level mains systems),

Rule curve storage on

1 January for 12.5 Ml/d demand	=	2887 Ml (14.95 m)
1 January for 9.75 Ml/d demand	=	2887 - (2.75 x 90)
	=	2600 Ml (14.24 m)
1 January for 7.00 Ml/d demand	=	2887 - (5.5 x 90)
	=	2392 Ml (13.67 m)
1 October for 12.5 Ml/d demand	=	2099 Ml (12.92 m)
1 October for 9.75 Ml/d demand	=	2099 - (2.75 x 182)
	=	1599 Ml (11.49 m)
1 October for 7.0 Ml/d demand	=	2099 - (5.5 x 182)
	=	1098 Ml (9.93 m)

CWMYSTRADLLYN RESERVOIR : WINTER REFILL CURVES, 99% REFILL PROBABILITY



Notes

1. Using estimated inflows for driest recorded winters (October-March 1933/34, January-March 1929), approximate return period 100 years, giving 99% refill probability.

2. Between mid-December and March, 12.5 Ml/d refill curve is adjusted to a uniform 14.5 metres, to allow for short-term fluctuations of reservoir level and inflow resulting from intermittent cold weather.

Appendix B.1

DERIVATION OF REFILL CURVES USING LONG TERM RUNOFF DATA

For Llyn Celyn (River Dee)

Llyn Celyn, with a total capacity of 80.9 x 10^3Ml, is the largest of the three reservoirs used for multipurpose regulation of the River Dee in North Wales. Significant regulation releases to augment low flows in the Dee are rarely required during the main refill period from October to April, when the seasonal uses of Llyn Celyn are for flood control and hydro-power generation (5 MW). The only basic demand is compensation water (31.8 Ml/d October to March; 63.7 Ml/d April to September).

The target storage for 1 May is 66,649 Ml, corresponding to 4.50 metres below spillway level. The generation and sale of hydro-power (£0.25M average annual income), and other discharges (flood control, extra fisheries releases) up to the maximum controlled rate of 1 thousand Ml/d, must not be allowed to prejudice attainment of the 1 May target storage. Uncontrolled overflow needs to be minimised, or effectively eliminated.

Figure B.1.1 (p,41) shows the refill curves corresponding to 90%, 95% and 99% probability of refill if only statutory compensation water discharges are made. Any particular risk level can be selected. As long as the Llyn Celyn level is above the chosen refill line (effectively an ACTION LIMIT), discharges in excess of statutory compensation water can be made for any appropriate purpose in the knowledge that they will not affect the 1 May refill target. A simple graphical plot of daily level is all that is needed for rapid, effective decision-making.

Two simple examples demonstrate the operational value of the Llyn Celyn refill curves:

(i) On 1 October 1976, after rainfall had recommenced following a severe drought, the Llyn Celyn level was 18.2 metres below spillway, which was very close to the 99% refill curve; Dee abstractors/Minister for Drought could be assured there would be no refill problem.

(ii) On 29 February 1984, hydro-power generation discharges were stopped three days after the Llyn Celyn level fell below the 99% refill line. During the subsequent severe drought, which lasted until September, it became clear that this prompt early action had been one of the most effective of all the water conservation measures taken in 1984.

EXAMPLE OF CALCULATION OF REFILL CURVE

The refill curves in Fig. B.1.1 were calculated using a 97 year monthly runoff record, based on the Llyn Celyn 1969-75 'naturalised' measured runoff extended by correlation with the nearby Lake Vyrnwy 'naturalised' measured records (1879-75). Initially, the reservoir inflows were listed for the periods:

(i)	April (alone)	
(ii)	March-April	(sequential 2 months)
(iii)	February-April	(sequential 3 months)
(iv)	January-April	(sequential 4 months)
(v)	December-April	(sequential 5 months)
(vi)	November-April	(sequential 6 months)
(vii)	October-April	(sequential 7 months)

In the 97-year record, three dry winters dominated the data. 1887/88 and 1933/34 had almost exactly equal lowest runoffs for the 7-month period, and were the driest for 6 month duration, but the driest 5,4,3,2, and 1 month periods occurred between December 1928 to April 1929.

By probability analysis of each separate set of runoff data (i) to (vii) above, the runoff (mm) for each n-month period corresponding to any selected per cent refill probability could be determined. Corresponding Llyn Celyn inflows (Ml) were then calculated for the 59.9 km^2 direct catchment area, enhanced by 8% to allow for a catchwater diverting runoff from an adjacent small valley into Llyn Celyn.

The table below Fig. B.1.1 shows the remainder of the calculations, in this case for the 99% refill chance. The net inflows (column D) are the 99% inflows (column B) minus the compensation water releases (column C); it will be noted that at this refill probability, compensation water in March/April exceeds inflow. The storage required at the beginning of each month (column E) is obtained by subtracting the figures in column D from the target storage (66,649 Ml) on 1 May. Finally, storage values in column E are converted to reservoir levels prior to plotting on Fig. B.1.1. Refill curves for other percentage refill probabilities are calculated using the same tabular method.

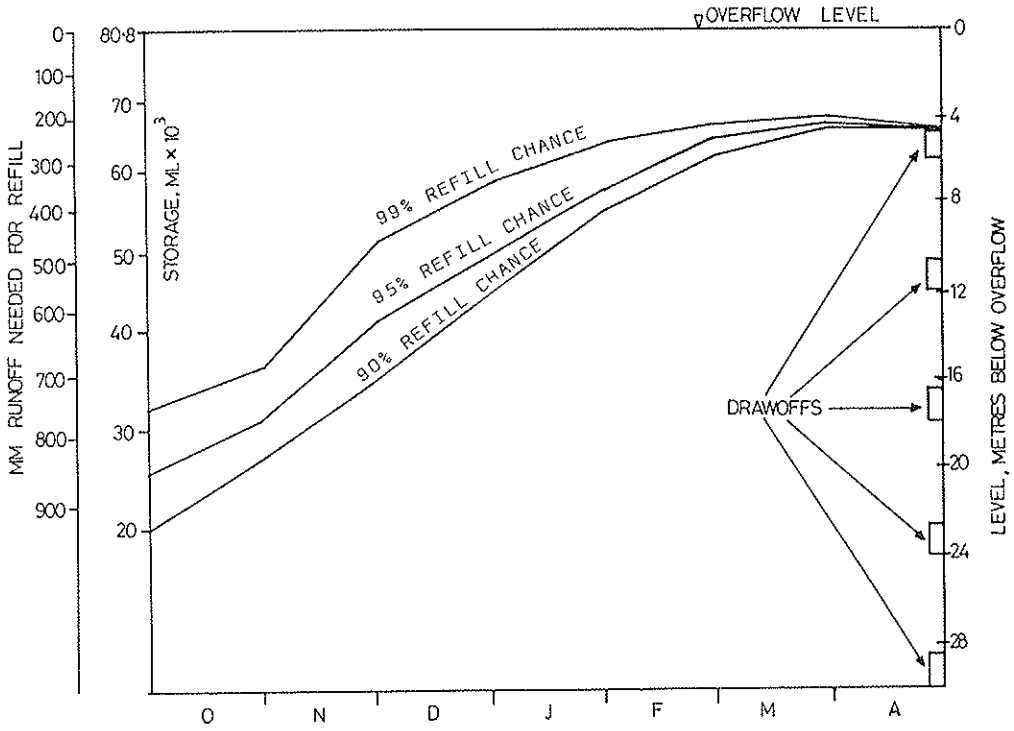
In addition to the 'Ml storage' and 'level' scales on Fig. B.1.1, the following additional useful data are added to the vertical scales:

mm runoff required to cause reservoir to overflow (zero release); this gives a quick assessment of flood storage capacity relative to forecast rainfall;

levels of drawoff tower inlet facilities.

The 99% refill curve is one of the several components incorporated in the overall Llyn Celyn annual control rule curves (Ref 1), which form part of the Dee General Directions.

Figure B.1.1 Llyn Celyn Refill Curves



Tabulated Calculations for 99% chance refill

Col. A Period	Col. B 99% res. inflow (Ml)	Col. C. controlled release (Ml)	Col. D net inflow (Ml)	Col. E Storage required at start of period (Ml)	m below spillway
April	631	1.909	- 1,378	68,027	4.04
Mar-Apr	2,860	2,894	-34	68,683	3.84
Feb-Apr	6,420	3,784	+ 2,636	64,013	5.37
Jan-Apr	12,061	4,769	+ 7,292	59,357	6.95
Dec-Apr	21,099	5,754	+15,345	51,304	9.73
Nov-Apr,	37,092	6,705	+30,387	36,262	15.57
Oct-Apr	43,217	7,690	+35,527	31,122	17.73

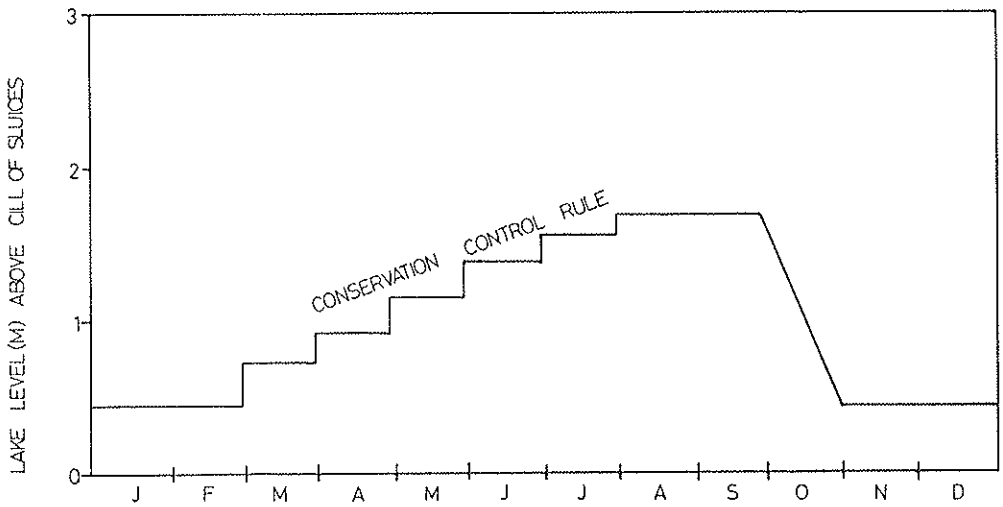
Appendix B.2

LLYN TEGID CONTROL RULES USING BANDWIDTH

Llyn Tegid (Bala Lake) is a natural, over-deepened lake formed during the last glaciation of North Wales. It has a surface area of 3.9 km^2, and is more than 40 metres deep. In 1955/56 the outlet channel was lowered and sluice gates were fitted to allow control of the top few metres of storage and the discharges therefrom for low flow river regulation and flood control.

The controllable storage for low flow regulation represents only about 12 mm runoff (less than 1% of the annual runoff from the 262 km^2 catchment area) and was designed to be used for occasional augmentation of low river flows in the July-September period during severe droughts. The degree of regulation was so small that no regulation releases were needed in most years. The original control rule is shown in Fig. B.2.1, the objective being gradually to build up water conservation storage from March onwards up to a peak in August and September, in case it should be needed, then to reduce it rapidly after the seasonal low-flow period had ended. Storage above the conservation control rule was used for flood control, with maximum seasonal discharges being linked to rising or falling lake levels. The 'steps' at the start of each month could not of course be achieved operationally, and are not recommended as good practice.

Figure B.2.1 Llyn Tegid Control Rules Prior to Llyn Celyn Construction



When a new large regulating reservoir, Llyn Celyn, was constructed on a tributary within the Llyn Tegid catchment during 1962-65, the degree of regulation of the Dee increased, with substantial low flow augmentation releases required at some time between May and October every year to support increased water supply abstractions downstream. It became necessary to review the conservation control rule for Llyn Tegid, because to continue with the original control rule would have meant discharging water to waste whenever Llyn Tegid level slightly exceeded the conservation control rule, and releasing water from Llyn Celyn to support the Llyn Tegid discharge whenever the level fell even slightly below the conservation control rule. Such a method of operation was clearly inefficient in that it did not make the best operational use of the Llyn Tegid inflows and storage.

The general constraints for Llyn Tegid operation in summer are as follows:

2.5 m^3/s non-statutory compensation water;

intensive summer water-based recreation requiring minimum levels, mainly as a sailing and boating lake within Snowdonia National Park;

Llyn Tegid storage needs to be used for balancing peak hydro-power generation releases of 12 m^3/s from Llyn Celyn into Llyn Tegid, to produce steady flow regulation releases from Llyn Tegid to the River Dee;

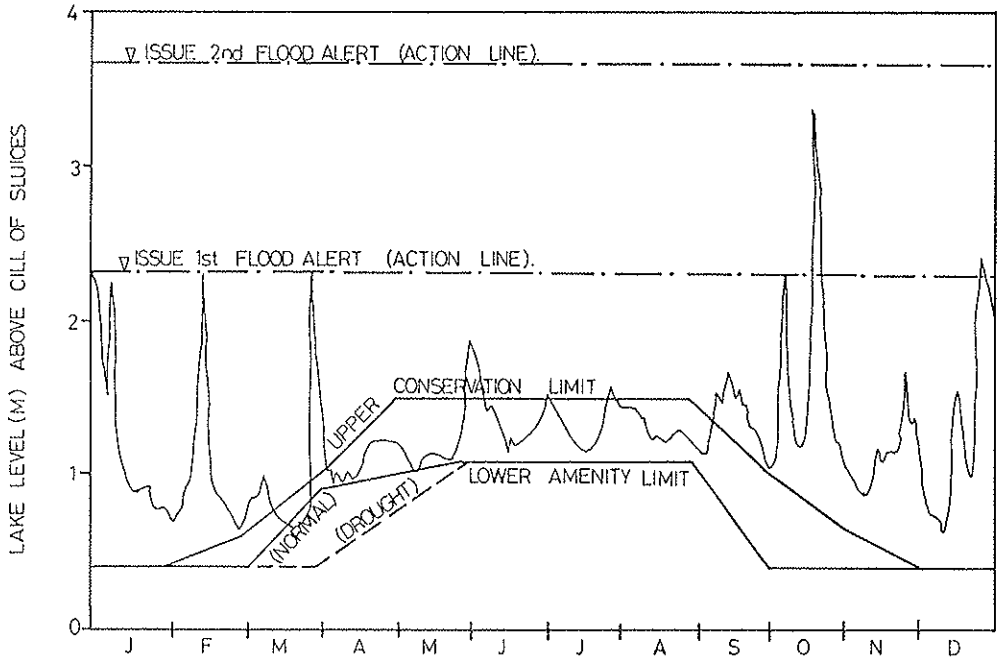
maximum conservation storage 1.5 metres above sluice cill level, remainder of storage used for flood control.

In addition, there would be an obvious benefit to operational yield if the intermittent summer inflows generated from showers of rain on the large catchment area (202 km^2, excluding Llyn Celyn) could be caught and stored, short-term, in Llyn Tegid for subsequent low-flow augmentation releases a few days later.

There have been several variations to the post-Celyn control rules for Llyn Tegid since 1965; the current version is shown in Fig. B.2.2. A compromise range of summer levels is used on a BANDWIDTH principle, with storage above the UPPER CONSERVATION LIMIT used for short-term flood control. The bandwidth of storage between the UPPER CONSERVATION LIMIT and the LOWER AMENITY LIMIT is used several times each year to catch approximately 9 mm of runoff after rain showers for subsequent low flow augmentation. This BANDWIDTH facility enhances the operational yield of the Dee Regulation System by some 48 Ml/d in the design 1 in 100 years drought. The variation of 9 am daily levels in 1987 is also shown, and includes the highest flood (in October) recorded since 1965.

The Control Rules include the facility to increase the BANDWIDTH in March-May by reducing the LOWER AMENITY LIMIT, but only if DROUGHT GENERAL DIRECTIONS are in force: for example, if the other two large Dee regulating storages, Llyn Celyn and Llyn Brenig, have not refilled sufficiently during the preceding winter. This arrangement recognises that recreational interests can enjoy extra benefits in most years provided that the resources remain available for their primary purpose when required.

Figure B.2.2 Llyn Tegid Control Rules after Llyn Celyn Construction, 1987 version.



Llyn Tegid levels can easily be prevented from falling below the LOWER AMENITY LIMIT by appropriate releases from Llyn Celyn. The BANDWIDTH storage is also sufficient to store 2 days of maximum controlled release from Llyn Celyn in Llyn Tegid. This is a very useful facility:

> for improving hydro-power generation income by operating Llyn Celyn at high output for short periods to take advantage of maximum demand tariffs for sale of energy to the Electricity Board;
>
> for timing of Llyn Celyn releases so they can be used for white-water and canoe slalom competitions and training on the Afon Tryweryn (the 8 km long tributary which conveys Llyn Celyn releases down into Llyn Tegid), which has been developed into a first class course on which the 1981 World Championships were held.

Also shown on Fig. B.2.2 are the ACTION LINES for issue of 1st and 2nd Flood Alerts for the Upper Dee when rising lake levels exceed these limits. The detailed seasonal schedules (Ref 6) relating discharges to lake levels (rising and falling) are not reproduced in this brief Appendix. The LOWER AMENITY LIMIT is also an ACTION LINE, in that releases from Llyn Celyn must be made to prevent Llyn Tegid level falling below the LOWER AMENITY LIMIT.

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