Expert System Management of Cascaded Hydro-Electric Schemes

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ABSTRACT

The conventional merit-order based dispatch of generating plant in mixed fuel systems is now frequently superseded by: the scheduling, at base-load, of plant in response to commercial agreements for the compulsory purchase of fuels such as gas; operation of coal-fired plant in the intermediate-load range; and the displacement of hydro plant to supply peak loads. Hydro plant may be dispatched to meet predicted peak demand, to trade electricity at commercially opportune times, to adjust water levels in the system, for environmental reasons or flood mitigation.

In countries where electricity supply utilities have a significant resource of large-hydro many of these plants operate in cascade systems. The hydrological interdependence of plants in cascade hydro electric systems means that operation of any one plant will have an effect on water levels and storage at other plants in the system. Water levels in the system are also affected by the weather. Hydrologically and commercially efficient operation of cascade systems requires that the water and energy are managed simultaneously. This requires considerable experience and expertise. The hydrological and electrical details of cascade systems are extensive but are consulted frequently by the hydro control engineers. Any requirement to schedule hydro plant has hydrological and commercial consequences which require expert judgement of the outcome as part of the decision process. These circumstances should be conducive to the application of computer-based modelling and artificially intelligent decision support.

This thesis describes the principles of cascade water management in the circumstances above and the development and validation of an expert system to predict rapidly the hydrological impact of possible despatch schedules.

Chapter 1 sets in context the requirement for expert system decision support in the operation of cascade hydro electric systems. Chapter 2 examines the operation of the electricity supply industry and the consequent role for large hydro plants in cascade configuration. Previous modelling techniques are reviewed. Chapter 3 reviews other applications of artificial intelligence to comparable processes and describes the attributes and ultimate selection of object-oriented programming and forward chained decision structures. Chapters 4 and 5 describe the assembly of hydro dispatch schedules and the representation of parameters, components and characteristics of

cascade systems. The incorporation of expert knowledge into a rule base is summarised in Chapter 6. Chapter 7 describes the software system developed in which cascaded hydro plant may be assembled and simulated under the control of an embedded rule base. Chapter 8 presents the results of validation and discusses the results of extensive modelling. Chapter 9 draws conclusions for the efficient management of cascade systems and suggests future work to interface with on-line control systems.

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DECLARATION

I declare that:

a. this thesis has been composed by myself, and

b. the work is my own, except where indicated otherwise, and as summarised below;

Signed :

Malcolm William Renton

DEDICATION

To my daughter Katie, who came into this world in 1990, the same year this research project was conceived.

CHAPTER 1 INTRODUCTION

1.1 Introduction

"We never know the worth of water till the well is dry."[1]

The above 18th century English proverb best describes most peoples' attitude to a somewhat vital resource. Today most developed or developing countries regulate the supply of water resources to ensure that the "well" rarely goes dry and the needs of the population are met. However water restrictions and rationing are widespread in much of the less developed countries and even affect developed countries in temperate Europe, notably Spain in the early 1980s[2] and throughout the 1990s, and the British drought in the Summer of 1995. It is at these times that people realise the true "worth" of water and the need to control it.

Water sourced high in the hills and mountains usually runs freely down through a natural river system towards the sea. Impoundment and controlled release introduces a measure of regulation, and many man-made water systems built since the 1900's have harnessed this flow by employing hydro-electric plants as integral parts of the regulatory control system. This provides an alternative meaning to the "worth" of water since the sale of electricity can bring additional revenue from the movement of water for traditional purposes. Thus water can be considered as having two important functions or "worths" within a hydro-electric scheme: to produce electricity and, in many cases, to regulate the flow of fresh water for either human consumption or land irrigation. Therefore the acquisition, storage and safe movement of water, together with the production of electricity on demand, requires a complicated control strategy to satisfy the diverse nature of the combined water and electrical systems.

This thesis describes the principles of water and energy management, together with the incorporation of these principles into intelligent software to simulate the operation and control of cascaded hydro-electric schemes. Due to the nature of software based research the description of the work cannot follow a linear progression but includes many parallel activities with considerable overlap in the principles involved and their method of representation. Thus the thesis structure contains a number of chapters each covering the main aspects of the work and within each chapter extensive cross referencing has been necessary.

1.2 Hydro-electricity

1.2.1 Water, a source of energy

By a variety of methods it is possible to convert the energy within a body of water into electrical energy, however the nature of the body determines the scale of energy transfer. The oceans that cover 72% of the surface of the Earth[3] are influenced by the gravitational pull of the sun, moon and atmospheric weather patterns, causing them to be constantly in motion with an unrestrained often turbulent surface. Consequently, the oceans are totally outwith human control making it extremely difficult to tap, in any quantity, the enormous potential energy contained within them. The search for a means to capture this energy has included attempts to either create nuclear fusion or utilise Ocean Thermal Energy Conversion[4] (OTEC), each having the potential to provide virtually unlimited energy. Unfortunately these are either beyond the bounds of current technology or at a very early experimental stage. Attempts at harnessing wave or tidal energy have resulted in the construction of several minor experimental power stations over the years, notably the first commercially operated tidal plant spanning the Rance Estuary, near St. Malo in Northern France. This is the largest station of its kind and has a rated capacity of 240 MW producing 550 GWh annually[5] for the French power utility, Electricité de France (EdF). However other than the odd exception, at the time of writing, virtually all commercially viable water (hydro) power plants operate above sea-level extracting the energy from fresh water as it returns toward the sea.

1.2.2 The role of hydro

Electricity Power Utilities (PU) throughout the world produce electrical energy from a variety of resources. In most of the major power stations, fossil fuels such as coal, oil and gas, together with nuclear fission, are used to raise steam in boilers to drive steam turbine generating sets. In some countries, alternative fuels such as peat, wood[6,7], rice husks[8] and combustible refuse are also used to fire steam raising boilers, whilst in others geothermal energy is tapped to produce steam directly. To a lesser extent, where the natural resource is found locally in abundance, or in isolated areas where the installation of large steam raising plant is uneconomical, gas and oil (diesel) are used in combustion engines to drive electricity generators directly. The "environmentally friendly" renewable energy resources (i.e. hydro and wind) have also been widely exploited using water or air turbines as the prime mover. Unfortunately both are, at best, seasonal where the incidence of the primary energy varies almost randomly with time. Wind energy is readily available, is naturally unpredictable, relatively uncontrollable and cannot be stored other than through the commercially unattractive d.c. generation with battery storage. In the case of hydro, there remains an element of unpredictability, but once the rain falls it can be stored or its progress to the sea understood and consequently controlled to be released when the demand for electricity merits. Thereafter the energy is absorbed by the grid where no storage exists either and is then consumed by the connected load. This leads to water and electricity management where efficient exploitation and conservation of the resource requires that the passage of water and generation of electricity are controlled simultaneously.

Unlike thermal stations, the terrain of the territory determines the exploitability of the hydro resources, such that in countries which are flat and dry, hydro makes very little contribution to the overall electricity demand. In other locations with high relief and large river systems, hydro can be the major producer of electrical energy (e.g. Norway where 98% of its electricity needs are met by hydro power stations)[9]. To place in context and outline its overall global importance, hydro accounts for almost a quarter of the world's generating capacity as shown in Table 1.1.

Type	MW($x10^3$)	%
Fossil Fuel	1614	66
Nuclear	274	11
Hydro-Electric	567	23
Others	<1	<1
Total	2460	100

Table 1.1 - Installed capacity (1986) of world-wide electrical generation[10]

In the United Kingdom the distribution of generation is quite different from the world-wide situation as shown in Table 1.2 below. This variation is due to several factors: the availability of particular natural resources; the Government-backed nuclear energy programme; and in recent years, the "dash for gas", utilising natural gas from the huge North Sea Miller field, in both combined cycle and gas fired boilers.

Type	MW	%
Fossil Fuel (Steam)	44,506	64.4
Combined Cycle	6,163	8.9
Gas and Oil	2,011	2.9
Nuclear	11,814	17.2
Hydro-Electric	4,220	6.1
Others	317	0.5
Total	69,117	100

Table 1.2 - Installed capacity (1994) of UK electrical generation[11]

Table 1.2 shows the current level of U.K. hydro capacity to be quite small, at only 6.1% of total generation capacity, however, this does represent 4,220 MW, a considerable energy resource. In Scotland and Wales there is a significant installed hydro capacity which becomes a large fraction of the plant mix available to the PUs.

1.2.3 The development of hydro-electricity

In the realms of power generation, hydro power plants can be considered to be the oldest of technologies since for centuries waterwheels, or more particularly mill wheels, were used to operate machinery by converting the kinetic and potential energy of water into mechanical energy in the form of rotation and torque. Each of these mills obtained their water supply by the construction of a weir across the width of an adjacent river, which diverted much of the water, via a lade or open channel, towards the waterwheel. The water flow over or under the waterwheel paddles produced rotation of the wheel shaft and the resultant mechanical energy was then transmitted to the mill machinery via a bobbin and a series of belt drives.

In the latter quarter of the 19th century, the arrival of the early forms of electricity generator[12] was followed rapidly by the first small scale hydro-electric station, whereby the mill machinery was replaced by an electric generator. The first hydro-electric installation, rated at 12.5 kW, was completed in 1882 at Appelton, Wisconsin, USA[13] Initially many mill sites were adapted for electricity generation, however, waterwheels are simply momentum converters operating at atmospheric pressure causing them to be relatively inefficient with low power ratings (much of the earlier stations were rated less than 2 kW)[14]. Thus other designs of water turbine were developed to operate at or above atmospheric pressure while converting kinetic and/or pressure energy in the water into mechanical rotational energy. The various types of turbine and their methods of energy extraction are described in Chapter 2.

Hydro plants, spawned from the early mill sites, tend to fall into two main categories: *run-of-river* and *storage*, each physically arranged and operated in a different manner. The former uses the natural flow of the river (directly or by diversion) while the latter involves water containment. However, since most mill sites tended to use the flow of water as it came downstream the majority of early hydro plants were run-of-river[15]. In some cases, mill ponds were used to provide water when the river flow was low, however, this "pondage" only offered limited storage which could only supply the station for a very short period of time. New run-of-river stations, often built on abandoned mill sites, tend to be constructed in river systems which offer a sustained flow of water throughout the year. These stations are relatively unobtrusive, being physically small and often embedded in the river or bank, and are classed electrically in the mini- or small-scale hydro capacity between 100 kW to 10 MW per turbine-generator set[16]. A major disadvantage of such stations was that any local hydrological change could immediately affect the operation.

Therefore, the potential for hydro power was greatly advanced by moving away from these run-of-river mill type hydro installations towards new larger storage stations. These storage installations had the advantage of smoothing-out the effect of hydrological variation and, in addition to the constancy of flow available, when the storage is elevated significantly above the powerhouse the potential energy released by the water is increased. Thus to gather this potential energy, a large quantity of water is impounded behind a dam in a storage reservoir at elevations often high above the power plant. This type of hydro plant is more expensive to build, due to the extent and cost of the civil work required, but on a cost/kW basis they tend to be more cost effective than a run-of-river installation[17,18], especially at the higher capacities. Consequently the capacity of storage hydro-stations has steadily increased over the century and today the largest hydro-electric plant, completed in 1982 and having a capacity of 12,600 MW[19], is **Itiapu** on the Paraná River at the border between Brazil and Paraguay.

The result of all these hydro developments is that much of the earth's natural fresh water resource is controlled to ensure that sufficient reservoir water is available to enable the production of electricity, as and when it is required. Consequently, this reinforces the idea that impounding is in effect the storage of potential electrical energy in the form of water, and that the movement of water and the generation of hydro-electricity are inextricably connected. Hence, the management of water becomes a central influence in the management and control of large-scale electrical energy production.

1.2.4 Cascaded-hydro

Water released from storage seldom flows straight into the sea but instead water collected at high elevations cascades in the form of a stream or river down through the countryside. As the river progresses towards the sea, additional infeeds from other rivers or tributaries increase the volume of water entering the system. At many locations the topography and extensive watershed ensure that the river systems are able to sustain more than one reservoir with associated hydro-station(s). Here several reservoirs are created along the river system, where the upper reservoirs each feed into others lower down, via a river or man-made channel, to form a cascade. Thus, in addition to the general increase in site generation capacity, the development of interdependent sites in multi-plant hydro-schemes has become common.

A further consequence of cascading is that hydraulic interlinking of storages and hydro-stations within one scheme (or subsequent schemes) creates a time and output dependence as water is passed to (or withheld from) lower plants. Due to this hydraulic dependency, there is a need for both sound electrical energy and water management to control the water flow through a multi-machine scheme, whilst at the same time optimising the conversion of the hydraulic energy into electricity.

1.3 Electricity grid systems

1.3.1 A brief history

For centuries, the human race has used fossil fuels (coal, oil, peat, gas, etc.) and other renewable natural resources (timber, wind, solar and water) for heating, lighting and operating various forms of machinery. However, due to the diffuse nature of the stored energy, its release from its primary form is not always efficient, sufficiently intense or in the required form to be fully utilised by man. Also, while these natural sources of energy are abundant, they are not always situated where they can be readily utilised, e.g. the main U.K. coal reserves are located in the North & Midlands of England, while the bulk of the population requiring the energy is concentrated in the South-East. Therefore, in the majority of situations, for the transportation and delivery of energy to consumers, conversion to electrical energy and subsequent transmission and distribution by overhead lines, or cables, became the most convenient, efficient and economical procedure. On delivery to the consumer, the electricity is then reconverted to the required energy form, i.e. light, heat, sound, mechanical movement, etc. Consequently, electricity systems were developed and installed using high voltage transmission to permit the bulk transfer of electrical energy between the generators and consumers.

At the turn of this century, electrical power systems usually consisted of an individual power station supplying low-voltage electricity to the local surrounding area. While this type of arrangement met the local needs, any failure at the station would black-out some or all of the area. To alleviate this situation, multiple machines were installed and the station capacity tended to be much larger than the load demanded, simply to provide the necessary back-up when an individual generating set failed. However, this meant that around the country there was massive overcapacity and consequent economical inefficiency, since every station had spare generating sets held in reserve for most of the time. A further disadvantage of this arrangement was that any increase in consumer demand required individual power station uprating or expansion. Such a situation could not be sustained indefinitely due to physical limitations on the space available and capacity ratings of auxiliary equipment within the stations.

As the utilisation and distribution of electricity became more widespread, several neighbouring stations were interconnected to provide electricity to a small grid network covering a larger area. This brought several advantages: any station could be out-of-service for maintenance or repair while the other stations supplied the total consumer load; spare capacity at each station could be reduced; and any expansion of the system could be achieved by building new stations at cheaper and more convenient locations away from the urban consumer load centres. Eventually these small grids began to join together to form larger grids with multiple stations providing a reliable electricity system at standard voltages and frequency. As described in more detail in Chapter 2, these electricity grids became universal, operating economically by generating at large efficient power plants and despatching the energy around the country over high-voltage, low-loss, bulk transmission networks to supply the local consumers via dispersed low-voltage, distribution networks. Today, most countries have a nationwide electricity transmission network (e.g. the U.K. National Grid) to provide the necessary flexibility of allowing the free flow of electrical energy from the large numbers of generating power stations around the country to the consumer load centres.

1.3.2 Grid Control

One major consequence of this high level of interconnection is that the electricity supply systems throughout the world have become volatile in their nature of operation, since there is variable availability of generation supplies from the PUs, coupled with a consumer demand for energy that is diverse and constantly changing.

Locally, the operator of any power station may have the capability to generate electricity at any time, provided there is sufficient fuel available to supply the prime mover(s). However, most major generating stations tend to be connected to the national grid system. They cannot simply generate at will, but, must produce electricity at the right time, for the right price, to satisfy the consumer demand and commercial pressures. This results in an electricity grid system that is centrally controlled and specifically constructed to ensure that the consumer demand for electrical energy is met by a nominated selection of generating stations. Operationally, at the grid control centre(s), the total power demand is continually monitored and, to provide both sufficient generation and a stabilised network frequency, the individual generating stations are despatched (switched-in and loaded) and switched-out as required. Chapter 2 explains this process in more detail.

Therefore, to an extent, the power system consumer demand in general and the grid controllers in particular, dictate when a power station (or PU), can generate onto the grid. However, as most PUs tend to have a number of stations and mixed fuel generation (i.e. a selection of stations operating on a range of fuels such as coal, gas, nuclear and hydro), they do have an element of control as to which of their own particular stations are selected to generate. For example, if a PU is contracted to supply a quantity of electricity, the relative proportions of thermal, nuclear and renewable derived electricity will, in most cases, be determined by the company itself and not the grid operators. Thus the control engineers within each generating company are involved in the operation and control of their own "local" power system, covering their own generation capabilities and the supply of their own contracted demand.

Notwithstanding this autonomous control within a PU, the generation capability of each station remains flexible, but beyond local station control, since they will be centrally managed by the company control engineers to satisfy the contractual demand. Prior to 1991, before UK power system privatisation, the Central Electricity Generating Board (CEGB) together with the two Scottish utilities, (South of Scotland Electricity Board (SSEB) and the North of Scotland Hydro-Electric Board (NSHEB)), maintained the grid network by a simple order-of-merit system where stations were despatched in order of running costs, beginning with the cheapest first and then progressively more expensive plants. However, since large nuclear and thermal power stations tend to be less flexible when it comes to changing generation, they were usually used as base-load stations to provide a stable level of generation. Traditionally hydro plant was used as intermediate priority and, as a consequence, at any time during the day the hydro generation programme may have been altered as stations were despatched and shut-down intermittently to track the rise and fall in consumer demand for electricity.

Since the exact supply and demand cannot be forecast, the process of scheduling and subsequent re-scheduling becomes a continuous task. The base-load stations supply a constant load but due to its inherent flexibility it now seems that the hydro generation allocation is governed purely by the power market.[20] Thus commercial or other pressures to despatch hydro will have an impact on the water resources and storage of energy while hydrological pressure to despatch will have a consequential economic impact. Therefore, any PU with a degree of hydro generation cannot simply be classed as, or operate as, a provider of electrical energy on demand, but, must also be viewed as a manager of the area water resources.

1.4 The need for an expert system

It is widely recognised that in order to achieve effective water and energy management, a hydro company's control engineers must have both a good working knowledge of the dynamics of demand in a national privatised Electricity Supply Industry (ESI), and, an expert understanding of the hydraulic dynamics of individual reservoirs within an interconnected system. In addition, the control engineers must operate the hydro system efficiently, acting in the dual role of power generator and water manager. This ultimately creates a conflict of interest, since from the water manager's point of view, the avoidance of spilling or draining a reservoir is more important than the generation (or not) of power whilst as a trader in the ESI, the optimisation of generation revenue is paramount.

Therefore, within a hydro company, the control engineers must be able to respond to system changes (e.g. station trip or sudden rise in demand) by deciding the best course of action through a series of choices, determined by the condition of the reservoir water levels, anticipation of the weather and an up-to-date knowledge of station availability. Consequently, a great deal of recorded data and experience must be combined frequently during the electricity trading day to produce fast reactions to balance the hydrological and economic demand.

Fortunately, the scheduling of hydro plant is undertaken by experienced engineers who, by their knowledge of the system, are able to assimilate, interpret and use the data to make the appropriate decisions with a high level of consistency. Although, these decision processes are heavily layered, they are both rational and repeatable.

The disadvantages of this situation are:

- the production of generation schedules can vary from engineer to engineer based on their knowledge, and subsequent use, of the data records, together with their (unwritten) experience, frequently leading to correct but occasionally inconsistent courses of action.
- the experience and knowledge will be transferred or retired with these staff and cannot be readily passed on to a newcomer.

- the extensive hydrological information used by the control engineers. The data tends to be recorded on paper in the form of large tables, although more recently, much of this data has been moved on to computer spreadsheets, simply as a more efficient means of data storage and retrieval.

Such circumstances are conducive to the application of a logical **decision support system** or **expert system** that, with direct access to these data spreadsheets, could be used to forecast or hindcast the consequences of water availability and generation scheduling.

1.5 Thesis Outline

This thesis describes the principles and practice of water and energy management proceeding to the development and validation of an expert system that is able to rapidly predict the hydrological impact of possible despatch schedules. The main thrust and aims of the research were not to develop the best possible expert system, but to design, test and prove the application of an expert system while investigating and adding to the knowledge of combined water and energy management of hydro cascades. The resulting suite of software, embodied in the **Water Manager (WM)** environment, is an expert system with the capability of providing decision support for hydro control engineers by simulating the complexities of operating <u>any</u> cascaded hydro-electric scheme within an integrated electricity network.

For the purpose of verification, the research focused on Scottish Hydro-Electric plc (SHE, described in Chapter 4), as an example of a PU that runs several cascaded hydro-schemes. Throughout the thesis SHE methods and schemes are used to illustrate specific points in the research, development and implementation of the Water Manager.

<u>Chapter 2</u> examines in more detail the operation of the ESI and the specific tasks of the control engineers. It continues to outline the water/electrical energy conversion in hydro stations, discusses the control of hydro systems and describes the hydro cascade scheme. This chapter shows that controlling cascaded hydro schemes is a complicated matter, requiring an intimate knowledge of the electrical and hydraulic systems in order to schedule generation with due regard to the operation of the water

network. Finally this chapter reviews previous computer techniques used to model different aspects of hydro scheduling and water control.

Chapter 3 provides an overview of artificial intelligence and outlines the structure of expert system software. The chapter then reviews other applications of artificial intelligence to comparable processes and describes the attributes and ultimate selection of object-oriented programming and forward chained decision structures. The selection of appropriate software to simulate the process of water and energy management is discussed and the merits and features of the chosen software, KAPPA-PC, are summarily described.

Chapter 4 describes the operation of a typical PU with hydro generation focusing on Scottish Hydro-Electric plc. The role of SHE within the U.K. ESI and the tasks of the loading engineer within SHE are discussed. The chapter then describes the procedures followed by the engineers to determine a schedule of generation for the cascaded hydro plants. Finally the representation of power stations and this scheduling process within the Water Manager framework is described.

Chapter 5 provides an overview of the hydrology and hydraulics associated with an individual reservoir or weir. The chapter then describes the representation of each of these components within the Water Manager. The chapter also discusses the representation of a fully integrated series-parallel cascade system.

Chapter 6 explains the creation of the expert system rule base. The determination and gathering of an expert's knowledge are discussed and the subsequent transfer of this knowledge into software is described. A detailed review of the Kappa-PC rule-based system is given and the incorporation of expert knowledge into this rule base to provide the DSS portion of the Water Manager is described in detail.

Chapter 7 describes the software system developed in which cascaded hydro plant may be assembled and simulated under the control of an embedded rule-base. The chapter provides a detailed description of the Water Manager environment highlighting the graphical interface screens with which the user can access or enter data information. The operation of each screen is explained, detailing the control of the software, the installation of a cascade and the operational aspects of a scenario run.

Chapter 8 presents the results of validation of the software and discusses the results of extensive modelling. Some sample results from the simulation of both simple and complex cascades with extreme event scenarios are illustrated and discussed in detail.

Chapter 9 concludes the thesis by recounting the aims and objectives, summarising the work involved, drawing together all interim observations and conclusions from Chapters 2-8 and finally extending from these to make suggestions for future work.

CHAPTER 2 ELECTRICAL ENERGY & WATER SYSTEMS

2.1 Introduction

The task of scheduling hydro stations is greatly influenced by the demand for energy in the electrical system to which they are attached and the hydrology of the water system that supplies them. Electrically the stations must provide energy as directed by the grid controllers and hydraulically they must act as regulators of the storage reservoirs and rivers. When cascaded, the control of both the electrical output and water systems become more complicated, requiring a high degree of expertise.

This chapter describes the control aspects of an electrical grid system (concentrating on the U.K. National Grid) and the operational and environmental constraints that affect water systems incorporating hydro-generation. The final section discusses various computer techniques used previously to model the operation of such systems.

2.2 The U.K. Electricity Supply Industry (ESI)

2.2.1 The ESI since 1991

At the end of 1991 the ESI in the U.K. was restructured under privatisation, a change principally aimed at introducing competition into the market for the generation and supply of electricity. Under the new arrangements, four privately owned generators, ScottishPower (SP), Scottish Hydro-Electric (SHE), National Power (NP) and PowerGen (PG), together with state-owned Nuclear Electric and Scottish Nuclear (due to merge at the time of writing), produce nearly all of the U.K. electricity.

With the exception of Scottish Nuclear each of these generators is able to sell their energy, via the England & Wales "pool"[21] which is administered by the National Grid Company (NGC), to the 12 Regional Electricity Companies (RECs), (see Figure 2.1). In addition to the above, independent generators and Electricité de France may also sell energy via the pool.

In Scotland, SP and SHE have virtual monopolies within their own geographic areas and control all but the smaller, privately owned plants within the generation, transmission, and distribution infrastructure.

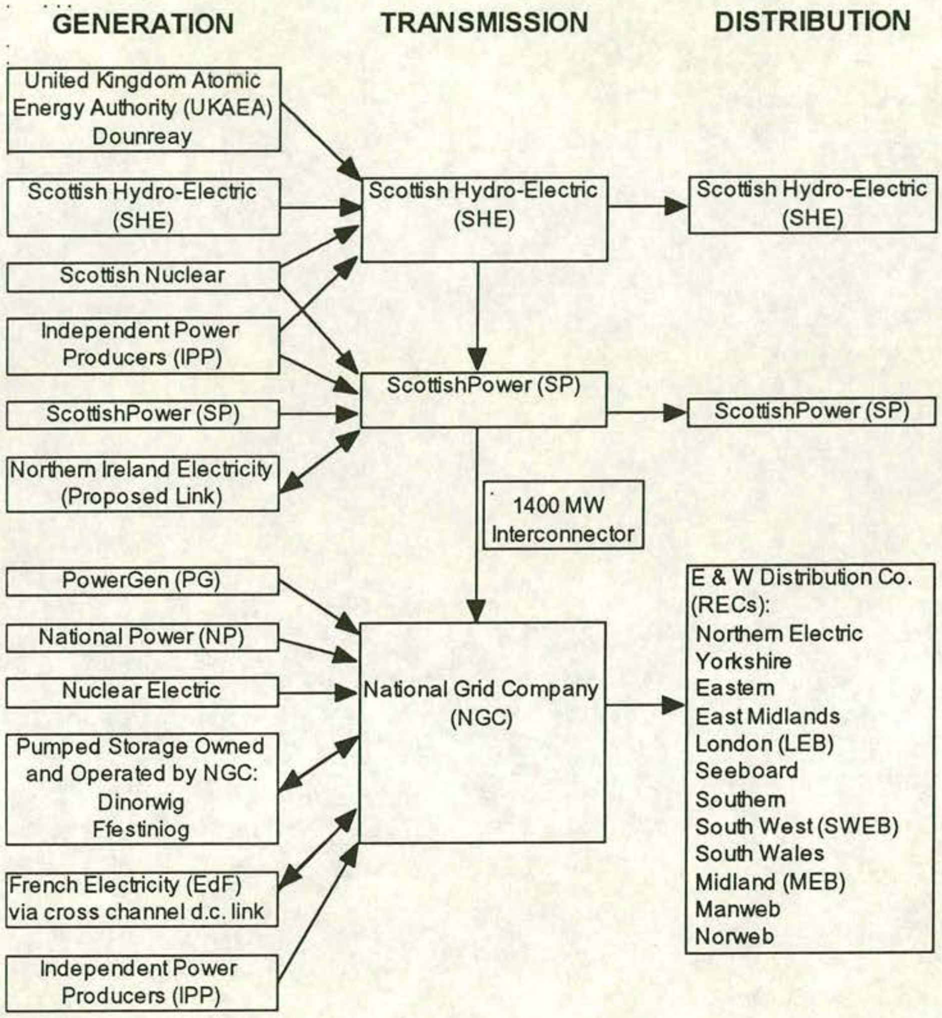


Figure 2.1 U.K. ESI (since 1991)

2.2.2 Power system control

Control of the U.K. power system network is effectively carried out by the owner/operators of the transmission network since this is the link between the energy supply (generators) and demand (distribution to the consumers). The U.K. transmission system is peculiar in that it consists of three solidly connected mainland area networks, in the North of Scotland, South of Scotland and England & Wales. A fourth section, covering Northern Ireland, is presently isolated from the mainland grid transmission system, although at the time of writing an undersea cable link to the main system is proposed. Each of these mainland areas is controlled, respectively, by the main grid control centres of Scottish Hydro-Electric (at Pitlochry), ScottishPower (at Kirkintilloch) and National Grid Company (at Wokingham). Therefore these three Central Control Rooms (CCRs) operate and control the entire transmission network, but in particular they are responsible for the following[22,23]:

1. Safety of the power system.
2. Continuity and security of supply
3. Meeting customer demand.
4. Energy trading.

The first three functions are stipulations of the Electricity Act 1989 and are overseen by the principal regulators of OFFER (Office of Electricity Regulation), the Secretary of State and the Director General of Electricity Supply[24].

Within the CCRs, among other financial, technical and management staff, the major operational responsibilities are performed by the following personnel: the **Control Engineer** (CE), the **Loading Engineer** (LE) and the **Day-Ahead Engineer** (DAE). (Note: these positions are notional, since the titles may vary from company to company and their general tasks may overlap or be carried out by several people, but, by defining the engineers, their functions can be separated.) The engineering function of each is briefly explained in the next sections.

2.2.2.1 The control function

The CE, deemed the Official in Charge (OIC), is responsible for the running of the Transmission and High-Voltage Distribution system. This task entails continuous monitoring of the system on mimic diagrams and SCADA (System Control And Data Acquisition) video screens. These provide details of the loading on each line, power outputs from each station and switching and line or station fault indicators. A separate satellite system is also used to monitor approaching lightning storms. Should any changes or system disturbances occur the OIC would co-ordinate corrective action to minimise interruption to consumer energy supplies. This may take the form of switching the energy flow through another route, reducing or increasing generation at a particular station or stations (with assistance from the Loading Engineer), or arranging for maintenance or emergency crews to locate and correct any fault that may have occurred.

An additional function of the CE is to act as Safety Officer, co-ordinating all switching/isolating/earthing operations and issuing Safety Permits to the Senior Authorised Person at Site involved with on-going transmission maintenance or repair in the field.

2.2.2.2 The loading function

The LE co-ordinates the generation and export/import of energy during the course of the day. His main duties are as follows:

- To co-ordinate/liaise between Generation (Production), Distribution and directly contracted customers (e.g. other transmission companies and large industrial users) and the OIC (system faults that require changes in generation).
- To maintain the MVAr Cumulative Transfer Error (between Transmission companies) at or near zero, i.e. ensuring each transmission company minimises their nett reactive power contribution to the network.
- To maintain the MW Spot Difference (between supply and demand) at or near zero, i.e. maintaining the electricity balance on the system.
- To ensure all consumer contracts are maintained.
- To request loading(despatching)/unloading of plant in accordance with a pre-determined generation schedule and as required for the above.
- To log all changes in generation and demand and record the actual output from all production centres (individual power stations or grouped generation).

The LE monitors generation and consumer energy needs on a SCADA monitor and acts on any changes that are either foreseen (i.e. from the day-ahead schedule) or unexpected (a fault or change in consumer load). This involves a simple loading procedure whereby the LE would request station controllers to provide additional generation despatch, turn-down or station switch-out as required. Normally, the LE would issue these requests over the telephone to the companies' stations, but in the event of MVAr transfer error or the MW spot difference being too high the LE may ask for generation import/export from one of the other transmission companies. For example, when an increase in demand occurs, the LE would have to decide where to obtain the additional energy by the most economical and/or practical option. This can be either by increasing load on specific generators, bringing on additional sets or importing energy from another source. In the event of a major loss of generation or system problem, the LE would assist the OIC by rapidly re-scheduling plant as required to cover the shortfall.

In addition to the general loading, the LE usually has authoritative control of any pumped storage hydro stations, since these tend to be used as a means of reducing or raising the reactive power (MVAr) on the system. To achieve this the turbine-generator sets can be run on standby as synchronous condensers, i.e. operating on no-load at low power-factor, thereby absorbing or contributing reactive power. However, in the event of a sudden change in load requirements, these machines have the capability of motoring or generating within two minutes to prevent frequency fluctuations on the system. On the SHE system Foyers (300 MW) is used for this purpose, Cruachan power station (400 MW) is the equivalent for SP and Dinorwig (1800 MW) & Ffestinog (360 MW) power stations for NGC.

2.2.2.3 The day ahead function

The DAE is responsible for the estimation of the forthcoming demand during the next day (see Chapter 4) and hence the determination of the overall generation schedule for any given period.

Since most grid networks are faced with the same operating philosophy, i.e. to ensure the consumer demand is met by the cheapest available supplies of generation[25], after assessing the likely demand, the DAE sets the prices for the purchase of sufficient generation and/or the sale of any excess capacity to adjacent networks.

In the SHE and SP CCRs, the DAE would be present as part of the generation function of the company, having the additional duty of preparing and lodging bids for export and/or import of energy to/from NGC (see Appendix 1). However, in England & Wales, where generation is separate from transmission, this additional function would be undertaken by a DAE in each of the generating companies.

2.2.3 System Loading

2.2.3.1 Estimating Demand

The amount of electrical energy that has to be supplied to the National Grid from the generating stations to meet the requirements of all the consumers simultaneously, is known as the System Demand. The system demand is not constant, but, owing to the daily routine of industrial, commercial and domestic consumers and the seasonal effects of the weather, the system demand varies, being high in the winter and low in the summer. Moreover, the demand at night is low relative to daytime requirements. Figure 2.2 illustrates these variations in the form of daily load curves for typical summer and winter days.

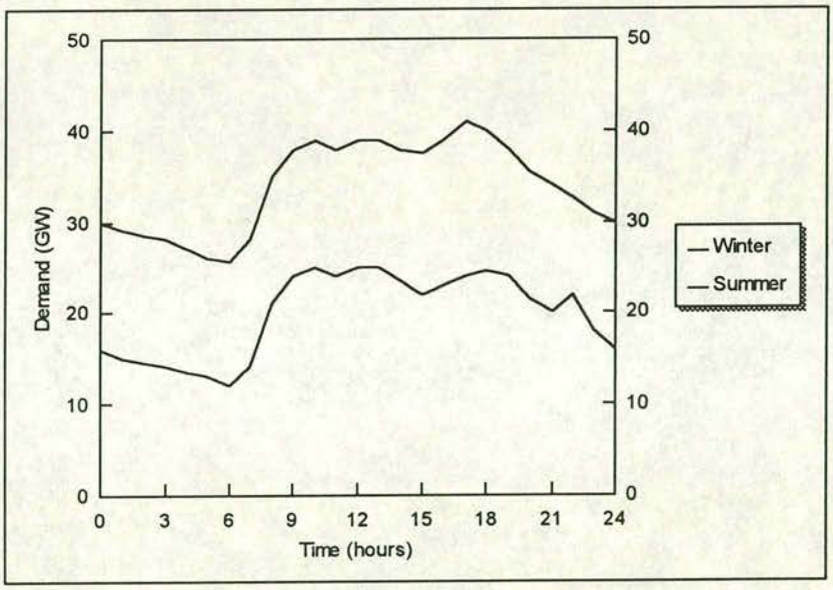


Figure 2.2 Typical Daily Load Curves[26,27]

The day of the week and the effects of advancing seasons will generally affect the timing of peaks in demand. The time of the morning peak remains fairly constant, usually occurring at approximately 0800-0900 hours, however, the time of the evening peak varies considerably from late evening in the summer, to early afternoon in the winter when both industrial and domestic lighting and heating loads coincide.

The effect of weather is one that can produce the greatest unexpected change, since a 1°C change in temperature can produce a variation in demand of around 500 MW during a winter day in the U.K.[28].

Thus for any day of the year a typical daily load curve can be produced and, with due regard to the weather effect, the likely demand on a transmission system can be estimated by the grid controllers. In particular, the peaks in demand must be established, since these are the times when all available generation plant may be required. This demand estimation becomes the basis for the DAE to determine the generation schedule of all stations available to him, with any available energy surplus being offered to the pool (see Appendix 1).

2.2.3.2 System capacity.

In accordance with the Electricity Act[29], the total generation capacity of the UK system must be able to supply at least the maximum system demand (the highest recorded in the UK was 54,500 MW during winter 1991/92 and 48,800 MW[30] on the E &W Grid in January 1996). Additional capacity is also required to ensure that sufficient generation is available in the event of a further increase in demand or to compensate for a generating station or transmission line failure. This additional capacity cannot include stations shut-down for routine maintenance or refurbishment, therefore the total capacity of the system is determined by the capacity planning margin. In recent years this margin in E & W has been 24%, although it is expected to be reduced to 20 %[31] in the near future. Thus the total working capacity of the system is:

$$\text{Total generation available (MW)} = \text{peak demand (MW)} + 24\% \quad \text{............}\textbf{(2.1)}$$

On a daily, monthly or annual basis a measure of the supply utilisation (or variability of load), which also has a direct effect on the tariff cost of electricity, is the System Load Factor[32] (LF). By definition, the system load factor is the ratio of the electrical energy generated (i.e. the time integral of the demand curve) to the rectangular product of peak demand and time.

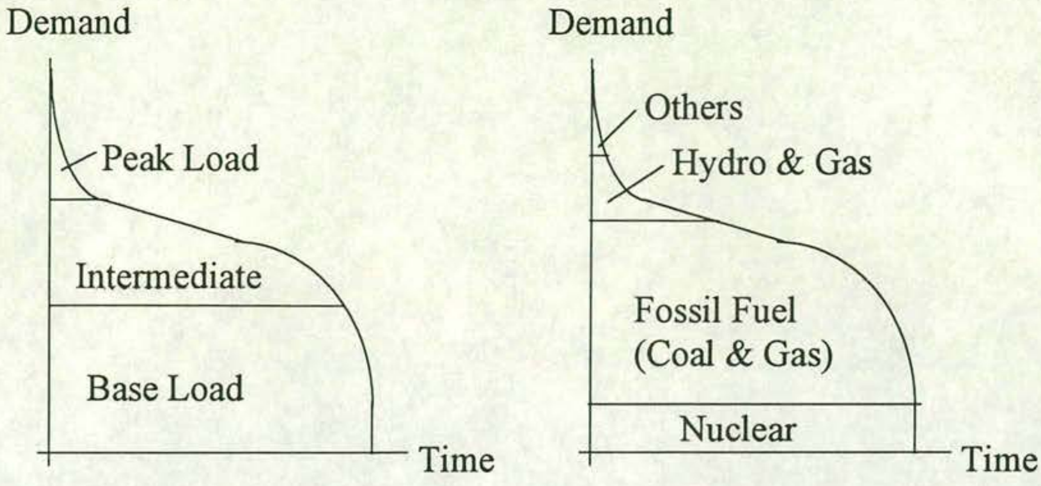
$$\text{e.g.}\quad \text{Annual System LF} = \frac{\text{Annual energy generated (MWh)}}{\text{Maximum Demand (MW) x 8760}} \times 100\% \quad \text{..........}\textbf{(2.2)}$$

A simplified approach to calculate the energy generated is often adopted by partitioning the day into sections then multiplying the average MW demand over the section by the section time period (e.g. a constant 2 MW for a day gives 48 MWhs).

Thus the total energy generated in MWhours and the load factor can easily be calculated from the daily load curve. For example, using the daily load curve for summer in Figure 2.2, the daily load can be calculated by multiplying the GW for each hour of the day, e.g. from midnight to 1 o'clock produces 15 GW x 1 hour = 15 GWh and so on, giving a total of 478.5 GWh for the day. However, taking the system maximum demand of 54.5 GW and a capacity margin of 24% the total working capacity of the system would be 67.6 GW. If this maximum demand were to prevail the total energy requirements for the day would be 67.6 x 24 or 1,622.4 GWh. Therefore, the daily Load Factor, in this case, is 29.5%, i.e. less than a third of the available generation was used. The Annual Load Factor of the U.K. national grid system is approximately 50%, therefore it follows that a large proportion of generating capacity, required to meet maximum demand, is spare for most of the year. To the electricity consumer this situation almost guarantees security of supply but to a generating company it restricts the despatching of available stations. Thus the method employed to meet demand and determine which stations generate becomes vitally important to a PU in its efforts to maximise revenue and ensure generation when the fuel stock (reservoir level in the case of hydro) tends towards a maximum.

2.2.3.3 Meeting the demand.

Previously, the allocation of plant was on an order-of-merit basis, where stations with the cheapest cost/kWh were despatched first and the most expensive last when required to meet the peak demand. The cost/kWh was determined by a mixture of fixed costs (e.g. capital investment, salaries, insurance, routine maintenance) which must be paid whether the station generates or not and variable running costs (i.e. fuel cost, additional wage and maintenance costs)[33]. Since the fuel cost is a large proportion of the overall cost, most stations using the same fuel would tend to lie in the same price bracket. Thus, an electricity network with mixed generation operating an order-of-merit system, would utilise those stations using the cheapest fuel all the time to supply the "base" load, i.e. they would generate constantly throughout the day and year irrespective of the peaks and troughs in the demand. This is best illustrated with the load duration curve (LDC), Figure 2.3(a) where the three categories of load are shown: base, intermediate and peak. The second curve, Figure 2.3(b) shows the generation types that are usually used to meet these loads.



(a) Load Distribution (b) Fuel Types

Figure 2.3 Load Duration Curves[34,35]

On a purely economic basis, it would seem that hydro stations should provide the base-load since the fuel is effectively "free"[36]. However, continuous generation at storage type hydro stations will almost certainly drain the storage reservoirs, limiting their use as base-load. This problem is overcome in countries with high hydro content, where a large number of stations can be used in rotation to meet the base-load.

Previously in the U.K. coal-fired stations supplied much of the base-load but with the advent of nuclear power and the change in relative cost of coal and gas, the base-load stations have now changed. There remains debate as to whether incorporating decommissioning into the costs of nuclear power would leave it as the cheapest form of fuel, however, the nature of nuclear power stations is such that it is impractical to operate at anything other than at continuous maximum generation. This is also true for the latest gas-fired stations that must use the continuous supply of gas to prevent "line packing" where a dangerous build-up of gas-pressure can occur in the supply pipe. Furthermore, it is uneconomical to switch-on and off large coal-fired power stations due to the lead time necessary to bring steam up to operating temperature, i.e. it can take days for a thermal station to ramp-up from cold and a half-hour to ramp-up from hot.

Therefore, it mainly falls on the hydro-sector to meet the fluctuating shortfall during a normal daily cycle, where the hydro generation must increase and decrease in line with demand curve. Of course, this is not entirely the case since the thermal station generators can be unloaded and some fast reaction gas turbines can be used to cover intermittent shortfalls, i.e. peak lopping.

Since privatisation of the ESI in 1991, the order-of-merit system has altered although much of the rationale behind it is the same. Today, the determination of which stations generate is as detailed in the following paragraphs.

Initially, the privatised generating companies must ensure that they have enough generation available to supply their contracted customers (e.g. Scottish Hydro-Electric must produce sufficient generation to supply their own distribution company). The grid controllers then begin by allocating generation to plant that has to run for security and other special reasons - voltage control (e.g. stations at the end of long transmission lines), transmission limitations (e.g. breaks in the grid or transmission capacity restraints), inflexibility of plant (e.g. must-take contracts such as nuclear and some gas-fired stations). The order-of-merit of the remaining plant will then be decided by the generating company using their own merit criteria. The stations at the top of the merit list will be used first to meet the contracted demand. Those stations on the list which are not required by the generating company themselves, may have their generation capacity offered by competitive tender to the National Grid Company (NGC), which uses then this "pool" of power to supply the remainder of the total National Grid demand.

The loading engineers at NGC create another order-of-merit list for these spare stations offered by all the generating companies. Included on this list is the cost of electricity from France which is treated as another power station. The engineers then allocate the plant as required, requesting generation from the cheapest station first and as the demand rises the next station on the order-of-merit list is despatched until, at peak demand, the most expensive plant available is used. As the demand falls the stations are switched out in reverse order, i.e. the most expensive first, etc.

To cover all contingencies such as loss of plant due to short-term availability, breakdown or errors in the short-term estimate, it is necessary to have the spare plant available in various stages of readiness. Thus in the event of frequency falling below the operational limit, due to the loss of the largest generating unit or infeed, or any underestimation of demand levels, the additionally required power stations or generating sets are categorised in the following manner[37]:

a) **Running spare.** Lightly or unloaded plant that is connected to the busbars, i.e. connected to the system but not running at full-load. When required the prime mover supply (e.g. steam to a steam turbine) is increased to increase power throughput and hence produce more electrical energy at the generator terminals.

b) **Spinning reserve.** Plant unconnected to the system but continually rotating. These units can immediately be synchronised to the grid and loaded.

c) **Hot standby.** A station in an advanced state of readiness, i.e. the boilers up to temperature, ready to produce the required steam to run up the turbine generators.

d) **Fast response.** Unlike steam plant which takes a long time to heat up, run up to speed and load, gas turbines and pumped storage hydro stations can start-up and produce electricity in a matter of minutes. These stations tend only to be used for peak-lopping or in an emergency. However, due to the current low cost of gas, many of these traditional reserve stations have become base-load stations.

To summarise, due to this grid system overcapacity, on a given day, power stations can:

- generate at full capacity;
- generate at part capacity;
- be held as spinning reserve;
- be on hot standby;
- be off-load but available
- be out of service for maintenance or repair;
- be out of service for economic reasons;

Thus the loading engineers, within each generating company and at NGC, operate and control the power system by continually monitoring the demand and, by despatching and switching-off plant as required, they always ensure that enough generation is available to meet the national demand. Furthermore, since U.K. hydro despatch is at the sharp end of the order-of-merit, it cannot be constant but must be flexible and available to meet the surges in demand.

2.3 Water Systems

2.3.1 A brief history

Since prehistoric times, natural fresh water systems, consisting of rivers, streams, lakes, etc., have been used by man mainly as a means of travel and a source of drinking water. Early efforts to control the water for irrigation of crops consisted of boulder dams constructed to create small ponds or to divert natural streams into artificial channels. From as early as 3000 B.C.[38] large scale irrigation projects were built, notably in Egypt, many using primitive water wheels and pumps (e.g. the Archimedean screw[39]) to raise the water between different levels of the system. Before the beginning of the first millennium, during the Roman era of dominance, large hydraulic engineering projects incorporating miles of cross-country aqueducts were constructed to carry potable water to man-made reservoirs at the population centres. Further advances in Europe did not occur until the mid to late 1700's when construction began of vast networks of transportation canals and locks[40]. Each of these water systems continued to use the natural features but were augmented by many man-made components including dams, weirs, tunnels, sluice gates, sewers, and drains. Eventually the development of world-wide water systems involving either the diversion (and subsequent return) or consumption of water, increased to embody a number of sub-systems: for the control of excess water (e.g. sewerage, flood prevention, storm drainage), and for the utilisation of water (e.g. potable water, irrigation and transportation). Finally, as described in Chapter 1, hydro-electricity was introduced into some of these systems, initially to utilise the flow of water to produce electrical energy but latterly as a means of controlling the water.

2.3.2 Control of water - environmental considerations

Today the management and control of the world's water resources requires the conception, planning and execution of hydraulic designs to make practical and economic use of water, whilst avoiding environmental damage from far too much or too little water. However, it has been well documented that during construction and in operation, hydro can have significant adverse effects on the environment:

- The local population displacement: the Three Gorges, Yangtze river project will submerge around 100 towns and villages, rendering 1 million people homeless.[41]

- The provision of a huge stagnant reservoir encourages waterborne diseases, and upsets the district ecobalance.[42]
- The change to the water system can cause rivers to silt-up or even seas to dry-up, as in the case of the Aral sea in the former USSR that has shrunk to a third of its size of 30 years ago.[43]
- A dam without a fish-pass creates a barrier to the migratory fish in the local river system.

These effects must be taken into account and minimised during the design phase of a new hydro-electric power station. However, once constructed, the control and maintenance of the water system passes from the civil engineers to the operators of the power stations, thereby transferring environmental responsibility to the hydro controllers. Thus, the utilisation of water for the purposes of electricity generation has to address:

- Flood prevention measures to protect property and lives. Rainfall and water levels vary wildly over a year and, unfortunately, it is usually uneconomic to design and build a hydraulic scheme to cope with the worst "100-year" floods but only on the probability of such an event. Thus the design of the water containment structure and regulating system (operated by the hydro controllers) must be suitable to minimise most flooding.
- Drought conditions. The lesser of the two evils, as far as property damage is concerned, but lack or waste of water not only causes ecological disaster for the local area but it can spell economic disaster to a hydro-generation scheme.

Thus it is accepted that an important function of the hydro-power generating utilities is the management of all the water in the reservoirs and associated rivers which form part of their hydro-scheme. Furthermore, the reservoir water levels and river flows form part of the natural environment, and therefore the controllers must take care to ensure that any operation of a hydro station does not upset the natural flow of a river or the rate-of-change of reservoir level. Also, maintaining this natural balance can become more complicated in a cascade system, where the water throughput of one power station feeds into the reservoir of another. Consequently, it becomes vitally important that hydro operators schedule their water resources in conjunction with the required generation (and vice versa), to produce an environmentally and economically sound schedule of generation output, whilst controlling the water levels and flows through the system.

2.3.2 Control of water - fuel stock considerations

Electrical energy is consumed the moment it is created and can only be stored in very small quantities within batteries. Alternatively as described earlier, potential energy can be stored in huge quantities in the form of water. To release this potential energy, hydro power stations convert the flow of water to electrical energy (refer to section 2.3.3), generally as required by the grid or company loading engineers. However, the ultimate proviso as to whether any station can or cannot generate is determined by the fuel stock. In this respect, a hydro station is similar to a thermal station, i.e. generation can only occur when fuel is available. The major differences are that, for hydro, the fuel delivery system (rainfall) is erratic, fuel (water) cannot simply be bought in when stocks are low and delivery cannot be halted if stock is high. To offset these anomalies in the fuel system, storage of water in large reservoirs can compensate for reduced rainfall during any dry spell, and increased volume due to the abnormal flows that follow heavy or prolonged rainfall. In effect, the dams and reservoirs permit the regulation of water to operate a hydro power station as efficiently as possible and as close to full capacity when required.

Thus the optimisation of revenue from hydro generating plants requires the operators to ensure that energy stored as water does not get dissipated by spillage or by generating unnecessarily when demand is low.

2.3.3 Energy Extraction

The configuration of water turbines varies with hydraulic conditions of head and flow but the two basic elements of all turbines are a means to channel the water through the machine and a runner which drives the generator. The choice of turbine depends very much on the water conditions and the method of extracting the energy from the water.

The energy within water comes in the two forms: pressure (or potential energy, PE) and kinetic energy of motion (KE). The exploitation of this energy and turbine design differs for two categories of head, i.e. high-head between 1800 m and 60 m and low-head from 60 m to a few metres[44].

This head difference leads to a fundamental division of turbine type between impulse and reaction as defined below:

High head

- **Impulse** is where water flows through the turbine runner at atmospheric pressure and surrenders KE only, as it is brought to rest. The energy is surrendered by the force exerted by the water on the runner due to loss of momentum as the direction of the flow changes.

  The most common form of impulse turbine is the **Pelton** wheel (Figure 2.4) which operates by directing one or a number of water jets tangentially onto a series of buckets (shaped to deflect the oncoming water) on the periphery of the runner.

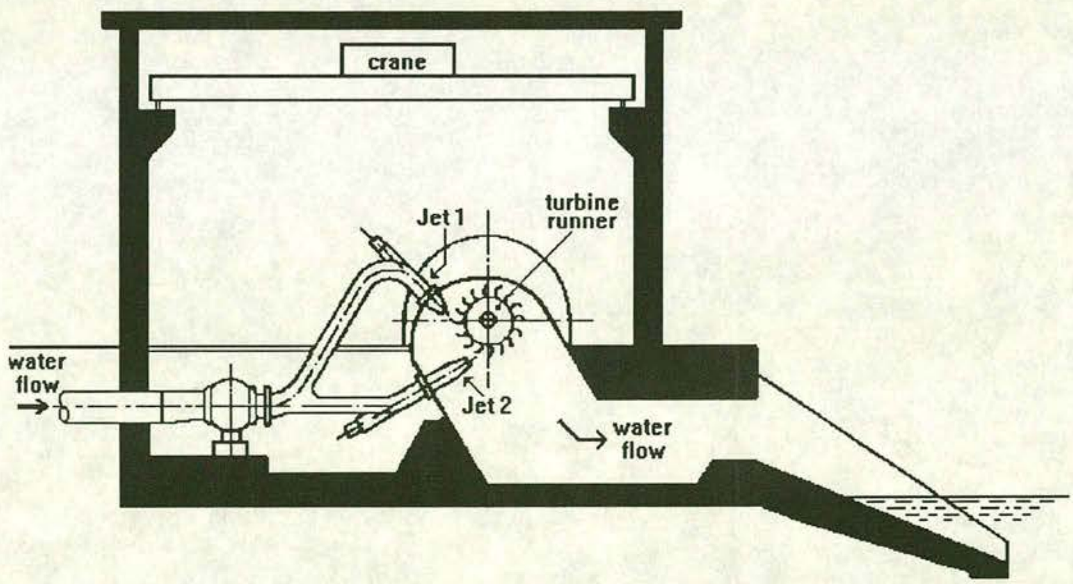


Figure 2.4 The Pelton Turbine

A variation on the Pelton is the **Turgo** impulse turbine[45] developed by Gilbert Gilkes & Gordon Ltd suitable for heads up to 300 m[46] This operates in a similar manner but the water jet enters one side of the runner and exits on the other.

Medium to Low Head

- **Reaction** is when water supplied to the runner possesses energy that is partly kinetic and partly pressure. Both types of energy are converted into work in the runner, resulting in a drop of pressure and a change to the absolute velocity of the water. The runner is in the form of a propeller operating on the principle that the flow and subsequent whirl of water produces rotation and torque. Several versions of the propeller turbine are used all operating on the same principle but with different arrangements. These are:

Kaplan (shown in Figure 2.5), **Tubular**, **S-type** and **Siphon** each having a propeller runner within a horizontal, vertical or inclined tube casing. The generator is usually at the end of a shaft emerging from a bend in the tube. Suitable for heads up to 15 m[46].

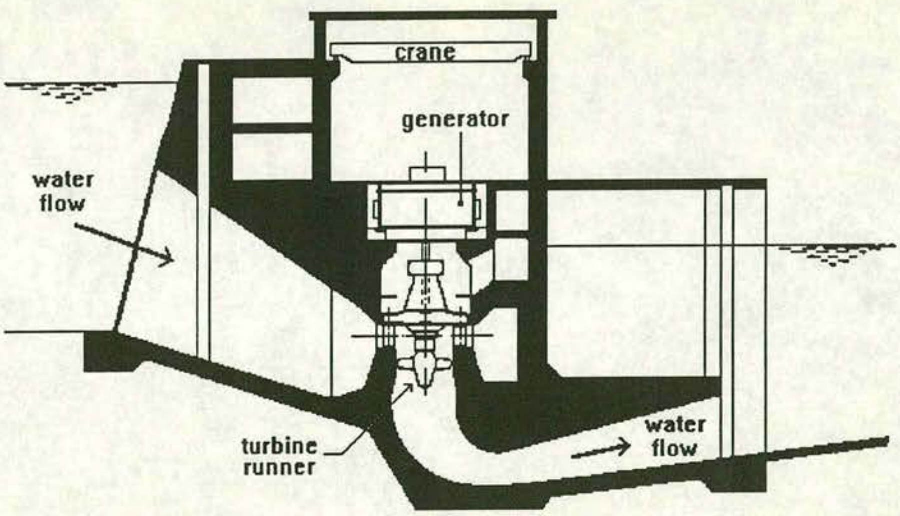


Figure 2.5 The Kaplan Turbine

Bulb turbine where the generator is contained in a bulb shaped structure and the water flows around the bulb to the propeller, normal heads 5-20 m[46].

Straight flow where the generator is located on the periphery of the turbine runner requiring no drive shaft, for heads of 2-30 m[46]

A **Francis** (Figure 2.6) is another commonly used reaction turbine being suitable for medium heads up to 400 m[46]. As with the propeller this again uses the whirl of water to drive the runner, but the main difference is that the water is delivered to the runner via a spiral casing which distributes the water equally and tangentially to all parts of the runner. The "mixed flow" runner is shaped to convert the whirling component of the water into rotating energy then discharge the water axially.

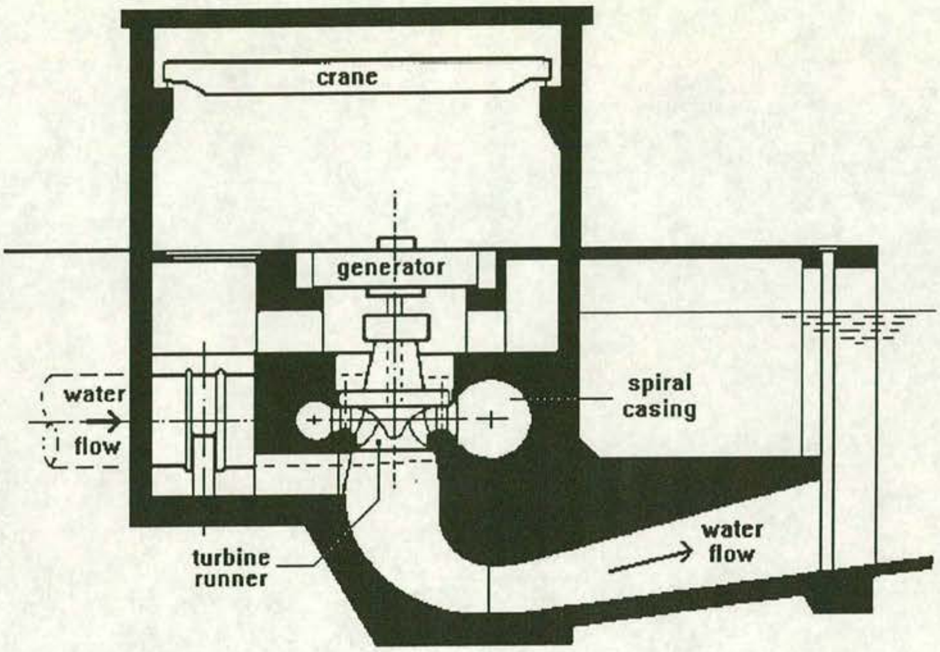


Figure 2.6 The Francis Turbine

Within a hydro scheme a variety of turbine arrangements may be present to best utilise the hydraulic conditions at each individual site. However, beyond the walls of a station one type of turbine-generator set behaves like any other, i.e. a head and flow of water ultimately produces an electrical output. Also the decision to generate is a function of the supply reservoir level and not type of turbine, thus when assessing or simulating the operation of any station the turbine arrangement becomes irrelevant and can be ignored.

2.3.4 Reservoirs and cascades

2.3.4.1 Reservoir/Station arrangement

A storage type hydro system operates much like a tank of water with a tap at the bottom. Open the tap and the water volume within the tank decreases by the volume that flows through the tap. In the hydro system the tank and tap analogy is replaced by a reservoir and power station (Figure 2.7), where the opportunity to generate is purely determined by the availability of water in the reservoir. However, this simplistic idea of a hydro station in total isolation from outside influences is highly unlikely, since, a simple hydro system is supplied with water from rain or runoff (see Chapter 5) and the station operation, i.e. tap open/close action, is largely determined by the power contributed to the electrical system.

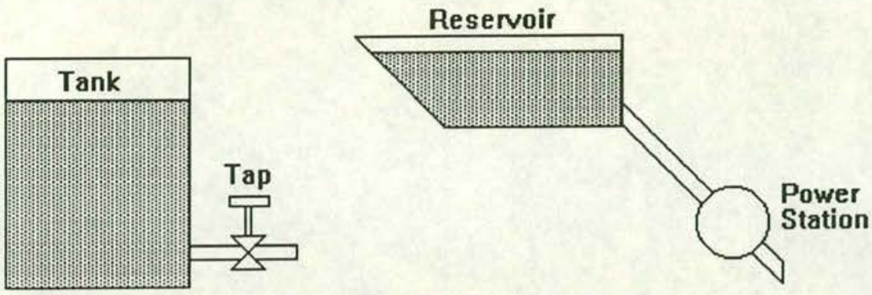


Figure 2.7 Tank-reservoir analogy.

2.3.4.2 Serial cascade

If the simple arrangement suggested above is connected downstream to another simple reservoir/station, the outcome is a serial cascaded scheme. Given sufficient height, a number of these reservoir/station combinations can be serially cascaded down a river valley. One such system, the Quoich-Garry cascade in the SHE Garry/Moriston Scheme[47,48,49], is illustrated below. The scheme comprises Loch Quoich reservoir supplying a head of water to Quoich power station which in turn feeds directly into the Loch Garry/Invergarry Power Station system.

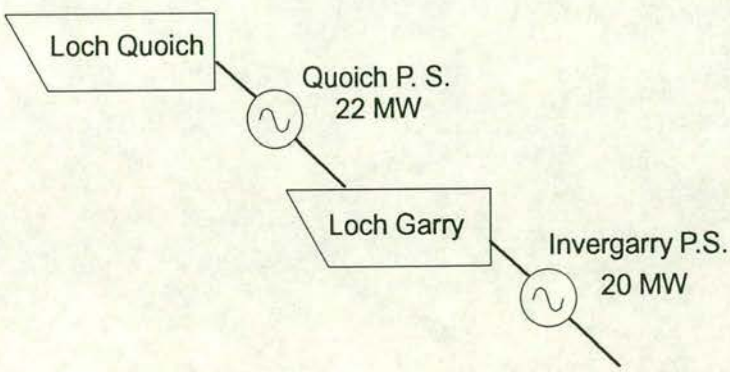


Figure 2.8 Serial Cascade: Quoich/Garry Cascade

By ignoring the electricity grid system and any hydrological effects the implications of cascading and the relationship between the reservoirs and stations can be explained by analysis of the above scheme.

In isolation Loch Quoich level effectively controls whether or not Quoich PS (Power Station) generates and when it does the water flow through Quoich PS draws the Loch Quoich level down while also raising Loch Garry level. However if Loch Garry level is too high then the flow through and subsequent generation at Quoich PS would be prevented. Thus the combination of both Lochs Quoich and Garry determine the generation at Quoich PS irrespective of the availability of water at Loch Quoich itself. Similarly reservoir levels have additional influences, e.g. Loch Garry level is not only drawn-down by Garry PS generation but can also be raised by Quoich PS generation. This also produces non-linearity in the system where previously a reservoir level would certainly fall while the lower station was generating it can now rise or fall depending on the flow through the upper station. Therefore the consequence of serial cascading is to introduce an additional controlling influence to each of the power stations and reservoirs.

2.3.4.3 Serial/parallel cascade

In practice many schemes do not form serial cascades, but may comprise multiple reservoirs, power stations and weirs interconnected in parallel as well as series. One such serial/parallel cascade is illustrated in Figure 2.9 below, where the diagrammatic representation of the SHE Tummel Valley scheme clearly outlines the added complexity of such a system.

The series/parallel hydraulic system also adds to the already complicated control system associated with the water and electrical management of a cascaded hydro scheme. Here a mid scheme reservoir or power station may be affected by several attached systems introducing more control influences to each component within the scheme. This further reinforces the need for decision support to assist the control engineers to tackle an elaborate and volatile electrical/water system.

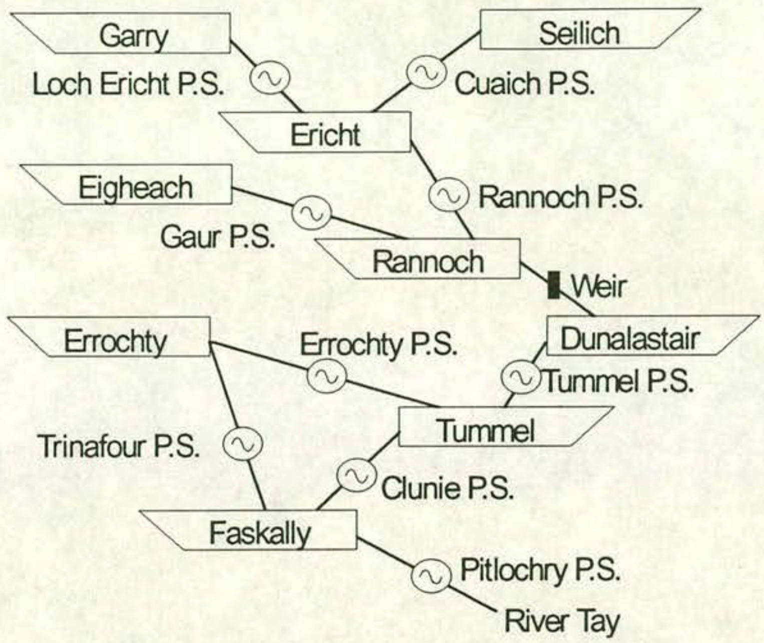


Figure 2.9 Tummel Valley Scheme[50]

2.4 Previous software models

2.4.1 Mathematical techniques

For over a hundred years the operation of cascaded hydro-electric schemes has been regulated by control engineers, whose knowledge and understanding of all aspects of the water and energy systems have kept the generators running and the water flowing. However, in the latter half of this century, the advent of early computers has led engineers to seek more efficient automatic systems to model and simulate the control procedures associated with hydro-generation.

In a localised sense much of this has already happened, where individual small hydro stations have had conventional electromagnetic control relays replaced by Programmable Logic Controllers (PLC) to provide remote control and monitoring of both the water and electrical systems. However, this level of automation only replaces the manual control of isolated reservoir/stations as described in Section 2.3.4.1. The advanced simulation of larger systems involves a more detailed problem domain combining the interlinked hydrological, hydraulic, mechanical, electrical and economic data to produce electricity efficiently from the stored water. Added to this domain are the extra physical effects of the cascaded scheme on individual stations and reservoirs together with the human decisions of the hydro controllers. Thus any modelling and simulation of hydro-electric cascades must combine empirical, conceptual and stochastic methods to provide a sound engineering solution to a complicated control issue.

In the early years, 1940 & 50s, most of the modelling involved calculus and co-ordination equations to solve simple problems involving the water flow through turbines and its effect on the associated reservoirs. Unfortunately, as the simulations tried to incorporate finer detail or more data, the "curse of dimensionality"[51] took over, i.e. the computational burden increases exponentially with increased state dimensions or data variables. Therefore, many of these earlier simulations, had to limit the processed data by using many constants that are in fact time-dependent variables. Also they tended to ignore the hydraulic coupling of cascaded reservoirs and neglect any electricity system restraints[52].

As computing power increased and mathematical analysis techniques improved, the simulation of various aspects the hydro-cascade were undertaken by dynamic programming using a variety of mathematical philosophies: Chebyshev's polynomials[51], minimising Lagrangian functions[52], and probability density functions (PDF) to eliminate randomness of the availability of hydro energy[53].

Many computer simulations have been developed to model the combined electrical and hydro systems, much of these include the simulation of mixed generation scheduling, notably Cristensen & El-Hawary[54], Wirasinha[55], Kirchhmayer[56] and Navon, Zur & Weiner[57]. A few previous investigations have used a variety of analytical techniques and scheme configurations to model the operation of both theoretical and practical cascade hydro systems. The short-term scheduling of hydro has been achieved by Johannesen & Faanes[58] applying a dynamic programming approach to three hydro plants, Bubenko & Waern[59] solving for a five-hydro plant system using the maximum principle and Di-Perna & Ferrara[60] proposed a linear programming approach based on the simplex method. However, each of these approaches have their limitations when applied to real non-uniform systems since they are only suitable for small systems with linear control variables and are unable to cope with non-linearity, e.g. reservoir volume to level correlation (refer to Section 5.6.1).

A non-linear algorithmic approach was taken by Brannlund, Sjelvgren & Bubenko[61] using reduced gradient algorithms and large scale mathematical programming to simulate a multi-river cascade, and Lidgate & Amir[62] programming in FORTRAN IV modelled the scheduling of the SHE (then NSHEB) system.

2.4.2 Introducing intelligence

Recently network flow algorithms have been applied to scheduling and cascade management with variable results, however, these remain simplified and linearised approximations of true system behaviour, giving erroneous predictions and results. Additionally, computers being mathematical in nature, tend to give precise solutions to these mathematical techniques, but are unable to cope with processing when faced with vague and unquantifiable links[63] during processing. Therefore, although much of this early work, provides reasonably accurate models of the physical operation of cascade schemes, they do not take account of non-linearity and the important role of the control engineer whose decisions can completely alter the state of the system. Thus it has become more appropriate to incorporate some level of reasoning within the algorithmic programming, and three distinct techniques are now widely used to provide this "intelligence" to the model. They are expert systems (ES), artificial neural networks (ANN) and the most recent, fuzzy logic (FL).

Expert systems use the concept of rules (see Chapter 3) to mimic the human decision making process. They have been used for many types of applications including energy trading[64], power system analysis[65], switched-mode power supply design[66], and micro-hydro site assessment[67].

An example of an expert system in the hydro sector has been developed by Floris, Simons & Simons[68]. This models the Mark Twain Reservoir System, St Louis, USA consisting of two serially connected reservoirs. The program, MTLES, was developed within GURU, a high-performance shell, using its own programming language (also GURU, based on C). The program was designed specifically for the aforementioned hydro system and operates by drawing on real and statistical hydrological information from a mainframe computer to determine the appropriate levels and generation, based on hydrological trends in the area. MTLES has operated successfully and has been created in a modular design to ease the process of adding and modifying the knowledge base. However, being site specific it cannot transfer easily to control other cascades making it impractical as a generalised cascade control system.

An Artificial Neural Network is a more mathematical approach that uses relatively simple processing units, designed to mimic the neural activity of the human brain. An ANN consists of a number of processing elements, called nodes or neurons which receive input signals and process these by functions using a number of weighted multipliers (links) to produce an output signal. The nodes are arranged in layers, i.e. input, output and one or a number of hidden layers in-between, each linked to one or several adjacent nodes. The completed network would then have a complicated input-to-output mapping structure that can represent the operation of a system by virtue of the massively interconnected parallel processing links. ANN models have the capability to learn, memorise and recall information associatively[69] and by these means, the weights are gradually altered to achieve the desired result[70]. ANN techniques have been used in various applications including load forecasting, power system stabiliser design and transient stability analysis[71]. However, ANNs were considered unsuitable for the development of a generalised water management system since, for correct adjustment of the weights, an ANN requires a large body of "training" data, either in historical form where outcomes are known or from sample problems with pre-determined solutions[72]. Unfortunately, this type of information is currently unavailable for cascaded hydro due to the uncertain response of the combined water and electrical systems. In contrast, expert system rules are determinable, directing the software development towards a rule-based system rather than the use of ANNs.

Fuzzy Logic is a more recent development and runs on similar lines to an expert system, however, the decision making process is not so "black and white", but uses linguistic or vague control descriptions[73,74], i.e. a series of possibilities exist for each uncertainty. For example, where an ES uses single value benchmarks to act upon, a FL program would have a range of benchmarks with alternative actions depending on the state of other variables. This difference obviously makes FL more powerful than ES when decisive action is required from a variety of unclear data, however, where the benchmarks for action are precise ES is much easier to deal with. At the outset of this work FL was relatively new, not fully understood and was itself under development, therefore it was considered to be too innovative and would detract from the main aims of the research. However, it may be advantageous to incorporate FL as a refinement in any future development of this work.

2.4.3 Choosing a modelling technique

Often the simulation models described above have rigid configurations of plant; operate by pre-prioritising the hydro-power stations (by discharge rate or capacity of plant); only offer fixed generation output (once set); assume constant inflows; tend to run a scenario over a fixed time period at a minimum of hourly intervals and consider all days of the week to be the same (a problem referred to specifically by Djukanovic et al[75]). All of these problematic features considerably reduces the flexibility and accuracy of any software model and therefore each must be addressed in any future simulation. Consequently, many of the previous mathematical methods were considered unsuitable for the Water Manager, which is intended to be non user specific, PC based and have considerable flexibility applied to all variables. However to provide an intelligent hydro cascade model, of all the techniques investigated, the application of an expert system was considered to be the best approach. This led to the selection of an appropriate programming environment as described in Chapter 3.

2.5 Summary

The task of scheduling hydro stations is greatly influenced by the electrical system to which they are attached and the water system that supplies them. Electrically the stations must provide energy as directed by the grid controllers and hydraulically they must act as regulators of the storage reservoirs and rivers. When cascaded, the control of both the electrical output and water systems become more complicated, requiring a high degree of expertise and computation.

Previous software models have shown that certain aspects of this control can be simulated, however, most models have either been designed for specific hydro system arrangements or had limited data flexibility. Finally the drive towards all encompassing software that could model any cascaded system while incorporating both intelligence and extensive data access and manipulation capabilities led the author down the expert systems route. The selection of appropriate software and the development of the Water Manager environment is described in the ensuing chapters.

CHAPTER 3 DECISION SUPPORT SOFTWARE

3.1 Artificial Intelligence

3.1.1 Introduction

Artificial intelligence (AI) is defined as the capability of a device, such as a computer, to perform functions or tasks that would normally be regarded as intelligent if they were undertaken by humans. Artificially intelligent devices and processes include robotic controls, sensory systems, language simulators and knowledge based systems[76]. **Knowledge based systems (KBS),** are used to replicate human expert activities, (sometimes known as **Expert Systems**) and are designed to mimic the expert whose activities involve decision making, recommending actions and generally controlling functions. The advantages of KBS are that they consist of knowledge databases filled with expert input, they are unaffected by staff changes, they provide consistent, repeatable decisions, they are easily serviceable and they draw on acknowledged (not speculative) expertise. An additional use of a KBS is to assist and train others to make the correct decisions by consulting a computer rather than a human expert advisor. This latter function gives rise to the alternative term, **Decision Support System** or **Decision Support Software (DSS)**. By definition, the goal of any DSS is not to automate decision making, but instead to assist the decision maker in a partly algorithmic, partly intuitive process. In contrast, an ES is able solve a problem on its own, possibly requiring additional information (but not problem solving ability) from the user.

3.1.2 Languages

AI development began in the late 1950s, but detailed work on KBS only began in the 1960s, and early expert system shells began to emerge in the mid 1980s. Most expert systems are generally designed to meet specific applications, and consequently, some specialised software was designed to show that these computer programmes could rival the performance of human experts in particular specialised fields. Early examples included DENDRAL (for the analysis of chemical compounds) and MYCIN (medical diagnosis and treatment of infectious blood diseases[77]), both developed at Stanford University in 1965 and 1972 respectively[78].

These particular applications used the specialised "symbol-manipulation"[79] language LISP (**LIS**t **P**rocessing language, initially developed in 1958), which together with PROLOG (**PRO**gram Language for **LOG**ic), became the main programming languages in the field of AI. More recently, many software applications have also been developed using a variety of high-level procedural programming languages, e.g. FORTRAN, COBOL or Pascal. Today, due to advanced programming techniques and personal computer (PC) language developments, many software packages, including expert systems, are now also produced in the C language or a derivative. C was originally developed to supersede the assembler language (the most direct way of programming a computer at almost machine code level[80]), thus it retains much of the flexibility of programming at the heart of the computer whilst providing the user with an extremely powerful high-level, multi-function, programming language.

Most knowledge representation languages use symbolic computation, where a symbol, (or object), is designated to represent a collection of associated data within a frame or structure. For each symbol, the structure defines the common characteristics of associated symbols and the particular characteristics of individual symbols. For example, symbols representing "spheres", would each have the characteristics of radius, diameter, volume and surface area, but, each sphere may have different values for each of these characteristics. In addition, the programming languages using symbols provide coding structures in the form of functions, methods or rules to allow the manipulation of symbols and their associated structures. Thus a symbolic program uses a problem area (or domain) in the form of a number of objects to represent a knowledge database, and a set of functions or rules to provide the "intelligence" by acting on changes to the database and predicting an outcome.

An unfortunate aspect of expert systems is that an individual system tends to be unique for a specific application, rendering it unsuitable for other applications. Thus, despite the basic common structure of knowledge representation languages, using a specialised language such as LISP always requires an expert system to be developed from scratch. Therefore, although each system is unique there are generally two common features: rules that are used to represent knowledge about the way the objects interact and an interpreter (or inference engine) which controls when such rules become active. Obviously, these features could be re-used across applications within the same development language, and this gave birth to the now familiar expert system shells[81].

Thus a software designer constructing an expert system for a particular application (in this case Water Management) can proceed with development in any of three ways:

- represent knowledge and control its application using primitive data and control structures offered by standard programming languages such as C.
- programme the entire system in a specialised rule-based knowledge representation language such as LISP or PROLOG.
- make use of a pre-packaged expert system shell.

3.1.3 Expert System Shells

For all types of AI applications, such as DSS, expert system shells provide excellent development environments. They are relatively inexpensive, user friendly, easy to learn and, most importantly, are able to run on commonly available PCs. Unfortunately, expert system shells are less flexible when programming at the rudimentary heart (i.e. at machine code level) of a developing system, but, in most cases the benefits outweigh this possible disadvantage. Hence, of the three avenues offered in the previous section, an expert system shell was considered the most efficient and powerful means of developing the Water Manager. To summarise, the reasons for this choice were:

- Programming within an expert system shell is much easier than programming in a knowledge representation language such as LISP or PROLOG, or a procedural language such as C.
- The knowledge base object structure and inference engine are both supplied with an expert system shell, reducing program development time.
- Expert system shells normally offer facilities to quickly design and build user and application interfaces, again reducing development time.
- Applications developed within expert system shells are easier to maintain than those developed using knowledge representation languages[82].

3.2 Knowledge Representation and the KBS

The basic structure of a KBS comprises a knowledge database, an inference engine, a user interface and software links as shown in Figure 3.1.

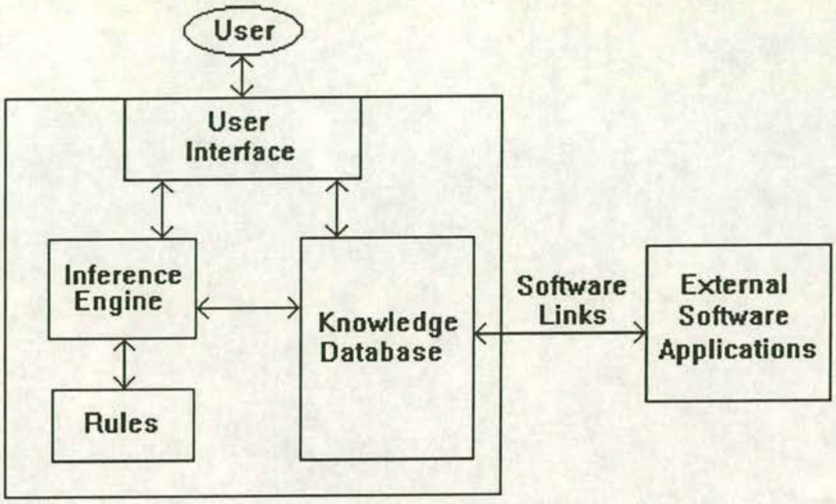


Figure 3.1 Knowledge Based System (KBS)

3.2.1 The knowledge database

The knowledge database holds all the information on which a KBS bases its decisions and recommendations. This information can be located in any number of databases or software files but must be drawn into the system in a form that can best represent the domain being investigated. Currently, the most efficient representation of a problem domain is through a collection of **objects** and **hierarchies**, each of which can be manipulated by a technique known as Object-Oriented Programming (OOP)[83,84], described in more detail in Section 3.5.1.

Each object contains two basic kinds of information: that which defines the object attributes or characteristics (also commonly referred to as slots) and that which specifies what the object can do (methods)[85].

An object hierarchy provides a pyramidal structure of inheritance where the characteristics from a class of object are passed on to sub-classes or instances of similar objects. Within the water management knowledge base, the class *Reservoir* can be defined as an object with several attributes, e.g. volume and storage, together with a method that determines the relationship between volume and storage. Subclasses of *Reservoir* would be the individual reservoirs, each of which would have inherited the common attributes (albeit with discrete values), and the common method of determining the volume-storage relationship. Thus this type of application is ideally suited for the application of OOP, since it comprises several major components contained within distinct class structures, i.e. power stations, weirs, schemes and reservoirs.

A more detailed description of the elements within an object-oriented program is given in the following sections.

3.2.1.1 Slots

Slots can be thought of as individual descriptors of an object[86]. In the same way that fields in a database record describe the elements of that record so do slots describe the data, structure and properties of an object. Slots can have the same degree of flexibility associated with them as fields in a database record, i.e. slots can be textual, numeric, Boolean or object type. In the more powerful systems, slots can have a single value or be a multi-valued list, they can be inherited by subclasses and instances of the object, and most importantly from an object-oriented point of view can have, or inherit, associated methods. An example of a slot associated with the object *Reservoir* is *volume*, i.e. if the volume of the reservoir is 1 million cubic metres then the value of *Reservoir:volume* is 1,000,000.

3.2.1.2 Functions

Functions contain the manipulative information to process basic data contained within the object slots or to manage the slots and objects themselves. Functions range from simple numeric operators such as "+" to more complex standard functions, e.g. "print", or user defined functions.

3.2.1.3 Methods

A method is a special function that defines each action that an object can carry out. Methods are procedures that are represented as object attributes. There are two ways of activating a method: attaching the method to a slot monitor, explained in section 3.2.1.4, in which case it will be executed as appropriate; alternatively it can be activated by sending a message to an object to execute the method. In object-oriented programming, objects inherit methods in much that same way as they inherit slots and different objects can respond to the same message with different methods (although the methods could have the same name). For example, since the value of *Reservoir:volume* is linked to the level of the reservoir, a method *LevVolCalc* could be activated to calculate the new level when the volume changed. Furthermore since the volume-level link is similar for any reservoir, the method can be inherited by all reservoirs.

3.2.1.4 Monitors

Event monitors are object based "switches" that watch the activity of a slot and trigger associated methods under certain conditions. For example, a method may be activated in the event that the value of a slot is changed or a slot value is requested. As described above, *LevVolCalc* would be activated if *Reservoir:volume* changed.

3.2.2 Rules

3.2.2.1 Basic Rule Structure

A rule is similar to the **if..then** statement used in a conventional programming language where the operation is "**if** something is TRUE **then** something else must occur". However, where a multitude of **if..then** statements are necessary, the conventional program becomes cumbersome and slow. In a rule based system the inference engine is a special program that organises the rules and applies them as and when appropriate, thereby eliminating the need to process all the rules each time a change in object data takes place. Where a reasoning process requires only a few conditions and calls for a predetermined series of steps, which is true for most mathematical calculations, rules are inappropriate. However, at a decision node, if there are several possible directions in which to proceed through a calculation, rules add the necessary flexibility and consequently increase the speed of execution.

The conditional statements following the **if** are known as premises, and those following a **then** statement are conclusions. Premises indicate when a rule should be applied, and conclusions indicate what happens when it is applied. For example, a simple rule in a water management system might be in the form:

IF	*a reservoir is spilling*	(premise)
	OR *a reservoir is draining*	(premise)
THEN	*change generation*	(conclusion)

3.2.2.2 Inference Engine

An inference engine is the section of a computer program that guides the application of the rules in a knowledge base in much the same way as a human would do. This inferential reasoning mechanism is distinct from the knowledge base. In a knowledge based system, there are many ways that the inference engine reasons inferentially and controls the reasoning processes for the manipulation of the data represented in the knowledge base. These are explained in sections 3.2.2.3 and 3.5.6.

In order to make the right choices the rules may be prioritised to ensure that they are activated by the inference engine in some order of precedence during reasoning. Thus the relative importance of specific rules can be represented by a priority number which allocates their position in the chain of events.

In deciding where to start a search for an answer, an inference engine can be either goal driven, called **backward chaining** or data or event driven, called **forward chaining**, each described in the following sections.

3.2.2.3 Backward Chaining

Backward chaining can be used to diagnose problems, i.e. to find out why *something* is happening. This processing method begins by asking the inference engine if a certain fact can be established. This is achieved by a chained reaction of affirming rules and the subsequent related (dependent) rules until the operation of the last rule confirms the fact. Thus the objective of backward chaining is to find a rule whose conclusion matches the initial question with a solution, or goal. Thus when a premise of one rule is investigated by seeking other rules with matching conclusions, the inference engine is backward chaining[87].

For example, for a spilling reservoir, the rule reasoning would chain back from the question *Is the reservoir spilling?*. The process would begin by checking the facts associated with the reservoir, e.g. *Is the level a maximum?*. If TRUE the next rule would be invoked to ask if the upper station was feeding the reservoir or the lower station was on outage, etc., until the reasoning process discovered what was causing the problem. Therefore this process would conclude when one of the goals offered the appropriate solution, e.g. *The reservoir is spilling because the level is maximum and the lower station is on outage.*

For a simulation, the disadvantages of backward chaining are:

- it is proactive such that whenever any data is changed the rules must be applied to assess the situation. This can greatly increase processing time in situations where the data is continually changing.
- the process only provides reasons for a problem occurrence not solutions to the problem itself.

3.2.2.4 Forward Chaining

Forward chaining tends to be used to simulate processes, following through the consequence of a change, initiated by entering (asserting) a new fact into the application inference engine, known as event-driven reasoning. The rules assess the effect of such a change and conclude the resultant which in itself may trigger further rules[88]. The final result may take the form of an action to be taken either by the user or the software program itself.

For example, when modelling the effects of a possible reservoir spill, the fact *the reservoir is spilling* is asserted. The inference engine would react by initiating the forward chaining process to consider what action(s) can be taken to prevent the problem, e.g. shut-down the upper station or load the lower station. Thus the main advantage of forward chaining is that it is only called upon to find a solution to a problem when the triggering fact has already been established.

3.3 DSS Development

Given the general features of the best form of KBS above, the steps required to develop a DSS include the following distinct processes in order:

- Overall project planning, which involves the determination of the domain. In this case, the domain is a cascaded multi-station hydro-scheme and all associated influential features.
- Situation analysis, i.e. determining the reasoning process of energy and water management through discussion with the experts and analysis of the mathematical relationships of raw data.
- System design - Selecting the appropriate software and hardware.
- Application development - Construction of the knowledge database, the rulebase and all system interfaces.
- Testing and implementation. - Evaluation and on-site installation.
- System maintenance.

During development the definition of the domain and reasoning process is an on-going task, however, having established the main features of hydro cascade management (detailed in Chapters 4 to 6), the next major step was to select the ES software that would provide the best development environment for the Water Manager.

3.4 Selecting the expert system shell

The general problem when selecting any expert system shell is to match the requirements of the particular application, in this case to simulate cascaded hydro systems, to the features that are available within the ES shell. The conventional approach is to ensure that all necessary features can be accommodated by delaying the selection of the development environment until as late a date as possible[89].

Unfortunately, it is possible, that having determined the domain and reasoning process without reference to a programming language or expert system shell, that no suitable environment exists, or those available are very expensive or have very long learning curves leading to excessive development times. Alternatively, during the software selection process, a number of the application features will be influenced by the array of development environments being tested, thus the selection is likely to have been decided, subconsciously, long before a final decision is made[89].

Therefore, in this case, it was decided to select the appropriate expert system shell, as soon as a thorough appreciation of the application had been gained. This favoured approach is justified since the development of an expert system is often of a prototyping nature, requiring continual revision in response to expert feedback.

Several software packages were evaluated using critical factor analysis[90], a technique where the key design parameters of the application are matched to the features of the available packages. The critical factors were:

- An object structure was necessary due to the high level of common features shared by the major components of the system and the requirement to group vast quantities of data information together.
- A requirement for rule-based reasoning in preference to conventional programming, to provide a fast inference operation over the large volume of data.
- Easily arranged software links were required to interface with standard database and word-processing applications.
- A user-friendly development environment was necessary for fast application building and future software maintenance.
- Application resident facilities were desirable to develop a robust, easily accessed, visually attractive, graphical user interface.

Of the packages investigated, three possibilities were quickly rejected for failing to meet one or more of the above criteria. These were:

Crystal[91,92,93,94]: A rule-based expert system, produced by Intelligent Environments Software, which has been successfully used within the University of Edinburgh on previous research projects[95,96]. Crystal is exclusively rule based with no object-oriented capability or procedural language programming facilities. It is text based, allowing easy portability between PCs, but, restricting programme development by limiting access to the program to single elements. Being a non-Windows™

application a further restriction lies in the limited user interface and access to externally created files from other applications. While Crystal has its place in ES development, it was clearly unsuitable for the Water Manager application.

Genesia[97]: Designed for plant and process control by Artificial Intelligence in Information Technology (AIIT). Although described as an expert system, Genesia appeared to be more akin to a data logging and event analysis system. Also the system had a limited user interface and language manipulation capability.

Alternative programming environments, **'C'**[98]**, Borland C++**[99,100,101,102] and **Pascal**[103]: All are procedural programming languages that were used in the early stages to help assess and simulate the mathematical processes and data handling requirements of a water management system. The initial intention was to link the code with a rule-based system such as Crystal, and a Windows™ based user interface, (e.g. Whitewater Resources[104], Microsoft® Visual Basic or Paradox[105]). However, as development ensued, it soon became clear that this approach was unlikely to provide a satisfactory programme development environment. Even with the object-oriented C++, the overall system became too cumbersome due to the complex nature and volume of data associated with water management together with restrictive application interfacing.

Two expert systems shells, Kappa-PC and Art-IM (Automated Reasoning Tool for Information Management) met all the criteria[106]. Each has their own alluring features, however, Kappa-PC was ultimately chosen for this development exercise for the following two reasons.

- While both packages have the ability to produce high quality, user interfaces, only Kappa-PC has the inherent capability to produce customised windows incorporating standard Windows™ tools, i.e. pushbuttons, edit boxes, etc., which are easily linked to the object code.
- The Kappa-PC shell is more user friendly with a multitude of Windows™ based editors available to the application builder.

A brief summary of the Kappa-PC development environment is given in the next section, and further features used during the software development will be discussed and illustrated later in Chapters 4 to 7.

Finally, it must be noted that even in the short space of time, since the choice of development environment had been made, several new, more powerful systems have entered the market, any of which could have fitted this application, e.g. CLIPS[107]. (C-Language Integrated Production System).

3.5 The KAPPA Development Environment

Kappa-PC is a Windows™ based expert system shell which incorporates rule-based reasoning, together with an object-oriented programming (OOP) environment and procedural language, Kappa-PC Application Language (KAL) (akin to C), which allows user-developed functions to be created[108].

3.5.1 Object-Oriented Programming in Kappa-PC

In Kappa-PC objects are created using the class, sub-class, instance structure where a Class is a collection of instances and Subclass is a class that is a subset of another "parent" class. An example of such a system in the Water Manager is Class:*Reservoir*, Subclass:*TummelLochs*, Instance:*Rannoch* (see also Figure 3.3). Instances have attributes (slots) which, through inheritance, can be common to all instances of the class, although these are made local for each instance, e.g. all reservoirs would have a minimum level, but, each particular reservoir would have a different minimum level. Specific information within a particular slot can be accessed by using its unique object:slot pair name, e.g. *Tummel:Volume* would only contain the volume of the Tummel reservoir.

Methods are attached to any object, be it class, subclass or instance, and again these can be fully inherited or local. During processing, these methods can be activated by messages passed to the object, either by procedural code or as a result of rule processing. Four event monitors are available in each object to trigger the methods[109]:

- **If Needed** causes the associated method to be executed when the slot is accessed and it has no value.
- **When Accessed** causes the associated method to be executed when the slot is accessed. It is executed irrespective of the current slot value.

- **Before Change** causes the associated method to be executed just before a change is made to the slot's value. (Useful for error trapping user entered information)
- **After Change** causes the associated method to be executed just after a change is made to the slot's value.

3.5.2 The Kappa-PC Development Tools

Kappa-PC is best described by examining the various components that comprise its development environment. The main Kappa-PC toolbox, shown below, comprises nine iconified software development tools.

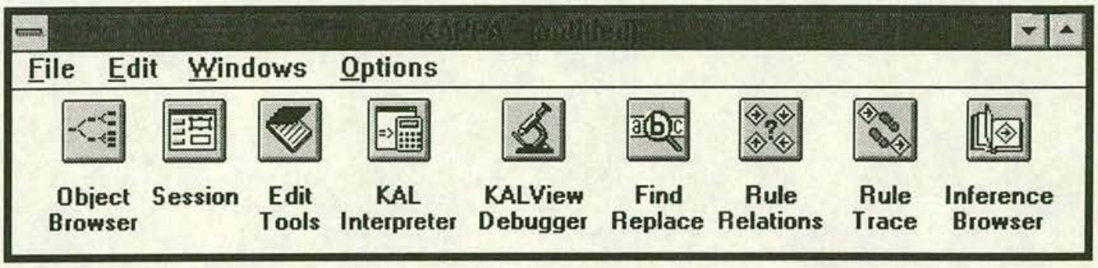


Figure 3.2 Kappa-PC Development Tools

These separate tools are included to assist the software developer. The first six of these are described in more detail in the following sections. The last three tools are specifically for the development of the rulebase and will be explained together with the Water Manager rules in Chapter 6.

3.5.2.1 The Object Browser

The object browser is used to create, modify and view an application's object network. The object network is presented graphically, expanding from the class Root through the various subclasses and instances of Root.

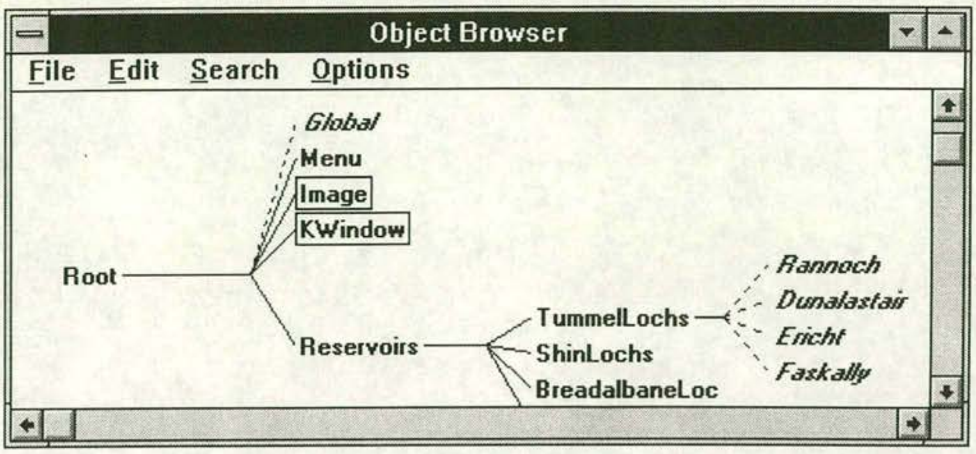


Figure 3.3 The Object Browser

The Object Browser window above contains part of the Water Manager hierarchy, and shows the object hierarchy from left to right spawning from the Root class. Root has two pre-defined subclasses; Image and KWindow shown by the unbroken line connection; and one pre-defined instance, Global, shown by a broken line connection. These pre-defined objects contain the standard information relating to all objects, user interface images and windows.

In this particular example, one user defined class, *Reservoirs* is shown as a subclass of Root. *Reservoirs* has a number of subclasses, e.g. *TummelLochs* for the Tummel Scheme, and these subclasses have a number of instances e.g. *Ericht* a reservoir in Tummel Scheme. Each class, subclass or instance can have a number of attached slots and methods as defined in previous sections.

In addition to the display of the object hierarchy, classes and instances can be easily amended, created or deleted within the Object Browser by use of an edit menu. This edit menu can also be used to navigate through the hierarchy by focusing on any class or instance, e.g. the example above is focused on Root.

3.5.2.2 The Session Window

Kappa-PC provides an easy to use graphical interface for software development, together with a graphical communication appearance that gives the operator of the final program a user-friendly, easily accessible and versatile visual interface, incorporating various images such as windows, buttons, dialog boxes, etc.

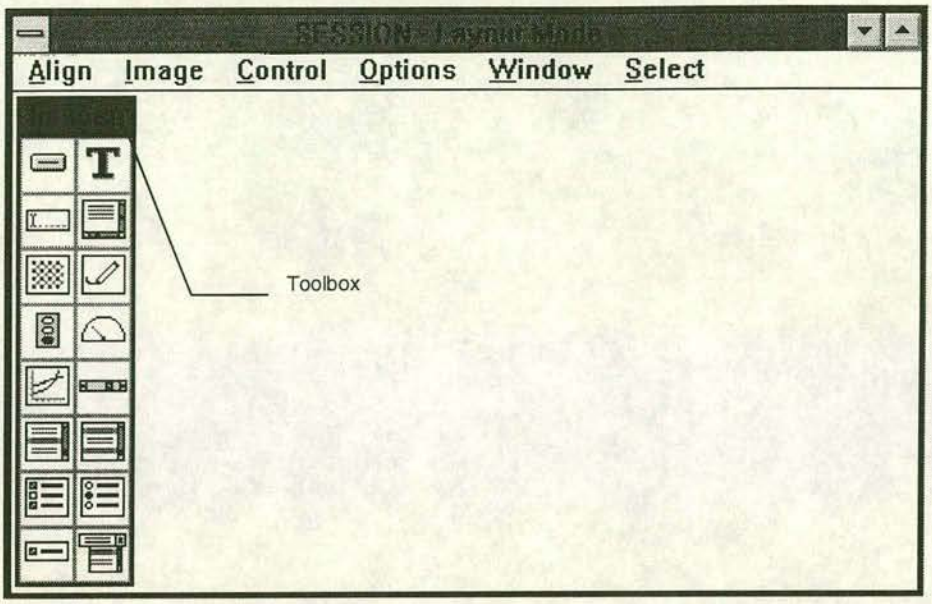


Figure 3.4 The Session Window

A Session Window, shown in Figure 3.4, is used to create and modify the windows that an application uses to communicate with the user. Kappa-PC uses these session windows in conjunction with an array of dialog boxes, including menu and input/edit boxes, to capture any information it requires and to display any information it produces. The controls toolbox (shown to the left of the window) appears during the design phase of a window when the session window is in "layout mode". These controls can be added to a window and attached to slots or functions in the knowledge base. The appearance of the window controls and menu bar can also be set, e.g. the menu or header bar can be changed or removed from view. Once the window design is complete the "layout mode" is toggled off, and the graphical interface is set, preventing further alteration by the user. Examples of completed session windows are given in Chapters 4 to 7.

3.5.2.3 The Edit Tools

The Edit Tools window below, is used to create, edit or delete the data object classes and instances. In addition, Edit Tools permits access to the system's function, rule and goal editors. The figures against each tool indicate the number of each type contained within the program under development. The above example shows the state of a program at the beginning of development where the 25 classes are mainly the images referred to in section 3.5.2.2.

Figure 3.5 The Edit Tools

3.5.2.4 The KAL Interpreter

Kappa-PC has its own, C-based, programming language KAL. Since KAL is an interpreted, as opposed to compiled, programming language, the KAL Interpreter can be used to enter any KAL command to check the condition of system variables or object slots. In addition the KAL Interpreter can act as a testing ground for KAL expressions and functions during development. The sample KAL Interpreter window below shows a developer's requests to find the values of specific slots in the knowledge database, e.g. the current level of Loch Ericht held in the slot *Ericht:Level* is 356.45 metres above sea level (m.a.s.l.).

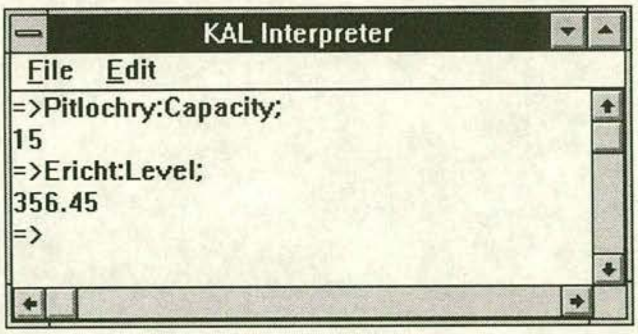


Figure 3.6 The KAL Interpreter

3.5.2.5 The KALView Debugger

Functions can be tested in the KAL Interpreter, but if the result of the test is wrong or the function execution fails, the KALView Debugger provides an environment for more detailed investigation. The KALView Debugger can step through KAL functions and methods as they are processed, indicating any programming errors and allowing the state of system variables to be monitored.

3.5.2.6 The Find/Replace Window

The Find/Replace window is an extremely useful tool within the Kappa-PC environment, which can be used during development to search for, or replace text appearing anywhere in the knowledge base - including all functions, methods, rules, goals, classes, and instances.

3.5.3 Rules In Kappa-PC

The rule system in Kappa-PC provides a straightforward implementation of forward and backward chaining strategies. Rules are written in the same easy to understand syntax, KAL, as that used to create functions and methods. Rules can be created in the specially designed rule editor shown below.

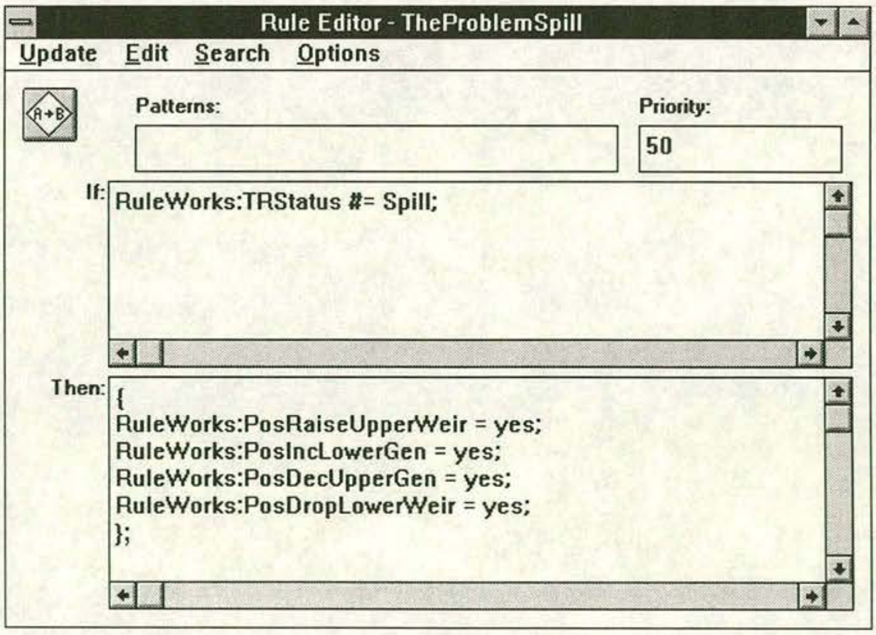


Figure 3.7 The Rule Editor

The example above is part of the Water Manager rule system explained in Chapter 6, however it illustrates the additional features of the KAPPA-PC rule system:

Patterns are variables that allow rules to address a range of objects. For example, given a class, *TummelLochs*, which has three instances, *Rannoch*, *Ericht* and *Dunalastair*, a rule written with a variable *reservoir* that represents any instance of *TummelLochs* is more general than a rule written specifically for *Rannoch*.

Priority, indicated at the top right-hand corner of the editor, is assigned to a rule to determine the order of precedence when more than one rule applies at a particular point in the reasoning process, as explained in the next section.

3.5.4 Forward And Backward Chaining

Kappa-PC includes a single strategy for backward chaining and four alternative strategies for forward chaining through the rulebase. During forward chaining, each evaluation of a rule is able to add information, in the from of object:slot pairs to the knowledge base. Kappa-PC maintains this as a list that is known as an *Agenda*. Forward chaining strategies are used to determine which rule to test first when more than one rule matches the list of object:slot pairs on the Agenda. The four strategies for forward chaining are[110]:

- **Selective evaluation** is Kappa-PC's default strategy. As it only follows a single path of reasoning it is usually the most efficient way to forward chain. Using this strategy, new information is added to the agenda which in turn causes new rules to be added to the *rule list* according to their rule priority. The rule list is a list of all the rules from the rule base that have a premise matching an item on the agenda. As soon as one of these new rules tests TRUE, the remaining rules on the rule list are removed. Only then is the next item on the agenda considered.

- **Depthfirst evaluation** reveals all possible implications of a new agenda item. Rules are never deleted from the rule list, instead new rules are added to the start of the rule list, according to their rule priority, thus becoming the next set of rules to be evaluated. All paths of reasoning are followed exhaustively, one at a time.

An example is given below where rules form a tree with different levels of priority. If *rule1* is invoked all those immediately below it would be added to the agenda for evaluation, but while evaluating *rule2* those deeper down *rule3* and *rule6* would be added to the top of the agenda. *Rule3* would add *rule4* and *rule5* evaluating each in sequence. If no solution is found the reasoning process moves back up the tree then down the next route and so on until a solution was found.

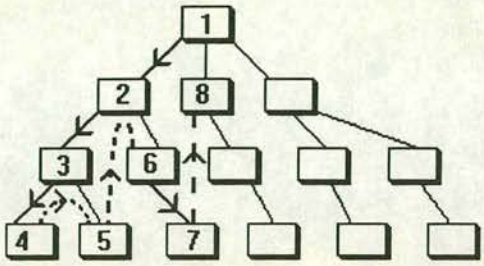


Figure 3.8 Depth First Evaluation

- **Breadthfirst evaluation** is similar to Depthfirst. The only difference in terms of processing is that new rules are added to the end of the rule list, according to their rule priority. All paths of reasoning are followed exhaustively, in parallel. This is illustrated by using the same rule tree as above but the evaluation follows the processing path as shown below.

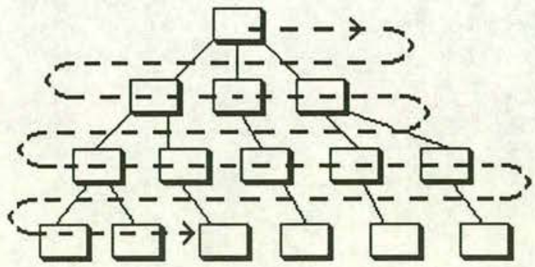


Figure 3.9 Breadth First Evaluation

- **Bestfirst evaluation** is also an exhaustive strategy. In this strategy, when new rules are added to the rule list they are mixed with the rules currently on the rule list according to the priority of all the rules on the list. It is similar to Depthfirst but makes greater use of rule priorities and thus proceed in the order thought by the developer to be most likely to provide a solution.

Broadly speaking, of the latter three cases, Depthfirst will, in the majority of cases, find a solution quickest whereas Breadthfirst will eventually find the shortest solution path. Bestfirst is something of a compromise between the two.

3.5.5 Interfacing

Since it operates out of the Windows™ environment Kappa-PC has an excellent compatibility with other Windows™ based applications, using Dynamic Data Exchange (DDE)[111]. DDE enables two Windows™ applications to "talk" to each other by continuously and automatically exchanging data. In effect DDE automates the manual cutting and pasting of data between applications, providing a faster means of updating information. Pre-compiled KAL functions[112] are available that use DDE to provide easy access to write to or read from any standard database spreadsheets or text files. Thus when running an application, external files can be used to store the vast array of information required to assist during the decision making and reporting process of the DSS. The diagrammatic form of the programming operating system is shown below.

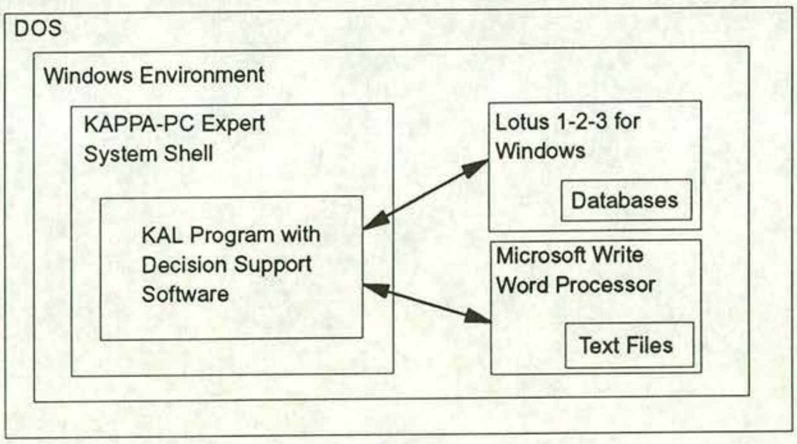


Figure 3.10 Program Operating System

3.6 Summary

A basic overview of AI and OOP is presented and different methods of rule-based reasoning are discussed. The relative merits of development environments and shells that provide these features are described and the selection of a suitable environment for the development of the Water Manager is discussed. The powerful nature of the chosen environment, Kappa-PC, is then described together with a background to the structure and operation of a DSS developed within this shell. With reference to this introductory chapter, the following describe the application of Kappa-PC to the development of an environment for representing and simulating any cascaded hydro system:

Chapter 4 Representing the ESI.

Chapter 5 Representing the water system.

Chapter 6 Knowledge & rule base.

Chapter 7 The Water Manager.

CHAPTER 4 REPRESENTING the ELECTRICAL SYSTEM

4.1 Introduction

Chapter 2 describes how the Grid Control Centres, using a revised form of order-of-merit despatch, meet the consumer demand for electricity by matching the available generation to the fluctuating demand curve. It was also previously indicated that any large PU with mixed generation must operate a microcosm of the National Grid System. With the exception of the two Nuclear generators, this is true for the other four large U.K. generating companies: PowerGen (PG), National Power (NP), ScottishPower (SP) and Scottish Hydro-Electric (SHE). Each of these own or operate both thermal and hydro stations, and SP and SHE also have "must take" contracts to purchase energy from Scottish Nuclear. While three of the four rely predominately on their thermal capability, SHE, as the name suggests, is heavily influenced by their hydro generation capability.

4.2 Scottish Hydro-Electric plc

4.2.1 Generation capacity

Scottish Hydro-Electric plc is one of six major UK power utilities, but, only one of two (SP being the other) which is vertically integrated in that it generates, transmits, and distributes electrical energy (see Figure 4.1).

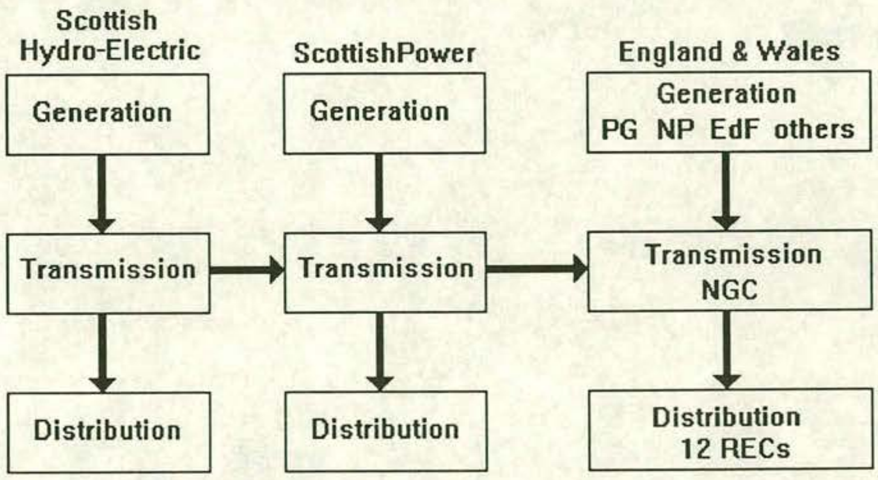


Figure 4.1 U.K. ESI (since 1991)(abridged version)

The company operation covers a total area of approximately 54,400 square kilometres in the North and Central regions of Scotland consisting of predominately rural countryside and four main commercial and industrial centres at Aberdeen, Dundee, Inverness and Perth. Within this area, SHE has over 49,000 kilometres of transmission and distribution circuits normally supplying a demand of around 1500 MW of electricity to almost 600,000 customers[113,114]

In order to meet the consumer energy demand SHE, either through direct ownership of generating stations or under contract (see Table 4.1), has access to a mix of nuclear, coal fired, dual oil/gas fired, conventional hydro, pumped storage, diesel engine and wind generation up to a total capacity of 3240 MW.

Up to 40% of Scotland's electrical power requirements are met by conventional hydro-electricity generation, provided by 133 hydro generating plants mostly within 8 major schemes, consisting of 76 reservoirs and 54 power stations with a total installed capacity of 1025 MW. The total hydro capacity shown in Table 4.1 includes 300 MW of pumped storage from Foyers Power Station on the shore of Loch Ness, and a number of isolated hydro stations.

Type	Owned MW	Available MW	Contracts to/from other power utilities
Oil/Gas	1284	648	50% of Peterhead PS to ScottishPower
Coal	0	576	Longannet & Cockenzie (ScottishPower)
Nuclear	0	660	Hunterston & Torness (Scottish Nuclear)
Hydro	1364	1164	200 MW to ScottishPower
Other	178	198	20 MW from IPPs
Total	2826	3240	

Table 4.1 - SHE generation capacity (1992)[115].

Overall management of electricity production and transmission is overseen by the system controllers in the SHE Central Control Room (CCR) at Port-na-Craig, Pitlochry. Control of all the hydro-electric power stations is undertaken by two production group control centres - Dingwall and Clunie. The Dingwall Hydro Group controls the northern area incorporating the Shin, Conon, Affric-Beauly, Garry-

Moriston and Foyers schemes. The Clunie Hydro Group includes the southern schemes of Tummel, Breadalbane and Sloy-Awe.

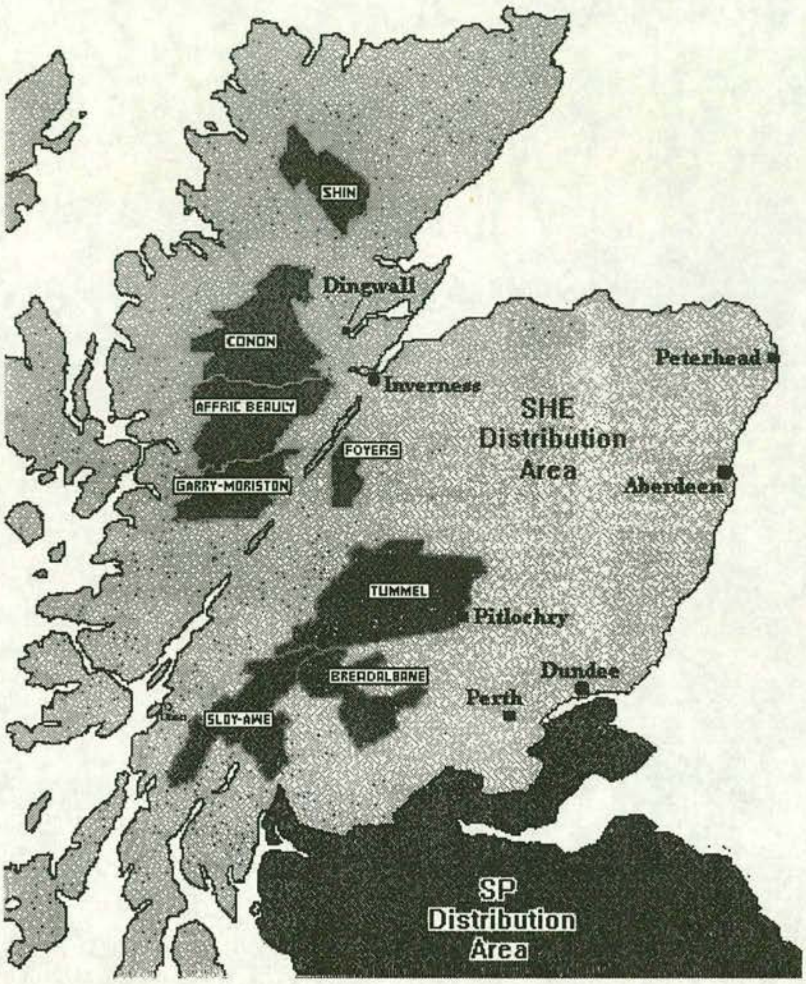


Figure 4.2 SHE schemes and distribution area

4.2.2 Energy management

The methods employed by a PU to efficiently manage the production of electrical energy varies from company to company depending on their particular fuel mix and contracted load. However, most PUs do follow similar basic rules for assessing the load and allocating generation. The SHE practice is used as a typical example of such a process where hydro has a major role to play.

With reference to Figure 2.3 in Chapter 2, consider the equivalent SHE load duration curves below. As with most PUs, base-load generation meets the bulk of consumer demand. For this purpose SHE mainly uses the generation from "must-take" contracts: electricity from Scottish Nuclear, gas to fuel Peterhead PS and some coal derived electricity from Longannet and Cockenzie. The latter three stations do, from time to time, have an element of flexibility that is normally used to meet the intermediate demand, while hydro generation supplies the remaining peak demand, shown in the curve on the left.

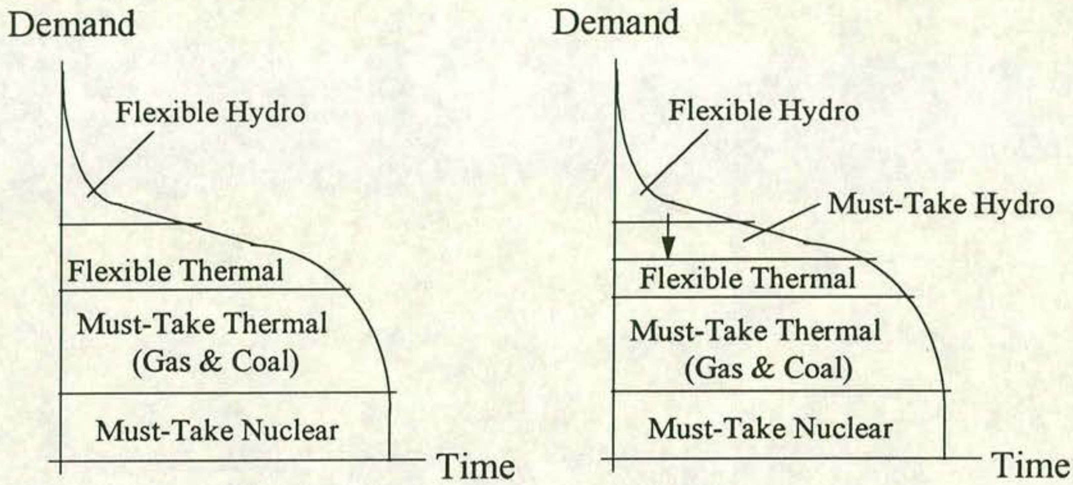


Figure 4.3 SHE load distribution curves

However, management of the water system periodically necessitates generation at some hydro stations outwith peak periods. This "must-take" hydro displaces the flexible thermal generation as shown in the curve on the right. Obviously this is economically beneficial to SHE due to savings in thermal fuel cost during periods of intermediate (medium cost) demand. Therefore, the determination of available hydro becomes an important part of energy management and generation scheduling, as described below.

Within SHE, the energy management structure operates on two levels: the overall power production group (incorporating the thermal generation group) and the two hydro production groups. In common with other PUs and Grid operators, each day staff at the CCR initially begin by assessing their own predicted consumer demand (system loading schedule). This task, undertaken by the DAE, begins with the typical daily load curve for the particular season and day of the week. The DAE then enhances the curve by superimposing the estimated effect on the curve of the ensuing weather conditions. In doing so, the DAE must obtain an accurate forecast of the current and predicted weather conditions within his area. For this purpose, the

Meteorological Office provides both long-term and short-term weather forecasts each giving details of temperature, force and direction of wind, height and cover of cloud and rainfall. Also manned points in the area would, every few hours, note and return the true weather conditions, while additional technical aids including satellite information systems indicate the movement of thunder and heavy rain storms crossing the country.

Having established the overall system loading schedule, the DAE must determine if there are likely to be any grid system capacity limitations or thermal power station restrictions. The former can occur where parts of the network are switched out for repair or maintenance, leaving some transmission lines vulnerable to overloading, while the latter can also happen if a station has low fuel stock or is on outage.

Next, in association with the hydro and thermal production groups, the DAE schedules all hydro and other types of owned or contracted generation plant, creating an overall generation profile to meet their total contracted demand and any export/import requirements. Due to over capacity, SHE chiefly exports surplus energy to the England & Wales grid, usually this tends to be limited only by the maximum loading capacity of the 1,400 MW grid interconnectors (two sets of transmission lines, shared by SHE and SP, which connect the Scottish and E&W networks). It is this excess capacity, together with flexible hydro, which provides SHE with excellent trading opportunities to sell energy to the remainder of the UK, via the "pool". Importing energy occasionally happens at moments of crisis when a major station such as Peterhead, is suddenly tripped out due to an equipment or transmission line fault. To partly counteract the need to import, during the scheduling process some hydro stations will be allocated to act as reserve in the event of an emergency.

During the overall scheduling, CCR request a quantity of energy from the hydro production groups. On the basis of their experience and accumulated knowledge of the hydrology of the land and storage systems, each of the hydro groups creates a generation profile by which they allocate generating capacity and time limits to all of their individual power stations. In common with a PU owning extensive hydro, the hydro production groups must operate their stations in a merit-order where the merit depends largely on the hydraulic situation of the station. For example, should a reservoir approach a high "spill" level at a time when rainfall is predicted, then the need to utilise the water becomes apparent and full generation of the lower station becomes a necessity, (this is explained in more detail later in the Chapter 5)

Eventually the completed generation profile is issued, in computer spreadsheet form, to the LE at CCR, who then uses it to allocate the appropriate generation. However, the generation profile is not resolute as the LE may have to deviate from it if supply or demand changes significantly. Unfortunately, these deviations do occur frequently, requiring immediate despatch of reserve plant and/or pumped storage and occasional energy importation from the E & W grid.

Electrically a generation change is a relatively simple operation, whereby one or a number of stations may be despatched, switched-out or have the(ir) load(s) varied. Unfortunately, as far as SHE is concerned, should any hydro power station output be changed, the revision of the hydro generation profile becomes much more complex, where it falls on the experience and estimation capabilities of key personnel to determine quickly the associated effect throughout the cascade water system.

To summarise, each day the hydro controllers must carry out a series of operations to determine and maintain the appropriate generation profile to meet the demand. These operations are:

- Estimate the total electrical demand on the hydro system alone;
- determine the available generation;
- establish if and when additional generation will be required for peak lopping;
- schedule these stations to meet the demand at the optimum times;
- relay the generation schedule to the Loading Engineer at CCR;
- respond to changes in the schedule.
- establish the impact of the schedule on the hydro resources.

Several factors affect these scheduling operations and all must be addressed in order to fulfil the obligation of the hydro controllers to meet contracted demand. To minimise the time taken for each task much of the data and some procedures have been transferred to computerised databases and assessment programmes, however much of the processing and assessment remains a repetitive manual task. Therefore there is an apparent need for a computer based system to draw together all aspects of energy management. The following sections detail the factors involved and describe the techniques employed to represent each within the Water Manager software suite.

4.3 Scheduling

4.3.1 The "electricity day"

Despatching stations to track demand takes a finite time to arrange. The grid controller, on seeing or anticipating a demand increase or decrease, must contact the appropriate station or company who in turn instruct the station operator to act. The electro-mechanical equipment would then take further time to respond, e.g. typical ramp-up time for a large on-load steam turbine-generator is 1 to 10 MW/min[116]. All in all, this sequence of events can take several minutes, but, to prevent continual system voltage or frequency disturbances, supply must track demand. Small variations in demand, causing fluctuations in frequency, are met automatically by the governing control systems[117] of the large thermal stations, each marginally raising or lowering the power output from their turbine-generator sets in response to the small changes. Therefore, when estimating the demand, the grid controllers are not required to accurately follow the estimated demand curve, but, instead they calculate the average demand over each half-hour segment throughout the day. Thus an *electricity day* can be defined as 48 sequential half-hour segments and the *system loading schedule* is a profile of the maximum MW demand estimated for each of these half-hour slots. The need to define the electricity day, rather than use the calendar day, is necessary to align with the system operation, i.e. during the normal working day the DAE creates the generation profile to take effect from early the following morning. Typically, the electricity day spans the 24 hour period from 6 or 7 AM to the same time the next day.

4.3.2 Priority times

The variable loading on the system has some additional financial implications, since some periods during the course of a day require more generation than others. In the U.K. the day can be partitioned into eight sections covering periods of high, low and intermediate demand. These *peaks*, when the price for electricity is at a premium, are considered to be priority times for generation. During *troughs* in demand the price is at its lowest, making it commercially unattractive to generate. It is obviously economically preferable to generate only during these peak periods, however this is impractical since a PU would always have to provide a large proportion of generation during the troughs to meet their own contracted base-load. When the peaks in demand occur, the additional plant is despatched and the PU receives a higher price per MWh, thereby increasing revenue for the company. Thus within a day these eight time periods are ranked in order of priority for high revenue generation to occur.

4.3.3 The price of water

Since hydro is ideally suited to peak lopping operation (i.e. generating when there is peak demand) and consequently is a key resource when selling energy to NGC, it follows that the water in a reservoir can be considered as having a varying value depending on the need to generate. For example, a station with a spilling reservoir must generate if the PU wishes to obtain revenue from the movement of water, therefore the generation could meet base-load and be valued at a lower cost/kWh determined by the System Marginal Price (SMP) for electricity, (see Appendix 1). Alternatively, a station with a reservoir at an intermediate level, where there is unlikely to be spill or drying conditions, need not generate but the water could be held in reserve until the electricity price rises. In effect, the value of water in these two reservoirs can be considered to be different, and the optimum management of water can provide the opportunity to increase revenue by ensuring generation need only occur at peak times. It is this concept that compels the hydro controllers to stabilise reservoir levels between dry and spill, where possible, to ensure the price of the stored energy is a maximum.

4.4 Hydro generation profile.

Sections 4.2.2. and 4.3.1 respectively describe the determination of the system loading schedule and the construction of a generation profile over 48 half-hour slots. At Group level, the generation profile would indicate the required output, in MW, of each power station for every half-hour during the day. In the case of hydro, particularly for water management, forward planning is extremely important to provide an opportunity to assess the effect of generation on the storage reservoirs.

Thus the estimation of demand and station scheduling is normally expanded to cover a weekly period (i.e. each station will have 336 half-hourly slots of scheduled generation allocation). To create this schedule by manually entering a value into each of the time slots can be a laborious task in itself. Moreover, the time involvement increases substantially when there is a requirement to schedule a large number of stations, while also accounting for some additional operational constraints (detailed below). Thus the task becomes almost impossible to achieve in a short period of time or for that matter by the day ahead when the information is required.

Essentially, a hydro generation profile must meet the following criteria:

- Provide sufficient generation to meet the demand.
- Generate, if possible, at peak times.
- Take account of programmed station outages.
- Take account of priority generation due to electrical restraints.
- Take account of priority generation due the water system constraints.
- Ensure the integrity of the water system.

Complying with the above criteria entails the analysis of several operational elements each having an influence on the construction of a hydro generation profile. The following sections describe each of these elements.

4.4.1 Generation requirements

For long-term scheduling and water management, the total GWh requirement for hydro is estimated for a week by the method outlined in Section 4.2.2. However, due to its flexibility, the hydro generation would tend to be spread throughout the week and across all schemes to meet demand mainly during the peaks in demand. Therefore this GWh figure is divided into a percentage allocation for each day of the week and where there is more than one cascade scheme, a percentage of the daily figure would be allocated to each. Hence, each scheme is allocated a daily demand in MWhs which it must meet.

4.4.2 Set availability

Where an individual station comprises several generating sets, a decision must be taken as to the availability of each of these sets, and in doing so the maximum generating capacity of each station can be established At any time, sets could be inoperable due to damage to the electromechanical equipment, the electricity network or the hydro system. Alternatively, sets can be out-of service for maintenance or the current reservoir level may limit the number of sets that can be used. Typically where there are three or more sets, one would tend to be out of service for routine maintenance or held as spare.

4.4.3 Station outage

An entire station may be out-of-service (on outage) for either scheduled maintenance or repair to the station equipment, local transmission system or the water system. Furthermore, outages can occur when the level of the reservoir is such that generation cannot occur, i.e. if the upper reservoir level is too low or the lower reservoir level is approaching spill. These outages normally last a day or a number of days and even for small repair or maintenance tasks a station would tend to be considered on outage for a full day. This prevents the possibility of committing the station to generate at some stage, then finding the outage takes much longer than expected. This is especially important since financial penalties can be severe, if a PU offered a station for generation but could not deliver when asked. In extreme cases the Regulator could revoke the PU's Generation Licence (or Scottish Licence for SP and SHE) preventing any generation by the company[118,119].

4.4.4 Priority running

The converse of outage is priority running where a station may be required to generate continuously irrespective of the demand, i.e. becomes part of the base-load. This situation can arise when the upper supply reservoir is about to spill or the lower requires additional water. More commonly a station may have to operate over a set period of time due an environmental constraint, i.e. to maintain a uniform river flow throughout the day or hold the same noise level over a set time period. An example of this is the Pitlochry station in the SHE Tummel cascade scheme. The station is located at the edge of the small town of Pitlochry and in the immediate vicinity of residences. Since the area is semi-rural, the sound (of both the generators and water outflow) from the station provides the bulk of the background noise for the area. Thus, any variation in generation can be heard by the local population, creating a disturbance. Additionally, the flow of the River Tay downstream must remain almost constant. SHE overcame these constraints by starting generation early in the morning, typically 04.00 hrs in the summer, sustaining a constant output and flow throughout the daylight hours until 22.00 hrs, then switching-off through the night. This action maintains the nightly silence, but also reduces the overall generation during the late night/early morning trough in demand.

4.4.5 Weir heights

As with a station, a variable weir can be used to regulate the flow of water between reservoirs. Normally, the height would be set for the day, only requiring alteration to prevent spill or drawdown problems with the attached reservoirs. The representation of weirs and the calculation used to determine water flow over the weir is fully discussed in Section 5.7.3.

4.4.6 Station priorities

When allocating generation, those stations with priority running are the first to be despatched. Next to generate is either those stations with full supply reservoirs or those feeding near empty reservoirs. In deciding between two, or more, stations in this "must generate" category, the relative priority of the reservoirs in question would determine which should generate first (see Reservoir Priority, Section 5.6.9). The remaining stations, if required, would then be despatched to meet the residue of demand. Hence, all stations in a cascade are prioritised in preferred order of despatch. Additionally, station priority determines which station generation level should be altered in the event of a reservoir problem, i.e. it is preferable to change the generation of those stations lower down the priority list.

4.4.7 Target levels

Sections 4.4.3 and 4.4.4 above describe the influence reservoir levels have on the generation capability of a station. Therefore to ensure station availability, the controllers try to maintain the upper reservoir at a *target level* somewhere below the spill level. Ideally, this level would be set to:

- ensure there is sufficient water volume to operate the station at any time,
- have spare reservoir capacity to absorb all inflows when the station is switched off, without pushing the level up to spill,

- have enough water to permit 24 hour generation without drawing the reservoir down to the dry condition.

As an example, Figure 4.4 illustrates typical reservoir levels for Loch Rannoch in the SHE Tummel scheme, for a more detailed explanation of these refer to Chapter 5, Section 5.6.6.

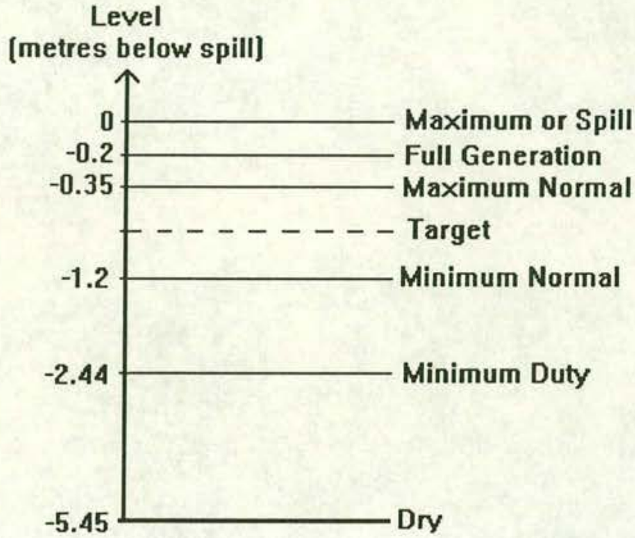


Figure 4.4 Typical reservoir levels (Loch Rannoch)

Of course, a middle level in a large reservoir can fulfil all the above requirements, whereas meeting all the criteria is impossible in small reservoirs. Nevertheless, each reservoir has a preferred target level which is set by the controller, and is used to determine the likely operation of the lower station(s). For example, a station whose supply reservoir has a level well above the target level would be given a high priority to generate.

The target level does not remain the same throughout the year but changes with seasons, i.e. lower in the winter months when periods of heavy rainfall are likely. Furthermore, the controller may lower the target level when he is aware of an impending station outage for maintenance.

4.5 Representing the generation profile variables

Having considered and determined the influential elements associated with generation, a hydro controller can proceed to create scheme generation profiles in any of three ways:

- Use his experience to arbitrarily enter the output of each station for each half-hour slot.
- Build up the generation of each station in accordance with the priority times.
- Determine the output of each station to comply with the required reservoir level.

Due to the variable influential elements, and since the first option is both time consuming and impractical, the creation of the profile becomes a combination of all three. Thus any attempt to simulate the scheduling process requires a system which addresses all possible influences in a flexible manner and which accepts a number of possible changes to the main data.

4.5.1 Representing the "electricity day"

Although an electricity day is divided into eight periods of different priority, these periods, unfortunately, are neither of uniform length nor do they have a consistent start-time. Instead both vary as the demand curve changes for different seasons and days of the week. Furthermore, when determining a weekly profile, the time periods and their priority status for some days may be different from others, i.e. the demand curve for weekends and local or national holidays tend to be quite different from the typical working day. Generally three priority time slot configurations are required to account for two standard time profiles, Winter and Summer, and an alternative variable Custom profile for the weekends and holidays. Additionally, whilst the standard profiles are normally fixed they can at times be slightly altered due to the change in daylight hours or unusual climatic conditions, thus even the "standards" have to be flexible. Furthermore, in a country other than the U.K. these profiles would almost certainly need to be changed to account for climatic differences.

This investigation established that time priority was a major variable control feature in energy management and consequently simulation of priority time periods must have an inherent flexibility to take account of all the above variations. Furthermore to provide this universal flexibility, it is not only necessary to access all period start/stop times and priorities but also to allow variation of the individual daily profiles over a weekly time period. For convenience much of the previous work simulating energy management assumed a rigid electricity day, however, to make the Water Manager more realistic it was considered necessary to incorporate an adaptable electricity day and week.

Within the Water Manager on a daily basis the effect of any time change will be incorporated by first recalculating the period duration(s) as a number of half-hours between the start- and stop-time, then allocating the location of the start-time in numbers of half-hours from the **daily** start-time (i.e. the first time of the electricity day, e.g. 0700 hrs). Slot priority is achieved by simply allocating a priority number from 1 to 8 to each time slot. Changing these numbers automatically regrades the time slot priority by replacing the attached slot priority number.

For clarification, the resulting user screen is shown in Figure 4.5. Here the Water Manager provides the facility to change the individual slot times of all three time profiles to suit the situation under investigation. Weekly flexibility is provided by allowing the user to select for each day of the week the appropriate user-defined profile from Winter, Summer and Custom.

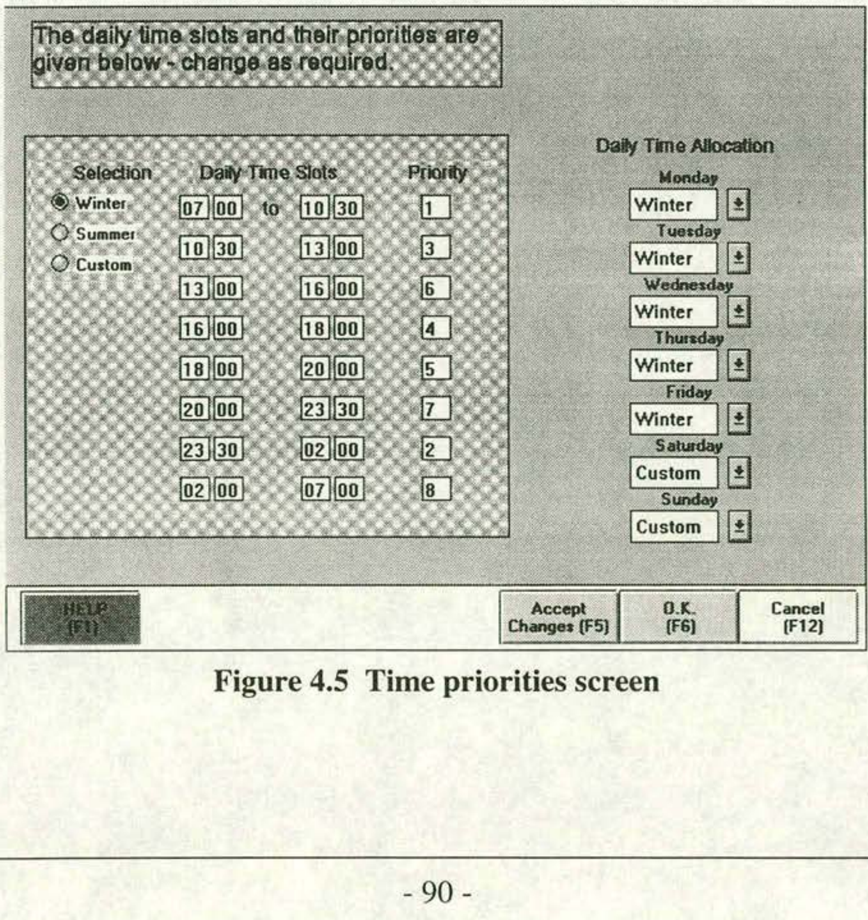


Figure 4.5 Time priorities screen

The above user screen clearly shows a typical setting for a Winter daily profile, whereby the start and stop times are given for each priority period throughout the day. The relative priority of each time slot is shown on the right of the panel. To the right of the screen a typical weekly arrangement is shown where the Winter profile is being used for Monday to Friday and a Custom profile is allocated to the weekend.

For total flexible operation any aspect of the time slots can be altered to suit, the only stipulations being: start-times must be either on the hour or half-hour, and the first (and last time) must be the same for all three types of daily profile. Protection routines built into the software ensure that these restrictions are adhered to.

Many previous software models have incorporated rigid priority timings and often run simulation calculations on a per hour basis[120]. Obviously this type of approach incorporates some inaccuracies due to unchanging time priorities from day to day and being unable to account for changeover of slot priority occurring on the half-hour. Therefore, the major advantage of this electricity day representation is the total flexibility within the ESI half-hourly time frame, which allows the user to set the system up to simulate any week of any year (normal or otherwise). Also, user control of the electricity day start-time, instead of the day start-time (midnight), ensures that any simulation can be set to start precisely where the day-ahead schedule begins. Consequently this total control of the time slots, leads to a more accurate simulation of the power system operation.

4.5.2 Representing a Power Station.

A power station can consist of one or a number of turbine-generator (TG) sets. Usually a multi-set station would house a series of identical TG sets, since it is normally good practice to maintain uniformity within a station, both for spares holding and maintenance operations. Whilst this is not always true, most large hydro stations, including those of SHE, tend to comply and consequently this simulation always assumes this to be the case. However the Water Manager can easily accommodate a station having differently rated TG sets. This can be done by simply treating the sets as separate stations with the same upper and lower reservoirs. For example where a 25 MW station has two sets rated at 10 MW and one at 5 MW, they would be entered (see Chapter 7 and assembly below) as stationA1: capacity 20 MW with 2 sets and stationA2: capacity 5 MW with 1 set.

Thus to simulate the operation of any power station, or part thereof, the Water Manager dialogue box in Figure 4.6 shows the minimum information required: the total station capacity; the number of turbine-generator sets within the station and the volumetric energy density (explained below) through each turbine in m^3/kWh. The capacity per set is automatically calculated by dividing the station capacity by the number of sets.

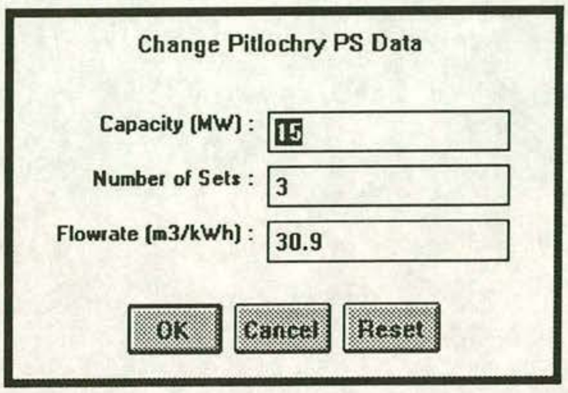


Figure 4.6 Power station data window

The water flowrate through a turbine is usually stated as Q in m^3/s, however, this flow is not normally measured. Therefore, for convenience the volumetric energy density in m^3/kWh is used since kWh are measurable and, when generating, the volume of water passing through the turbine can easily be found. This flowrate can be established for any TG set as follows:

The electrical power output of a TG set is determined by the water conditions and set efficiency (see Section 5.3.1),

Thus, $$\text{Power, } P = \rho g H Q \eta \times 1000 \quad \text{(kW)} \qquad \text{.......(4.1)}$$

And the electrical energy produced by the set over the time period, t, (in hours) is

$$E = P.t = \rho g H Q \eta . t \quad \text{(kWh)} \qquad \text{.......(4.2)}$$

But the total volume of water that would have passed through the turbine in the time period can be established by multiplying the volume flowrate Q by the time:

Thus, Volume of water = Q.t (m^3) ....**(4.3)**

Finally the relationship between volume and energy can be established thus:

$$\frac{\text{volume}}{\text{energy}} = \frac{m^3}{kWh} = \frac{1}{\rho g H \eta} \text{ (a constant for the station)} \quad \text{..............}\mathbf{(4.4)}$$

Hence, the total station water volume throughput for any half-hour period can be calculated as:

volume (m^3) = station output (MW) x1000 x flowrate (m^3/kWh) x time (hrs)

For example, if *Pitlochry* had one set operating over a half-hour period the total water throughput would be:

$$\text{volume} = ((15 \div 3) \times 1) \times 1000 \times 30.9 \times 0.5 = 77{,}250 \text{ m}^3.$$

Using the above method, the water volume flowing out of the upper reservoir and into the lower reservoir can be determined for any time period given the generating state of the station over that time.

Before any station can be used it must first be assembled within the Water Manager environment during the scheme assembly process, (a one-off event described in Chapter 7, section 7.4.1). The data for each power station is entered through the Water Manager dialogue box shown above and the associated upper and lower reservoirs (if any) would also be declared during the appropriate reservoir assembly procedure. Subsequent to assembly, an instance would be created in the *powerstations* hierarchy, inheriting the appropriate slots from the Class *stations*. A method would also be activated to pre-set a series of default values to be used as a starting point when first running a simulation. (These actions are illustrated in more detail in Chapter 5, section 5.7.2.)

Figure 4.7 is an example of the Kappa-PC instance editor, showing the *Pitlochry* power station instance. The full list of slots and methods associated with a power station are detailed in Appendix 2. (Note: the asterisks denote inheritance from the *stations* class)

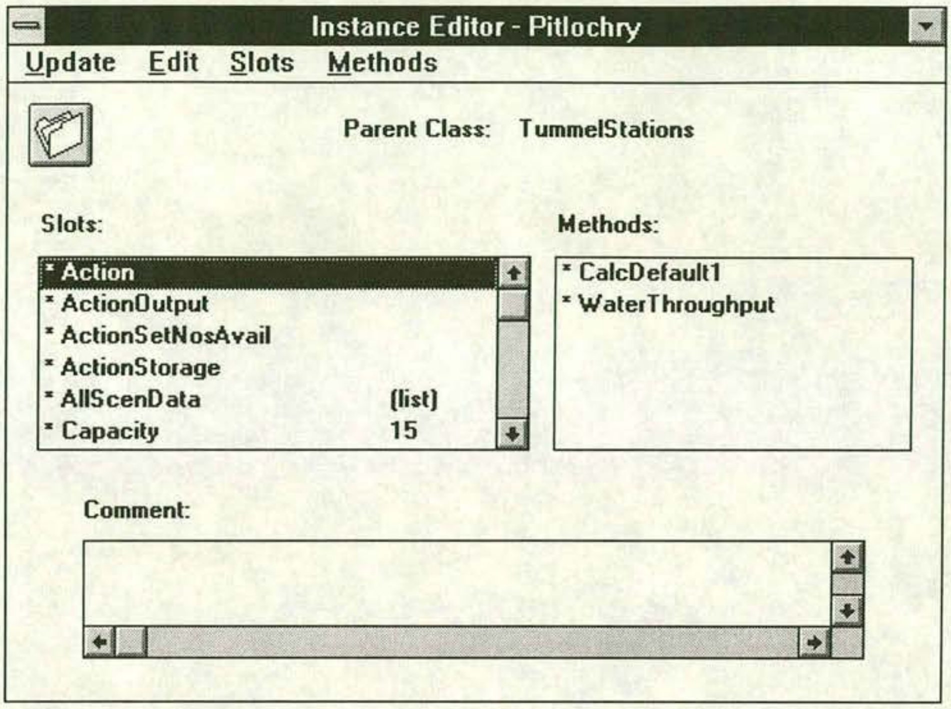


Figure 4.7 Power station object

4.6 Generation Regime

Generation Regime is a sub-routine within the Water Manager which creates an optimum generation profile which: meets the total demand for each day; prioritises generation for peak periods of demand, acknowledges station priority running and set outages and takes account of the electrical and hydraulic state of the system. Initially, a series of screens prompts the user to provide the information (detailed in Section 4.4). Using this information the program proceeds to select from the available generation a regime of plant usage which meets the required demand. A summary of operation is as follows:

4.6.1 Energy requirements screens

The user initially enters details of the demand requirements for the week, taking the form of an overall Group total GWh (not shown) based on the estimated demand, together with a percentage loading for each scheme and each day of the week, see Figure 4.8.

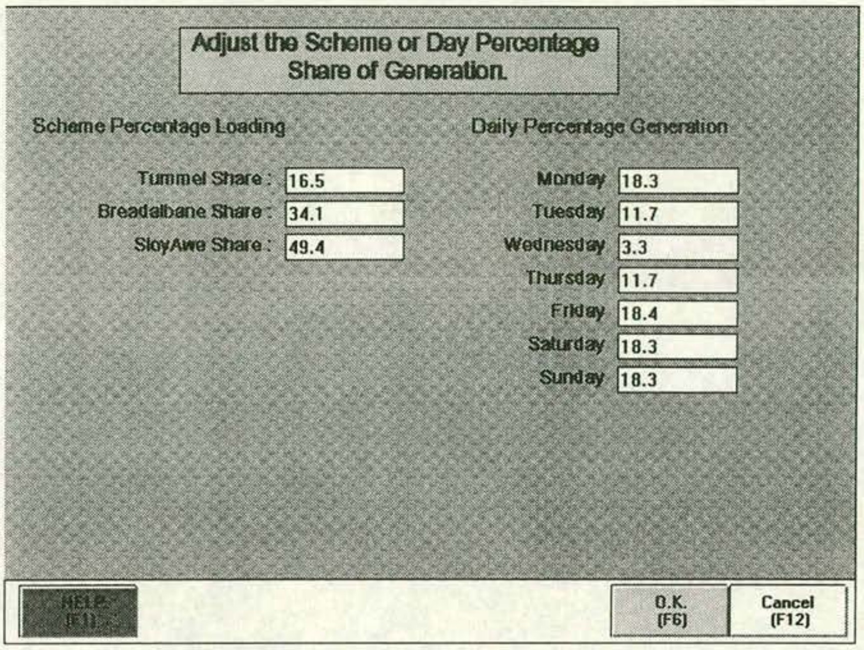


Figure 4.8 Energy requirements screen

Often the percentage loading would remain the same from week to week with only the GWh requirement being adjusted. However, scheme loading may change if, for example, a major station was on outage, or alternatively daily loading may change due to a public holiday. From the information entered, the daily demand for each scheme (in MWh) is calculated and displayed in a second screen, as shown in Figure 4.9.

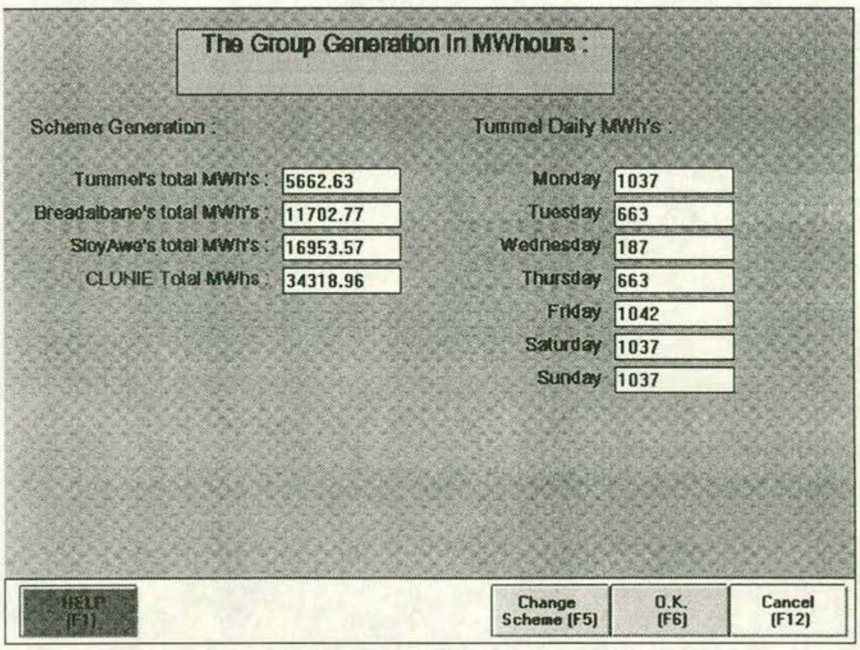


Figure 4.9 Energy share screen

In the example shown the *Clunie* group could have been requested to supply 34,318.96 MWh over the period of a week. Each of the individual schemes was allocated to supply a percentage of that total, e.g. *Tummel* 16.5% equating to 5662.63 MWhs (shown in Figure 4.9). On the Monday 18.3% generation was required representing 1,037 MWhs for *Tummel*.

For added flexibility the user can either accept these calculated figures or adjust any as required. Procedures within the software prompt the user to ensure that all adjustments remain within the percentage framework, i.e. increasing any value, other than the Total GWhs, will necessitate the reduction of another to keep the total MWhs at 100% of the total generation requirements.

4.6.2 Set availability screens

Figure 4.10 illustrates a typical screen display, where all stations appear as radio button groups[121]. This gives the user the opportunity to select, on a per station basis, the number of generating sets available. An added feature, although undetectable in the monochrome diagram, is a colour change to the station name if there are any proposed station outages (see Special Conditions below), a situation which would override any set availability, i.e. sets available would automatically be taken as zero.

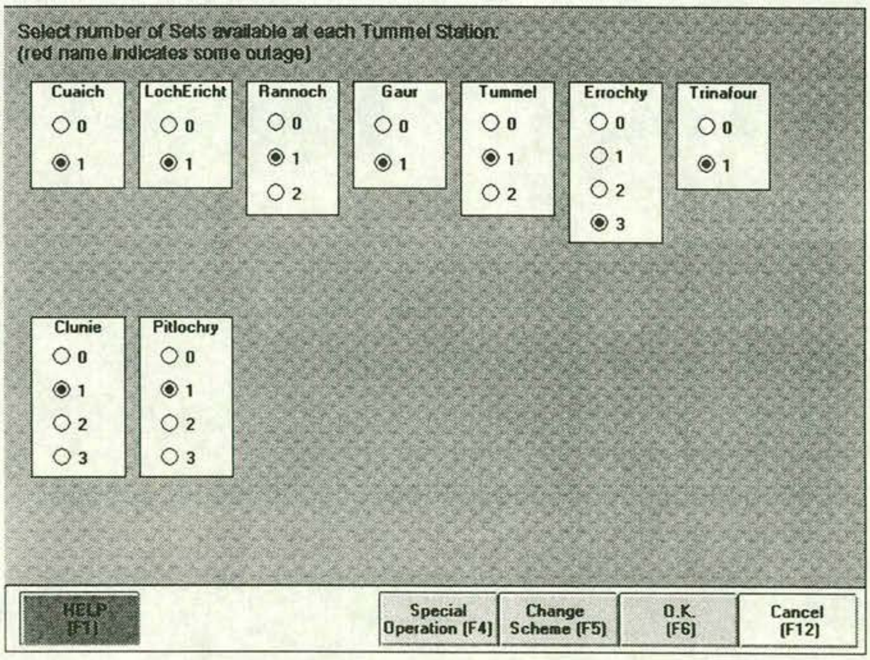


Figure 4.10 Sets available screen

Where there is more than one scheme within a Group, the user has the opportunity to access a similar screen for each in turn by virtue of the Change Scheme button. The same is the case for most screens in the Generation Regime series.

4.6.3 Special conditions screen

Two special conditions can be applied to any station - Outage or Priority Running. In this screen, Figure 4.11, the user can enter or change the status, priority start- and stop-times, or the outage days for any or all stations. Each scheme has associated with it a textfile, e.g. *TuSpecOp.txt* for the Tummel scheme, which contains all the special conditions currently in place for the scheme stations. Before opening the screen, the program retrieves from this textfile the current status of the scheme stations and displays the information in an on-screen Log. If the user makes any alterations these appear, date and time stamped, in the Log for reference. Once the user has completed any alterations, the new Log is automatically downloaded back into the special operations textfile. The user can then review or print the full status of the hydro scheme at any time.

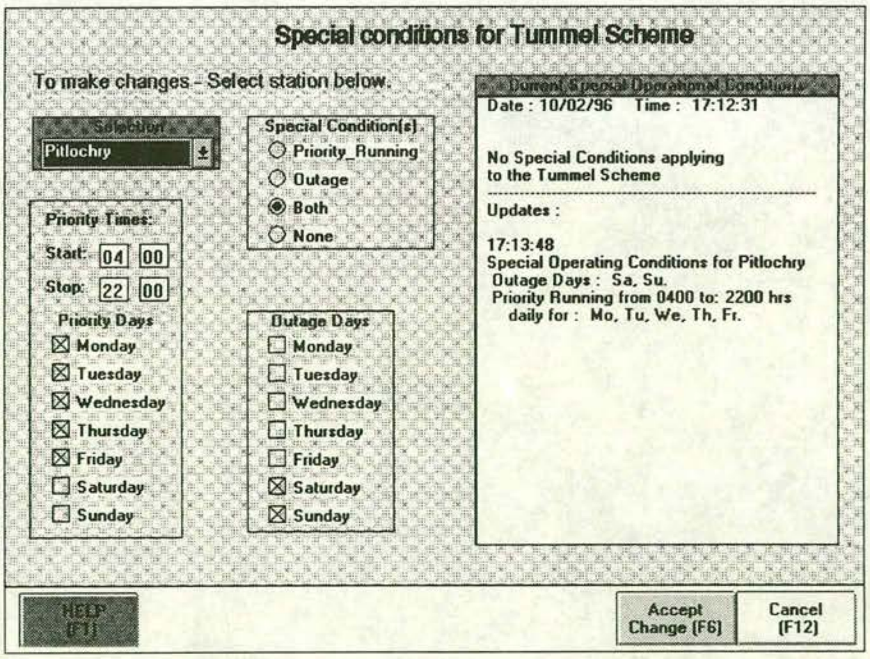


Figure 4.11 Special conditions screen

The example screen above, shows a situation where originally no special conditions prevailed, but, *Pitlochry* has now been allocated as prioritised running between 0400-

2200 hours during the week and is on outage for the weekend. The station settings appear on the left of the screen and the new conditions in the Log on the right of the screen. Should a user enter a station to be both on priority running and outage on the same day, the software ignores the call for priority running.

4.6.4 Target levels screen

Figure 4.12 illustrates a typical screen display, where all reservoirs appear as slider control indicators[121]. Each level indicator can be adjusted by the user if required. The target level is automatically constrained by the maximum and minimum levels of the reservoir. The current reservoir level is also indicated below each slider as a guide to the user when selecting the target. For example Loch Tummel is shown as having a current level of -2.10 m, but the target level has been set at -2.52 m.

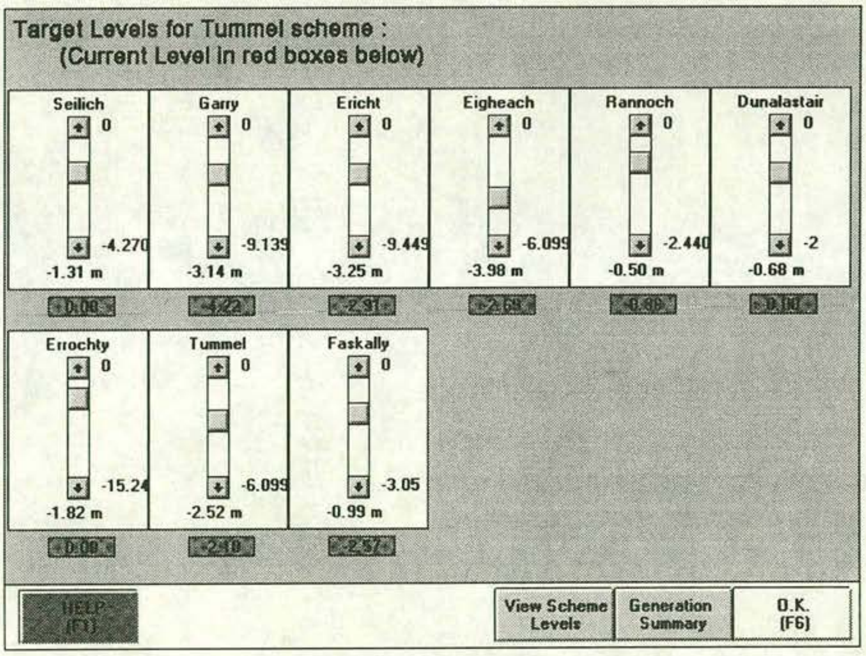


Figure 4.12 Target levels screen

4.6.5 Weir heights screen

As with the station capacity, a weir height must be set by the user. A screen similar to the target levels screen appears, but each slider represents the height of a weir and the limits between which it can operate. Again the current height is indicated to assist the user.

4.6.6 Station priorities screen

Although this particular screen, shown in Figure 4.13, does not form a part of Generation Regime, within the general program control it allows the user to set the priorities of all stations, reservoirs and weirs. Joint priority is acceptable, e.g. *Tummel* and *Errochty* stations are each prioritised at 2, but in the rare event of a clash in priority, the station installed in the software first will be considered highest priority (in this case *Tummel*).

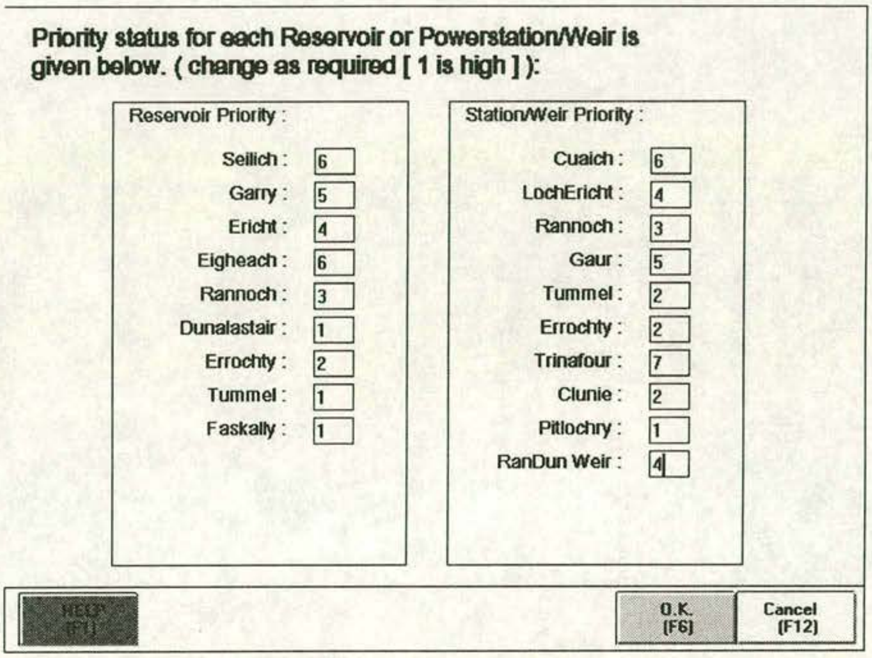
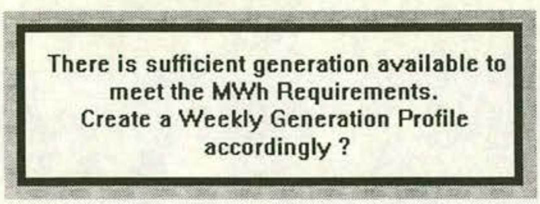


Figure 4.13 Priority screen

4.6.7 Running generation regime

Once all the information is entered, the Water Manager initially calculates the total possible generation if all available stations and generating sets ran throughout the week for 24 hours a day, taking due account of intermittent daily outages. Usually, this should produce a surplus of generation, and consequently the Water Manager response would be as shown below.



However, should there be a shortfall on any day, the Water Manager prompts the user to reassess the GWhs, percentages or availability's for a particular day or days. The user would return to the preferred option screen and adjust any of the previously entered information. The generation is recalculated and continues the cycle until the generation needs are satisfied. The Water Manager can then proceed to create an appropriate weekly generation load profile taking full account of the various priorities and availabilities. The profiling would begin by filling the appropriate half-hour slots associated with a priority running station. For example, from Figures 4.10 and 4.11, *Pitlochry* has one set available and requires priority running between 0400 and 2200 hrs, therefore the associated 36 half-hour slots would each have 5 MW entered in them. The next slots to be filled are those of the highest priority station during the highest priority time-slot. For example, from Figures 4.13 and 4.5, *Tummel*, *Errochty* and *Clunie* are all priority 2 (after Pitlochry on 1) and the first priority time slot is 0700-1030, therefore the current capacity of each would be entered in turn in their appropriate slots. This profiling continues until the generation requirements of that day have been fully met mainly by the high priority stations.

The profile data is then stored internally within the list slots of each power station instance, e.g. *Pitlochry:AllScenData* in the instance editor shown in Figure 4.7. However, while the software can use and manipulate this data during a scenario run (see Chapter 7), to prevent software corruption, the user cannot access the data directly. Therefore, an extra facility has been included to permit easy transfer of the data from the station instances to a "load profile" spreadsheet, and vice versa. This feature is useful if the user wishes to view or edit the 'idealised' generation profile prior to running a scenario.

Finally, Generation Regime gives the user an opportunity to run a fast 7-day scenario, where the software computes the daily changes in reservoir levels due to the **averaged** generation profile. This can only be used as a guide to the possible effect of the profile on all scheme reservoir levels and would indicate if there are likely to be problems by the end of each day. However, being averaged it does not "see" all possible problems or take account of instances where two stations are working directly against each other. For example, where an upper station is constantly feeding a reservoir during a day and the lower station only operates for the latter half of the day. If the stations were similar, averaged over the day the reservoir level would rise, however, in reality by the middle of the day the reservoir level would have risen much more until the second station came on stream. Therefore, the more detailed scenario run operating in half-hourly increments would provide the full picture. Chapter 7, section 7.7. describes this full scenario run.

4.7 Storing the generation profile

During software development it was assumed that any PU likely to use the Water Manager would have standard spreadsheet software available, e.g. Lotus 1-2-3 or equivalent. This requirement was necessary to provide the Water Manager with storage facilities for data used or generated during programme operation. In particular, as indicated above, the generation profile can be transferred directly into a storage file where the data can easily be accessed to view or be changed.

For the generation profile, a template spreadsheet file was created which can hold the generation profile of any scheme consisting of a maximum of 12 power stations and 3 weirs. This arrangement allowed the simulation of most schemes including all those of SHE. The creation of an individual scheme file linked to the Water Manager, then only requires the user to enter the names of each station and weir in the spreadsheet, save the file under the scheme name ***LoPro.wk1 (e.g. *TumLoPro.wk1* is the data file for the Tummel Valley Scheme) and enter the file name when prompted at the initial start-up of the Water Manager. (See File Handling in Chapter 7, section 7.4.3.2.)

Sc:	Tummel	Time	7	7.5	8	8.5	9	9.5	10	10.5
No	Station Name	½hour	1	2	3	4	5	6	7	8
1	station1	Mon	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	Cuaich	Tue	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
		Wed	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
		Thur	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
		Fri	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
		Sat	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
		Sun	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
2	station2	Mon	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
	Loch Ericht	Tue	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
		Wed	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
		Thur	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2

Figure 4.14 Generation profile (extract)

The figure above shows an extract from the generation profile for the SHE Tummel scheme - *TumLoPro.wk1*. In this particular instance the two stations displayed have been scheduled for all half-hour slots shown, starting from 0700 as dictated by the electricity day common start-time.

4.8 Summary

Throughout the chapter it is shown that there are many factors involved in the determination of an optimal generation regime for a hydro-based PU, and that the incorporation of these into software requires a significant level of user access and background procedural coding. The operation of a typical PU with hydro generation is described focusing on Scottish Hydro-Electric plc. The role of SHE within the U.K. ESI and the tasks of the scheduling engineer (DAE) within SHE are discussed. Details are given of the variables and operational constraints that affect the creation of a generation profile for a series of cascaded hydro stations. The procedures followed by the engineers to determine this schedule of generation are described. Finally, the representation of power stations and this scheduling process brought together as a computer simulation program within the Water Manager framework is described.

CHAPTER 5 REPRESENTING the WATER SYSTEM

5.1 Introduction

Water management of cascaded hydro-electric plants entails the control of water flow through the infeed and outflow power stations to generate electricity economically whilst ensuring the integrity of the water system taking due account of external uncontrolled factors. Thus any cascaded scheme model, designed to simulate the change in all reservoir water levels over a period of time: must incorporate the availability and limitations on generation (as discussed in chapter 4); the variable environmental conditions; the interrelation between hydraulically linked reservoirs and finally reservoir priority. This chapter describes the essence of a water system through basic hydrology, hydraulics and water dynamics as they apply to complicated cascaded hydro systems. The chapter then continues to describe the methods used to incorporate the variability of each of these features within the Water Manager software.

5.2 Hydrology

5.2.1 Introduction

As described previously, water management of hydro plants entails the control of water often stored in open natural reservoirs. However, whilst the flow of the water through the system can be controlled reasonably accurately, the total volume of water in a storage reservoir cannot be precisely controlled due to the unpredictability of the associated inflows from other sources, i.e. the local hydrology.

5.2.2 The Hydrological Cycle

The supply of fresh water to sustain a hydro-electric scheme comes from two sources, natural spring water and precipitation. Spring water, originally derived from precipitation, seeping from natural underground reservoirs and normally provides a steady flow into a reservoir via streams and rivers, whereas, precipitation which relies on the **hydrological cycle** is relatively unpredictable.

Water, mostly evaporated from the world's oceans by the heat of the sun, is transported over the land by the moving masses of air in the earth's atmosphere. When this moisture bearing air crosses an island or continental landmass, the heat from the land causes updraughts which push the saturated air up to the cooler regions of the atmosphere. The air is thus cooled to its dewpoint temperature, causing the vapour to condense into water droplets thereby forming skyborne clouds or, at lower elevations, fog. The water droplets in these clouds merge with each other to produce larger and heavier droplets, darkening the cloud until their weight causes them to fall as rain. Mountains accelerate this process by driving the air mass upwards faster, thus within any country the mountainous regions are frequently the wettest and fortunately the best suited to form man-made reservoirs. Much of this rainfall (or precipitation) returns to the atmosphere through evaporation and plant transpiration, while the remainder of the water returns to the ocean via the river systems, thus completing the hydrological cycle.

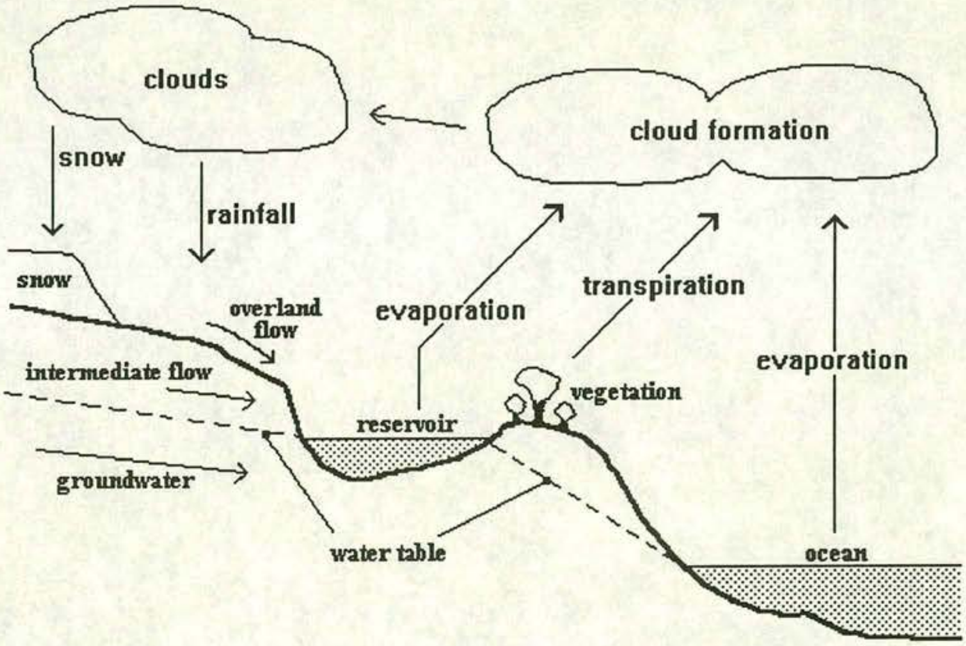


Figure 5.1 The Hydrological Cycle[123]

5.2.3 Precipitation

Precipitation includes all forms of water that fall from the atmosphere onto the earth's surface. It manifests itself in two major forms that are of interest to the hydro industry, these are liquid precipitation (rain) or frozen precipitation (snow, hail and sleet). Rainfall runs off the land, hence the term **runoff**, into the streams, rivers and reservoirs almost as soon as it reaches the ground. On the other hand, frozen precipitation can remain where it falls for a long time before it melts. Therefore, the former is available almost immediately while the latter provides an additional store of water to be used at a later date.

The amount of rainfall is usually expressed in mm depth that falls on a level surface and is normally measured as the depth of water that gathers into a standard sized, open, straight-sided container.

5.2.4 Reservoirs and Catchment

Naturally, at various depths underground, the soil becomes saturated with water, this is known as groundwater, the upper limit of which is termed the water table. The level or depth of the water table depends on the porosity of the soil, e.g. the higher the porosity of the soil the greater is the volume of water stored, and the higher is the water table towards the ground surface. In some situations when the water table level appears above the surface of the soil, a reservoir is created. Thus, a natural reservoir is a body of water formed in a depression in the landscape contours. Where the terrain is suitable, i.e. a steep sided valley, the storage volume of the reservoir can be enhanced with the addition of a man-made dam with side linings to prevent seepage.

As each reservoir has an elevated, sloping area surrounding it, it follows that any rainfall over the area would runoff directly towards the body of water. This area is termed the catchment or basin, of the reservoir/river system. By studying the topography of the area surrounding a reservoir the catchment area can be established, i.e. tracing the relief contours from the edge of the reservoir up to the highest ridge or series of ridges that separate the catchment from another adjacent catchment. Knowing the total surface area and average rainfall, the total volume of water falling on the reservoir catchment can be calculated. For example, given a catchment of 100 km^2 and a rainfall of 20 mm over a period of time, the total volume of water descending on the area is $2x10^6$ m^3. Additionally, given the duration of the rainfall, the figure can be converted to a volume flow rate in m^3/sec.

As an example of a typical catchment area, the Shin hydro-electric scheme is shown in Figure 5.2 Here the main reservoir, Loch Shin, has several streams, rivers, smaller reservoirs (lochans) and man-made channels which all convey the runoff from the surrounding mountain area into it.

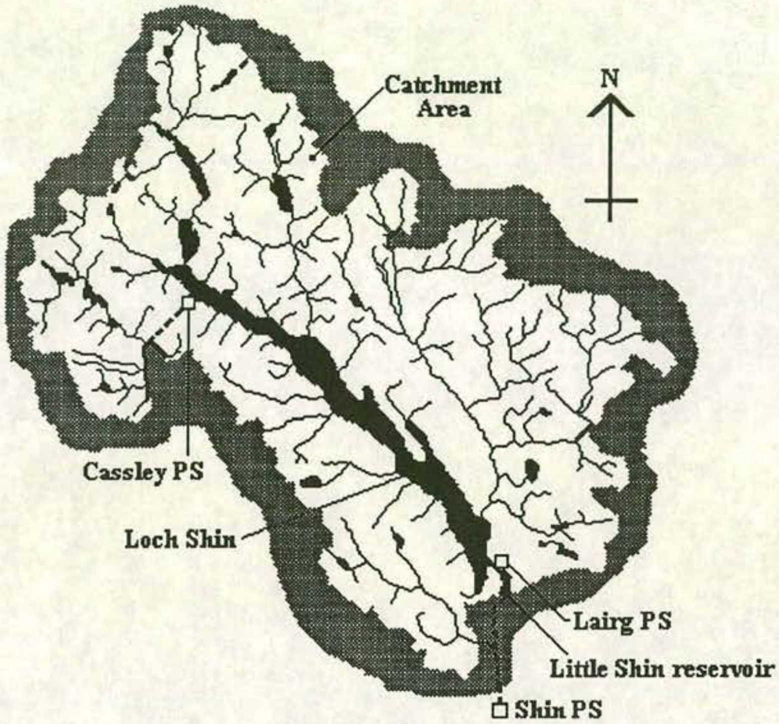


Figure 5.2 Typical catchment

5.2.5 Runoff and runoff co-efficient

The rainwater falling on a catchment flows down towards the reservoir, in the form of runoff, which in turn can be split into three bands: surface, interflow and groundwater[124]. Surface runoff is simply the water that flows over the land into the nearest open stream or directly into the reservoir, interflow is the water that is initially absorbed by the soil, but flows laterally towards the reservoir and groundwater is where the soil is saturated deep below the surface. Water can move between the three bands, but eventually all the water flows into the reservoir, however, a large proportion of this runoff fails to reach it destination, due to the terrain and vegetation.

A collective term, basin recharge (B), is used to describe this retention of runoff by the storage of water within depressions in the catchment landscape and the interception, absorption and transpiration of plants. Transpiration is the process where plants absorb the water from the soil via their root system and release water vapour from the leaves into the atmosphere.

A further reduction in runoff is caused by groundwater accretion (G), where the water percolates down to the water table and is absorbed by the soil. Therefore runoff can be quantified by the expression:

runoff = precipitation - basin recharge - groundwater accretion........**(5.1)**

$$R = P - B - G \qquad (5.2)$$

Which can be simplified to: $R = k.P$ .... **(5.3)**

where **k** is the runoff coefficient that can be established for, and applied to, a particular catchment.

The the local ground conditions and vegetation play a large part in the correlation between rainfall and the useful runoff volume, this is illustrated in Table 5.1 that shows the variation of k for different types of surface.

Surface	**Value of k**
Urban houses & gardens	0.2-0.3
Commercial and industrial	0.9
Asphalt and pavements	0.85-1.0
Parkland	0.05-0.3
Mountain Moorland	0.5-0.75

Table 5.1 Runoff coefficients[125].

Thus given the runoff co-efficient the depth of rainfall can be converted to a volume of water likely to enter the reservoir, however, the runoff coefficient cannot be relied on during heavy rainstorms since the surface runoff percentage can greatly increase..

Finally, the remainder of runoff from the catchment entering the reservoir would be subsequently discharged through the lowest point of the catchment, which in hydro schemes can be a hydro-electric generating station or a pipe feed to a lower reservoir.

5.3 Hydro-Electric Power Stations

5.3.1 Conventional Storage Hydro

Being the outlet from a reservoir-catchment system a hydro-electric power station effectively controls the flow of water. Disregarding evaporation and transpiration, there are three ways in which the water can be released from the reservoir: through a water turbine; via a controlled bypass for compensation and by spillage (intentional or accidental). Of the three, flow through a water turbine for the production of electricity is obviously the most useful and favoured method.

A hydro-electric plant effectively converts the potential and kinetic energy within water, characterised by head and flow, into electrical energy in the form of kW capacity or kWh of electrical energy production (refer to section 2.3.4.).

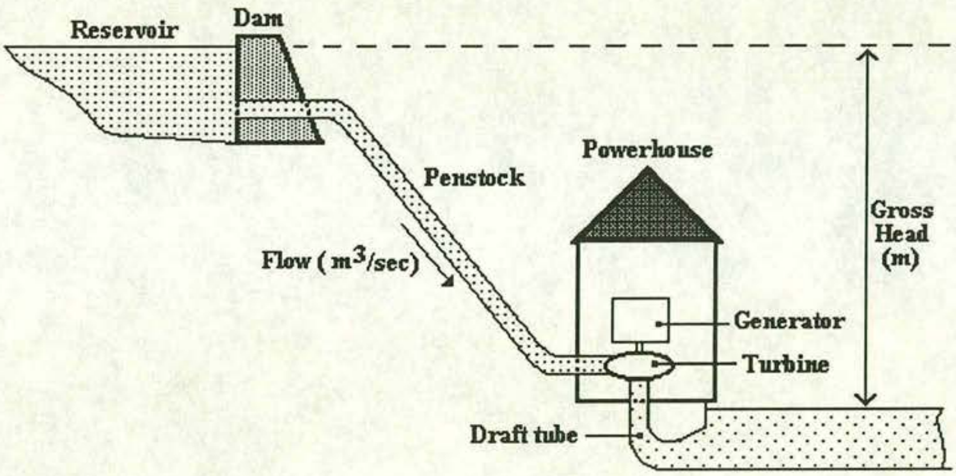


Figure 5.3 Arrangement of a typical hydro-electric station

The general arrangement of a storage station is shown in Figure 5.3. Spillways adjacent to a dam are normally provided to discharge water whenever the reservoir level is too high. A penstock pipe or conduit channels the water down to the turbine in the powerhouse below the dam to be discharged through the draft tube into a river or lower reservoir. Conversion of kinetic or pressure energy in the turbine (as described in Chapter 2) causes rotation of the runner that drives the rotor of the generator, directly or through a gearbox, to produce an electrical output from the generator terminals.

The gross head is the difference in height between the intake water level and the outlet from the water turbine. The net or effective head (H in metres) is the head available for energy production after deducting losses due to pipe friction and unrecovered velocity head in the draft tube. The hydraulic efficiency of the system is the ratio of the net head to the gross head.

The volumetric flowrate of water down the penstock is measured in cubic metres per second (m^3/sec or cumecs) denoted Q. Using these water parameters, the density of water, ρ in kg/m^3, and the acceleration due to gravity, g (9.81 m/s^2), the power developed by the turbine can be found from:

Developed power $P = \rho gHQ$ (W)..(5.4)

The power calculated is based on the maximum energy available from the water, however, during the conversion of water energy to electrical energy, both the turbine and generator incur additional energy losses. Firstly, due to friction losses in the turbine casing and runner, the mechanical output of the turbine is somewhat less than that calculated by the equation above. Secondly, the generator converting the mechanical energy to electrical energy incurs electrical losses due magnetising and heating, and mechanical losses due to bearing friction and windage. Therefore, the overall efficiency (η) of large hydro-electric stations can be of the order of 85-92% with the turbines between 90-94% (η_m) and the generators around 93-96% (η_e)[126].

Taking account of the overall efficiency including the hydraulic efficiency, the capacity of the power station can be determined. This value being the maximum electrical power, in kW, which can be developed by the generators operating under normal head and flow.

5.3.2 Pump Storage

Some hydro-plants are reversible pump-storage types, where water can be moved in either direction between upper and lower reservoirs. When required for peak generation the water is released from the top reservoir to drive the turbines but, when the cost of electricity is low, the synchronous machines convert to motor operation driving the turbines in reverse. In this reverse mode the turbines act as pumps, pumping water from the lower reservoir back up to the upper reservoir where it is held in storage until the price of electricity is high and the sets can return to generation mode.

Therefore, generation usually occurs during the daily peak periods or in extreme cases of emergency to meet a surge in demand or shortfall in supply. The pumping action would normally replace the storage during the nightly periods of low demand. Thus, a unique feature of pump storage scheme is that the water requirements are small compared with conventional storage hydro, since daily generation occurs over short periods of time and in reverse the full volume of storage can be replaced overnight.

5.4 Generating water - the runoff kWh

The relationship between rainfall (mm) and runoff volume (m^3) has already been described in Section 5.2.5, and the correlation between volume flow rate through a turbine (m^3/sec) and generator output (kW) has been described above. If these factors are drawn together, a relationship can be established between weather conditions and the runoff in kWh. For example, expanding equations (5.3) and (5.4), the energy output for any level of rainfall is given by:

$$\textbf{energy output} = \eta_e.\eta_m\,(\rho.g.H_{net}.(k.r.A/t_1)).t_2 \quad \textbf{(kWh)}\ldots\ldots\ldots\ldots\ldots\textbf{(5.5)}$$

where **r** is the rainfall in metres.

A is the surface area of the catchment in m^2.

$\mathbf{t_1}$ is the duration of the rainfall in seconds.

$\mathbf{t_2}$ is the duration of generation in hours.

To establish the value k or verify their interrelation, both the rainfall level and station output are monitored over a period of time, and the volume of water through the turbine is calculated from the relationship in equation (5.4) The monitoring period ends when the reservoir level returns to the initial level. Providing no spillage occurred, rainfall in mm can be associated with a volume of water (i.e. runoff) and generation output in kWh. Thus, rainfall, runoff and possible electrical output can be linked such that for any given rainfall, the increase in reservoir storage (in m^3 or kWh) can be determined. Additionally, runoff can be expressed in kWh, hence the term **generate runoff** when all the runoff water is used by the power station.

Indeed, this type of analysis and verification, has been carried out by Scottish Hydro-Electric on each of their reservoirs. This has produced a vast array of data, covering the average daily rainfall and runoff for each catchment over the last 25-30 years. As a result, given the weather forecast and the time of the year, etc., SHE can estimate the maximum generation output that will be possible, maintaining the level of a reservoir or conversely the effect of additional demand on reservoir levels. Fortunately this data is now stored in computer spreadsheet form, is regularly up-dated and is accessible manually or by DDE links to other software.

However, the above only shows the relationship between the input (rainfall) and output (kWh) from a catchment while assuming the rainfall is constant and the reservoir level is to remain the same throughout. In practice, the operation of a reservoir is very different with additional factors to be considered and included in any computation. This next section describes these factors, their effect on the water system and the methods employed by SHE to evaluate them.

5.5 Reservoir dynamics

Consider a simple hydro system consisting of a reservoir of rectangular area and straight vertical sides, one power station constantly feeding water into, and a second power station constantly being supplied from, the reservoir. To assess the effective operation of this system, it is essential to calculate the water level, or change thereof. In this case the level calculation is simply:

$$\textbf{Reservoir level} = \frac{\textbf{(inital volume + inflow volume - outflow volume)}}{\textbf{reservoir area}} \quad \textbf{.........(5.6)}$$

However, in practice reservoirs are not simple standard geometric shapes, generation and associated water flow does not remain steady and there are also additional environmental and physical factors which affect the change in water level.

Therefore, the hydrological dynamics of the reservoir must be examined to establish the effect on the constantly changing reservoir level, due to various known and predicted hydrological factors and full, partial or zero generation at any associated power station.

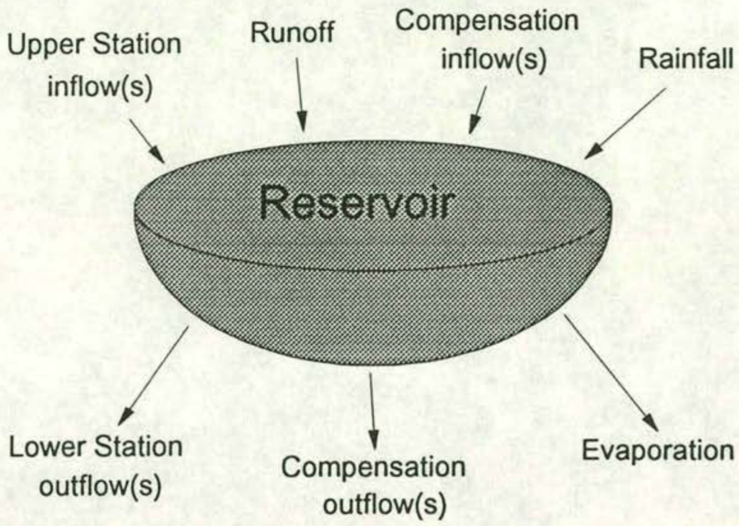


Figure 5.4 Reservoir Dynamics.

A reservoir is thus subjected to a number of inflows and outflows, each constantly changing and occurring independently (Figure 5.4). For any intermediate reservoir, these operational variables are:

i) Rainfall and Evaporation.
ii) Runoff from the surrounding catchment.
iii) Compensation inflow/outflow.
iv) Inflow from upper power stations.
v) Outflow from lower power stations.

i) and ii) are weather dependent, iii) is decreed by Government or local By-laws, and iv) and v) are controlled by the power station operators. The contribution of each can vary over time, and will obviously change the volume and level of the reservoir, therefore, to compute the changes and describe the state of a reservoir a number of variables need to be taken into account.

Although the dynamics of an individual reservoir in isolation are relatively simple, the cascaded schemes, described in Chapter 2, with a combination of multiple reservoirs, rivers and power stations are much more complex since the level of each reservoir, or power station output, relies heavily on the reservoir dynamics of upper and lower systems.

5.6 Reservoir variables

The data attributes that have been defined for individual reservoirs are outlined below. As an example of their use and evaluation, the approach and methods employed by one hydro generator, SHE, have been included.

5.6.1 Storage and volume

The reservoir volume can be evaluated in millions of cubic metres (MCM) for any particular surface level using the topography of the area and a contour-volume method of calculation. Alternatively, man-made reservoirs would be surveyed dry during the construction phase and the volume would be accurately calculated. However, since the slopes of the sides of a natural reservoir are usually uneven, the change in volume with level tends to be highly non-linear (shown in Figure 5.5). Here at the bottom of the reservoir the steeper sides cause the volume to increase slowly as the level rises, but at the upper levels the volume increases greatly with a small change in level due to the large surface area.

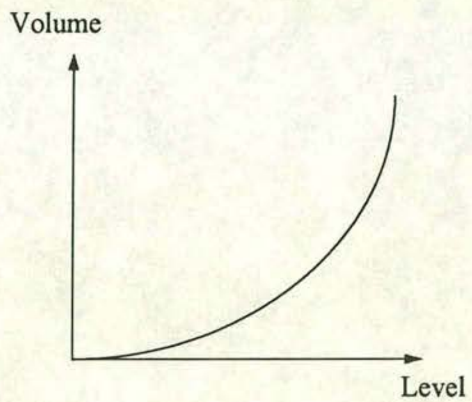


Figure 5.5 [127]

However each reservoir has a degree of "dead storage" at its lower reaches. This volume is unusable as a feed to a hydro power station since it usually contains a significant quantity of solid debris and silt brought into the reservoir by the rivers and surface runoff. Normally the minimum position of the station intake determines where the dead storage begins. Thus the maximum useful volume of a reservoir is the body of water between the reservoir spill level and the top of the dead storage. Hence the curves used by the hydro controllers are the useful volume against level, typically as shown in Figure 5.6 for Loch Eigheach in the Tummel Valley scheme.

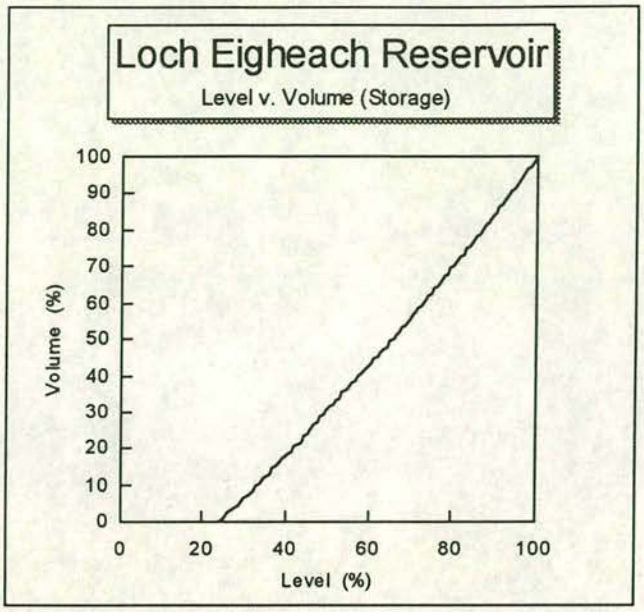


Figure 5.6 Reservoir Level v. Volume[128].

The figure shows that for Loch Eigheach the useful volume begins above 25% of maximum level, and thereafter the volume rises steadily with level. In some instances the useful volume starts at around 50% of maximum level, such as Loch Rannoch also in the Tummel Valley, and in many cases the relationship between useful volume and level follows a similar curve to that shown in Figure 5.5.

Therefore a list can be created for each reservoir to correlate reservoir level with corresponding useful volume. Hence the reservoir storage capacity in kWh can also be established, using the known volume and the relationship between m^3 and kWh, defined by the volume throughput of the outflow turbine(s) (see section 4.5.2).

SHE and other PUs with hydro have adopted this approach giving every reservoir in their system an associated "Look-up" table that gives an exact storage figure in kWh for any water level expressed in metres below spill, i.e. at zero level the reservoir would be full and the storage capacity would be at maximum.

5.6.2 Runoff

The calculation of runoff and its association with the weather conditions has been described in Section 5.2, and is normally specified as a volume of water, or translated to a kWh figure, per mm of rainfall. However, since the runoff needs to be predicted in advance of likely rainfall, a short term estimation must be used, whereby the typical runoff for the particular time of the year is assumed. This has the disadvantage that if it is only based on the previous year's runoff for the same time period, exceptional weather conditions in any one year would give abnormal runoff, therefore, the runoff has to be normalised by calculating average runoff over a number of years.

SHE uses two averaged figures, the simplest and least accurate of which involves a fixed value of runoff for each reservoir over the year, known as the Long Term Annual Average Runoff (LTAA). This figure has been calculated (in kWh) as previously described, by measuring the generation, compensation and intentional spillage over the year to maintain the reservoir level at the initial level.

A monthly average can be calculated from this LTAA runoff figure. This figure is then multiplied by a monthly factor to give a value which is classed as the 100% runoff for any particular month. However, depending on the weather and environmental conditions at any particular time, a further percentage is incorporated to produce a total runoff figure.

For example, given a LTAA runoff of 1200 kWh would produce an average monthly runoff of 100 kWh and January may have a factor of 1.5, thus, 100% run-off for January is 150 kWh. An additional multiplication factor is required for extraordinary conditions, for example, if the rainfall was very heavy and ground absorption was low, the actual runoff may have to be doubled (say), normally quoted as 200%. Under these conditions, the total runoff for this particular month would be 300 kWh.

Due to the extensive data records available to SHE, the 10-year average runoff (in MCM) tends to be used which is a more accurate figure. This consists of a monthly volume per reservoir, averaged over a rolling 10 year period. However, this runoff figure may also be subject to the extraordinary multiplication factor.

5.6.3 Weather

The local direct rainfall/evaporation effects on any reservoir are generally unpredictable and are normally taken into account within the computation of runoff. However, to create a more accurate response to the effects of different weather conditions, extensive monitoring of the localised conditions and resulting runoff becomes necessary. To date several methods have been devised to model the evaporation from large volumes of water. However each tends to be site specific depending largely on the geographical relief and ambient conditions[129], and would require a power station operator to complete a major study of all their reservoirs.

Again SHE is in the fortunate position of having sufficient historical runoff data, which in turn is easily modified to incorporate the general effect of the meteorological conditions. Thus they simply add or subtract an appropriate percentage of the total runoff to compensate for the weather (see above description of runoff).

Although this approximation is not precise, it has to be incorporated to make any reservoir dynamics model fully weather dependent.

5.6.4 Generation Inflow and Outflow

Each turbine has a design volume flowrate (m^3/sec) which can be converted to electrical energy output in kW, (equation (5.1)), using the appropriate efficiencies. Therefore, taken in reverse, given the generation over a period of time (in kWh) the volume of water required to flow into or out of a reservoir can be determined (see section 4.5.2).

SHE has established design flow capacities in m^3/kWh for each turbine. Thus the generation flows are simply calculated by multiplying the current kW output (from the generation profile of each station) by the relevant turbine flow capacity and taking account of the time period. For example, Gaur power station has a total capacity of 6.4 MW and a design flow rate of 15.72 m^3/kWh, therefore, if the station was generating for an hour at full capacity, the volume throughput and consequent water input to Rannoch reservoir would be (6.4 x 1000 x 1) x 15.72 = 100,608 m^3. Hence this change in volume can be used to determine the new levels in both upper and lower reservoirs.

5.6.5 Compensation and Freshet

Each reservoir may require a fixed value of compensation inflow or outflow to maintain the appropriate river flow above or below the reservoir. Additional water flow, known as a freshet, is required at certain periods to assist fish migration or water based sports events, e.g. salmon freshets are agreed in advance with angling associations. These are both quantified in m^3/hour and each tends to be constant over a short period of time, e.g. a week, however, due to seasonal changes the flows will vary in the medium and long term.

Since the construction of the Scottish hydro schemes, their effect on the natural flow of the river systems has been minimised by strict laws governing the lowest permitted flow. This compensation flow, having been established over the years, is an obligation to which SHE must rigidly adhere, by allowing a continual flow of water to by-pass or run through their stations even when they are not using it to generate. In addition to compensation, SHE is also contracted to provide a small amount of freshet flow as required by other water users.

5.6.6 Levels

Using the above data, and knowing their effect, the variation in reservoir level may be calculated over a given time period. The new level can then be compared with a number of fixed or variable levels (see Figure 5.7) which are important for correct water management. These levels define the course(s) of possible action that should be taken by the control engineers.

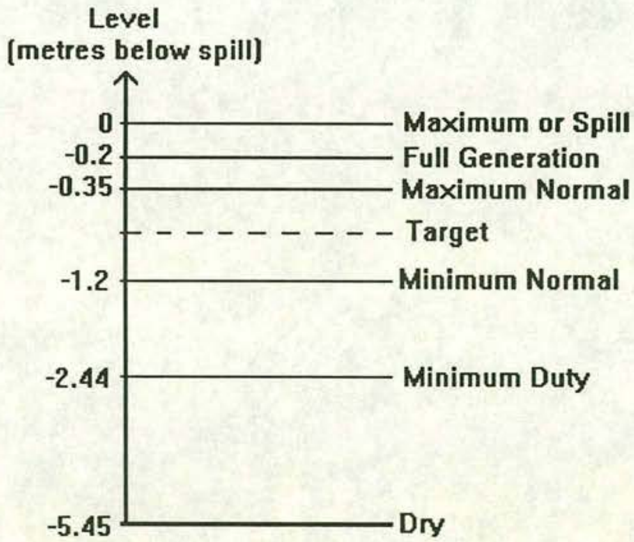


Figure 5.7 Loch Rannoch Reservoir Levels[130].

These benchmark levels are[131]:

Maximum or Spill Level: The top level at which the water in the reservoir would begin to spill over the edges or through a spillway, wasting valuable resources and possibly flooding the adjacent area.

Full Generation Level: The level above which the plant should continuously operate at full-load output. Failure to operate in this mode would eventually lead to spillage.

Maximum and Minimum Normal Levels: Controllers adjust flows to keep the reservoir within these levels, (these may vary with season or for operational reasons).

Minimum Duty Level: The lowest level to which the reservoir should be allowed to fall, whilst retaining enough water for emergency generation and compensation flow.

Dry Level: The absolute minimum level to which a reservoir can fall, i.e. empty, resulting in land damage and loss of fish stock. Good water management would never allow a reservoir to reach this level, although it is a possibility during periods of severe and prolonged drought.

Target Level: The control engineers' preferred level such that the best use of the runoff can be exploited. This level is estimated by taking account of all foreseen outages of generation plant, predicted system load and average monthly runoff. It is the target level that is determined by the experience of the control engineers and therefore is fundamental in effective water management.

All benchmark levels have been fixed for each SHE reservoir, but occasionally the maximum and minimum levels are changed according to the season, e.g. the minimum level during the summer would be higher than in winter to compensate for the likelihood of drought.

5.6.7 Rate-of-change of levels

A further operating limit of any reservoir is the rate-of-rise or rate-of-fall of water level over a fixed time period, (i.e. hour or day). This is particularly important where a reservoir is used by the public, since a gradual change in water level goes unnoticed, but a fast change could cause a public nuisance or danger to life, e.g. grounding of boats, inundation, etc.

5.6.8 Time constant

Optimal control of cascade systems is further complicated by the phenomenon known as the reservoir time constant, which is defined as the time taken for inflow entering into the reservoir to be experienced at the other end or outflow. This effect is due to the long distances between upper and lower dams or weirs, and large surface areas of the catchment. A large volume of water entering the reservoir may not raise the downstream water level for some time usually measured in hours. Similarly, there is another time constant relating the time taken for rainfall over a catchment area to runoff and produce a rise in level.

5.6.9 Reservoir priority

In any cascade system, water flows from higher reservoirs down through the system to the lower reservoirs, and in simple schemes it is normal practice to analyse the upper reservoir dynamics then assess the consequent effect on the lower reservoirs. However in the more complex SHE schemes, the upper reservoirs are usually in isolated areas whereas the lower reservoirs are within populated recreational areas where rapid changes in level and extremes in level would be intolerable. Thus in complex schemes, the highest priority reservoir may be selected in the middle of the cascade whilst the lowest priority is at the highest point of the cascade. Therefore the analysis of the dynamics needs to be done in order of priority, to ensure stable operation of the most critical reservoirs first. Simulations have shown that moving the priority reservoir lower down the cascade has little effect in slow changes in level over long periods of time. However when the timescales are compressed either due to an emergency, or planned high flow situation, in crisis water management or for rapid despatch of large plants at excess capacity it has been established that the choice of priority reservoir can significantly affect the results of the water management.

If conflicts between two reservoirs occur, reservoir priority allows the controller to determine which reservoir should be protected against spill or dry, over another reservoir. For example, if both an upper and lower reservoir were about to spill a linking station would have two possible actions: go to full-generation to protect the upper reservoir or shut-down to protect the lower reservoir. The appropriate controller response would be dependent on the relative priorities of the two reservoirs and the station itself.

5.7 Representing the Water System

5.7.1 Schemes

The simulation of any hydro-electric scheme requires mathematical models to represent evolution and transfer of water reserves, the variations in the water storage levels and the generation outputs from the stations. The main components to be modelled are the power stations and associated reservoirs (including pump-storage units), weirs, water inflows and outflows, spatial and time relationships (rivers and time constants) of interconnected reservoirs[132,133,134].

Hydraulically, a cascaded hydro-electric system can be partitioned into schemes comprising a number of reservoirs, weirs and rivers. Each of these items can easily be represented by an object exhibiting all the common properties. Therefore, within the Water Manager a series of base object classes were created having the appropriate characteristic slots but containing limited stored data. This permits the creation of new instances of each class as schemes are entered into the Water Manager.

For example, the class *Reservoirs* has sub-Classes *TummelLochs*, *SloyAweLochs*, etc. and *Tummellochs* in turn has instances *Rannoch*, *Ericht*, etc. (Figure 5.8). This hierarchical approach keeps each scheme separate but allows the inheritance of each reservoir to be from the same root, *Reservoirs*. Bracketing instances in scheme subclasses, simplifies scheme creation, deletion and data manipulation. A similar approach has been taken in the creation of the sub-classes: *Weir*, *Schemes* and *Stations*. An additional class, *Groups*, has also been created to permit the amalgamation of schemes within a PU.

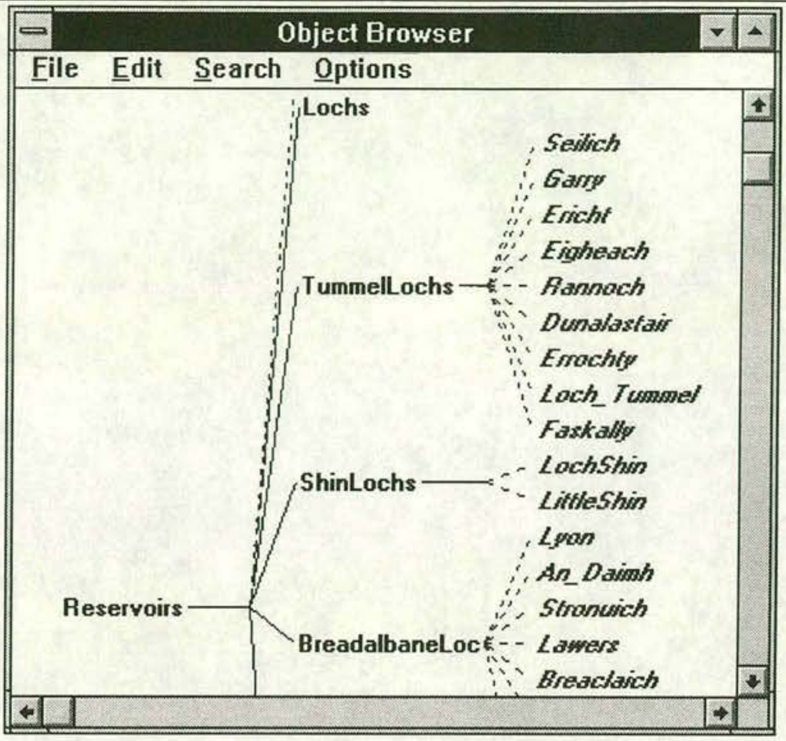


Figure 5.8 The Reservoir Hierarchy

An example of a Group is the hierarchy of the SHE Clunie Group which can be written in textual form thus:

CLASS: Reservoirs
- INSTANCE: Phantom (a special reservoir used in the rule process)
- SUBCLASS: Lochs
  - SUBCLASS: TummelLochs
    - INSTANCEs: Seilich, Garry, Ericht, Eigheach, Rannoch Dunalastair, Errochty, Loch_Tummel, Faskally.
  - SUBCLASS: ShinLochs
    - INSTANCEs: LochShin, LittleShin.
  - SUBCLASS: BreadalbaneLochs
    - INSTANCEs: Lyon, An_Daimh, Stronuich, Lawers, Breaclaich, Lednock, Earn.
  - SUBCLASS: SloyAweLochs
    - INSTANCEs: Tralaig, Sloy, Shira, SronMor, Lairige, Nant, Awe, Oude, Glashan, Tarsan, Lussa.

A typical scheme object listing is given in Appendix 5, however, the main information associated with a scheme is:

- the name lists of all reservoirs, weirs and stations, (in order of entry during assembly in the WM).
- the priority order of all reservoirs, weirs and stations as decreed by the engineers.
- name and location of external files for data retrieval and storage.
- scheme overall weekly and daily generation requirements.

5.7.2 Reservoirs

As discussed previously, an individual reservoir has a large selection of data associated with it, e.g. volume, levels, average daily runoff, etc. However, all reservoirs have the same associated type data, and consequently each individual reservoir can be described in similar terms.

Figure 5.9 shows typical information required when defining a reservoir. Taken together with details of the associated stations and/or weirs fully this defines the reservoir and its position within the cascade scheme. This particular window is one of three presented to the user either during the assembly of a cascade for simulation or if any basic data needs to be altered.

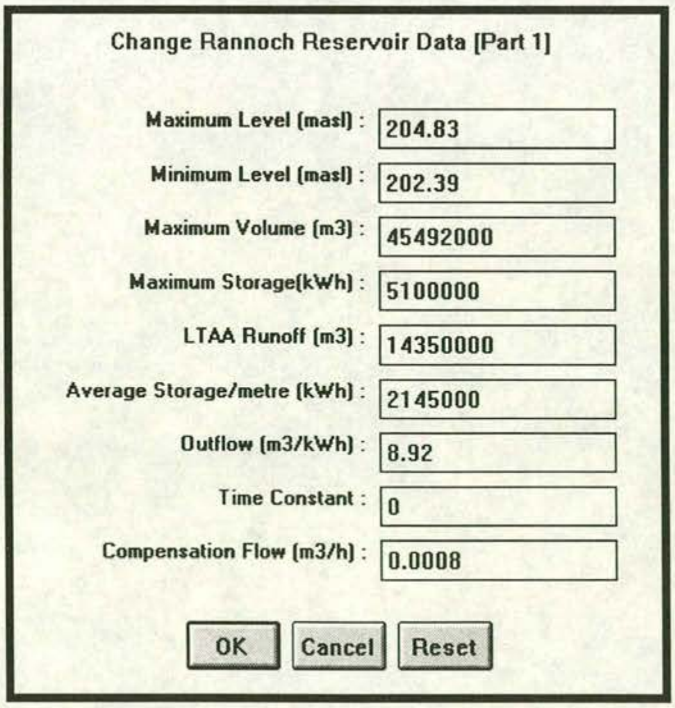


Figure 5.9 Reservoir Data Entry

During the assembly process, an individual instance is created with the above information, as shown in Figure 5.10. Note, the asterisks denote inheritance of the slots from the class *Reservoirs*. and the methods are mainly used to initialise a number of other slots that are required for simulation purposes. The information entered and derived is detailed in the typical object slot listing in Appendix 2.

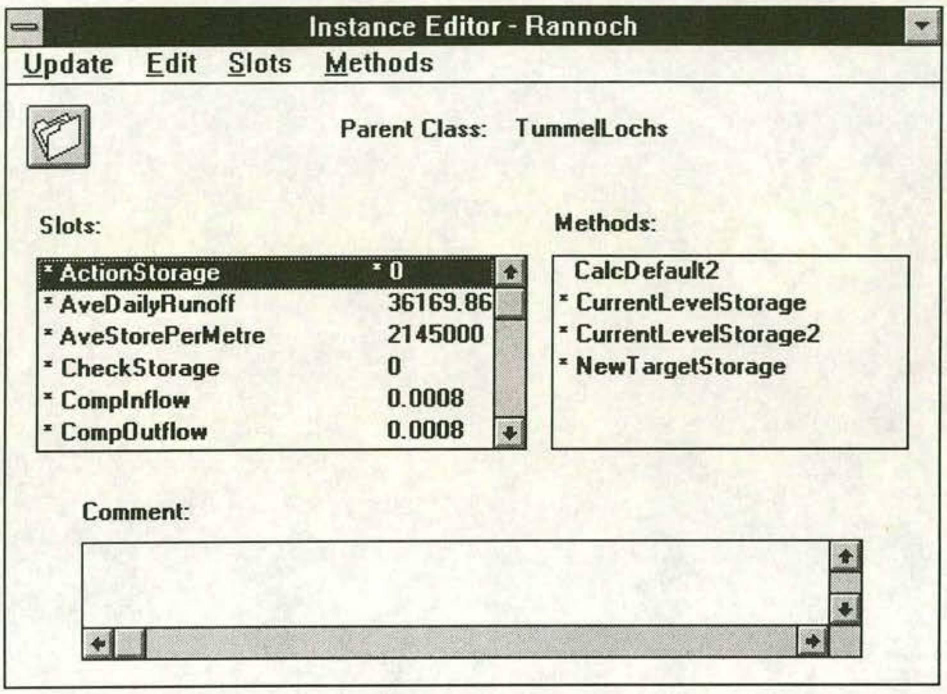


Figure 5.10 Reservoir Object

The example slot editor, Figure 5.11, shows the added information related to an individual slot, *Rannoch:MinLevel*, which holds the reservoir minimum level in metres above sea level. (m.a.s.l.). This displays type and range attributes of the slot, in this case a single value number with no pre-set limits.

The slot editor also indicates an AFTER_CHANGE monitor attached to the slot which activates a method *CalcDefault2*. This method, displayed in the method editor in Figure 5.12, calculates a number of additional items of information related to the minimum level, when activated during the assembly process or if any changes are made to the basic reservoir information.

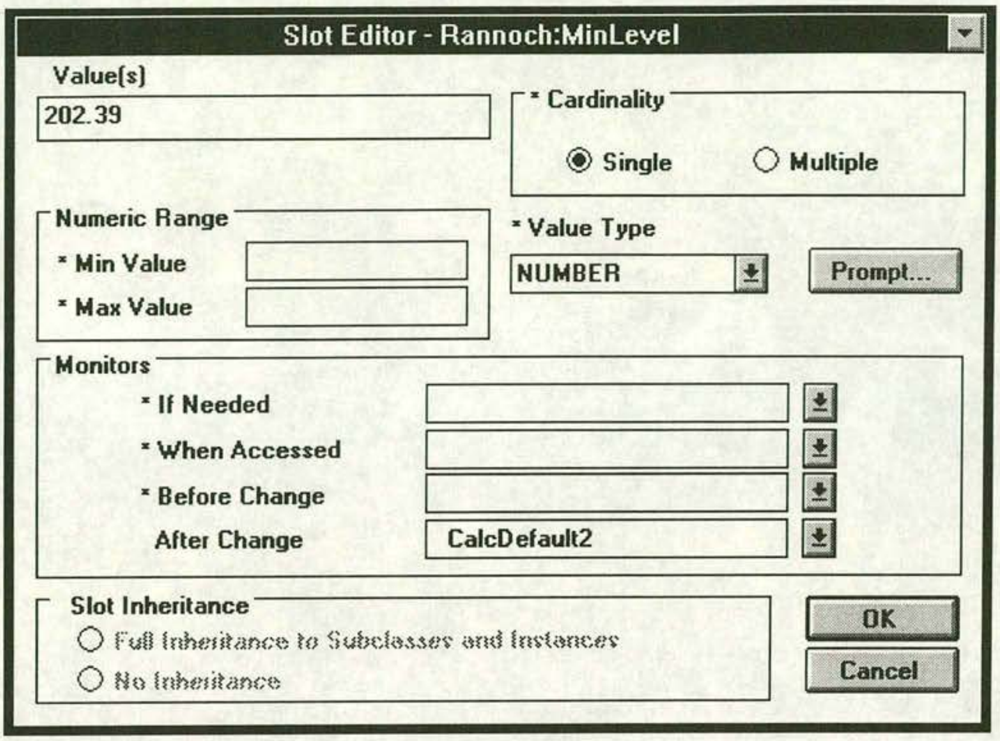


Figure 5.11 Slot Editor

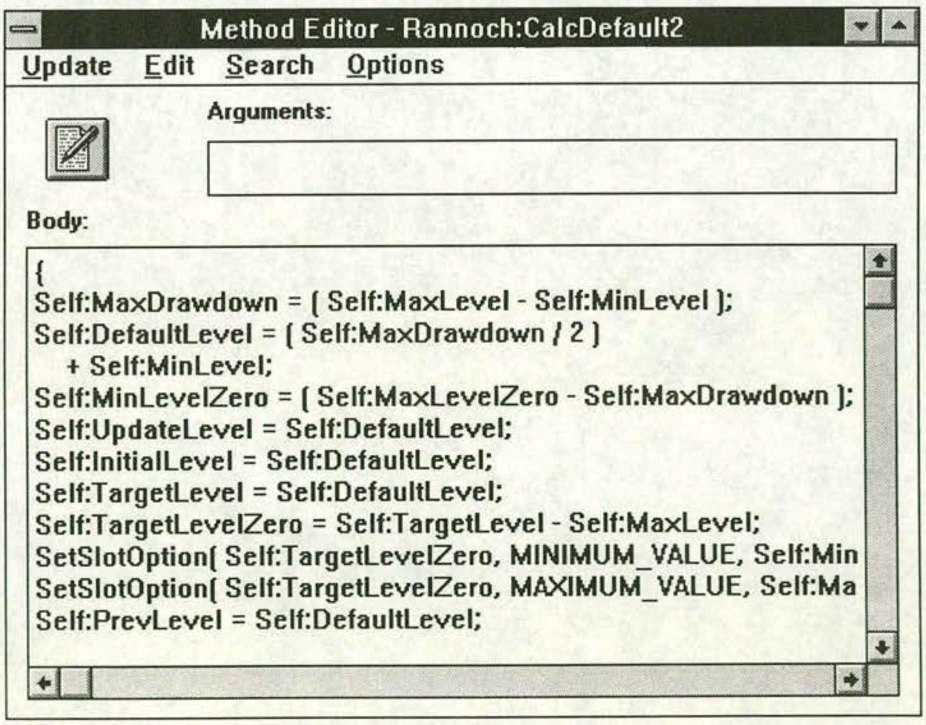


Figure 5.12 Method Editor

In addition to the assembly process and the change data facility illustrated in figure 5.9, two further windows allow changes to user adjustable data (current level and runoff percentages) associated with each reservoir.

5.7.2.1 Reservoir current levels screen

The Reservoir current levels screen, Figure 5.13, shows the present state (the number below each slider) of each reservoir prior to a scenario run. The slider bar is constrained between the maximum spill level (zero) and the minimum level in metres below spill. For example, Loch Ericht reservoir has a minimum level of -9.45 metres, but is currently at -2.91 metres. Any changes to one or more levels would automatically cause the software to calculate or "look-up" the corresponding storage and volume.

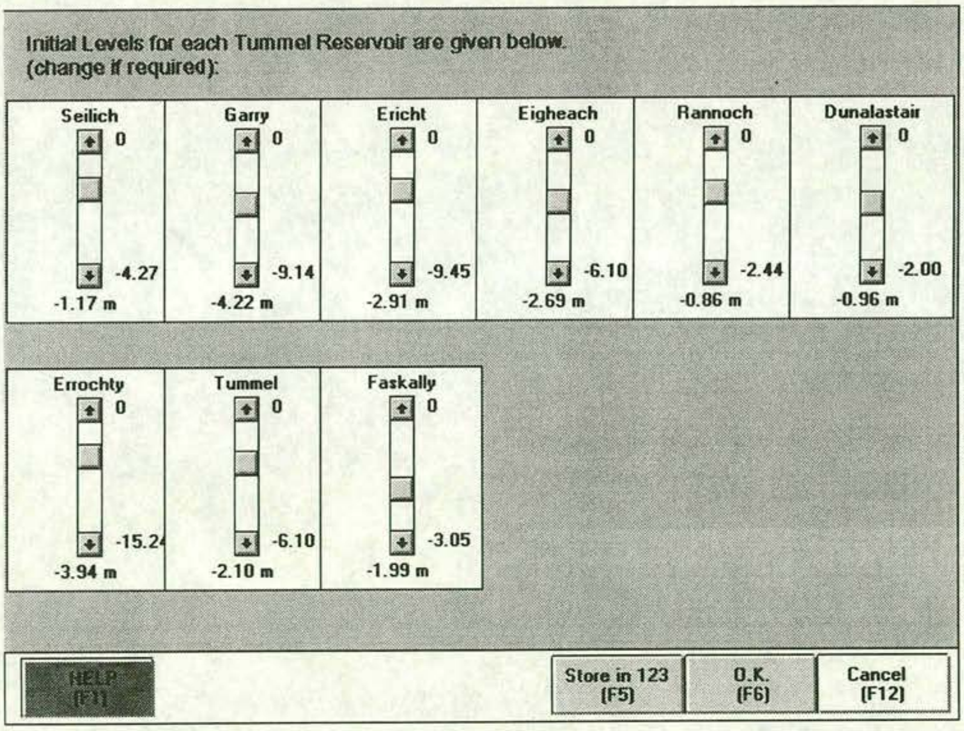


Figure 5.13 Reservoir Current Levels

The "Store in 123" button allows the user to transfer the adjusted levels to the *LoProDat.wk1* storage file (see Chapter 7).

5.7.2.2 Runoff percentage screen

The window shown in Figure 5.14 is used to adjust the runoff multiplication factor (explained in section 5.6.2) to take account of the anticipated weather conditions. All runoff percentages have a maximum value of 200%[135] but each reservoir in a cascade can be set individually as required.

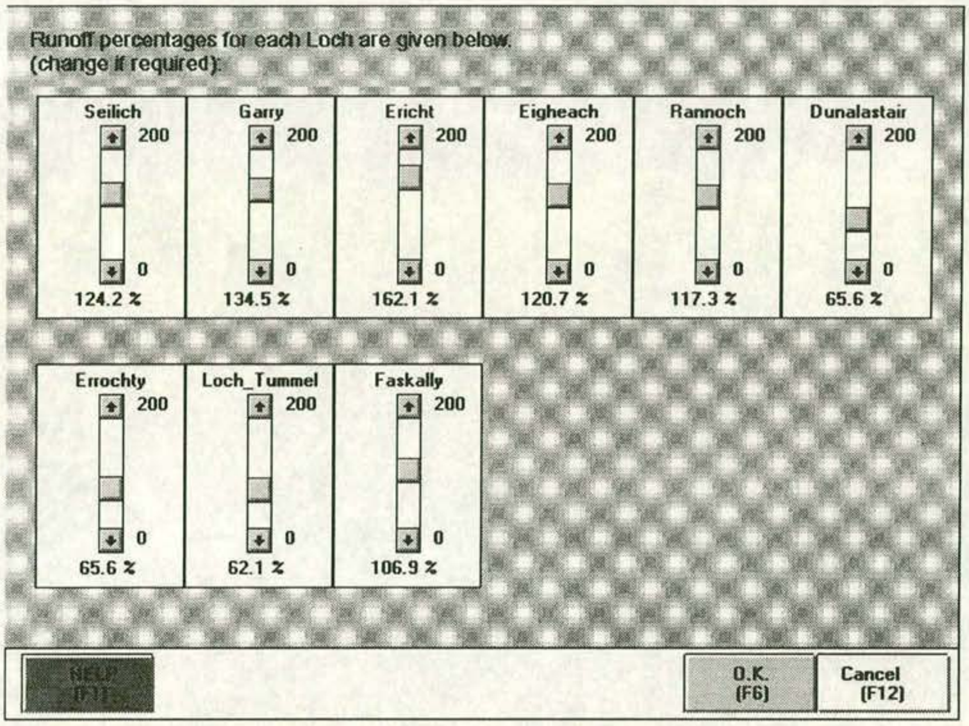


Figure 5.14 Runoff Percentages.

Thus, using the various interface screens all the data associated with each and every reservoir can be entered or altered individually to provide maximum flexibility and serviceability of the reservoir database.

5.7.3 Weirs

As with reservoirs and power stations, weirs are considered as objects, requiring a number of standard items of information to be entered during an assembly process. These are the physical dimensions and height limits as shown in the user data entry window shown in Figure 5.15.

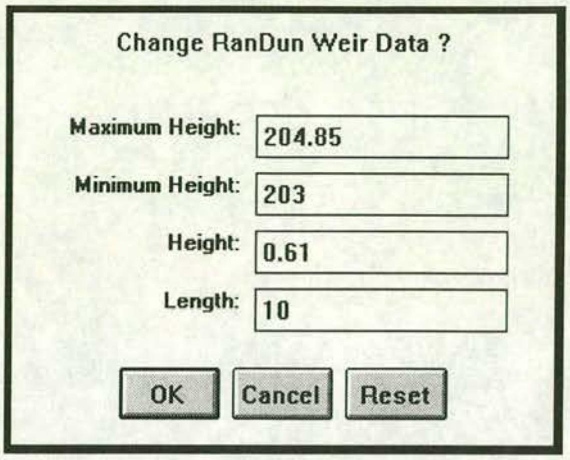


Figure 5.15 Weir Data Entry

The information gathered allows an assessment of the volume flow (discharge) over a weir which is dependent on the level of the upper reservoir, i.e. if the reservoir level is below weir height, the discharge is zero, whereas above weir height, the difference in reservoir level and weir height, together with the length of the weir crest permits a flow to be calculated using the formula for discharge[136]:

$$Q = C_w'.0.66\sqrt{2g}.L\left(\left(h + \frac{V_o^2}{2g}\right)^{1.5} - \left(\frac{V_o^2}{2g}\right)^{1.5}\right) \text{ (ft}^3\text{/sec)} \ldots\ldots (5.6)$$

where **h** is the difference in height between the weir crest level and the upstream (reservoir) level

C_w' is a coefficient relating the height of the weir to **h**

g is the acceleration due to gravity = 32.2 ft/s^2.

L is the length of the weir crest

V_o is the upstream water velocity

Using a modified C_w which takes account of the velocity of approach (i.e. relating the head to the flow) and incorporates a conversion factor, times 0.552, for metric systems, the value of discharge can be found from the revised formula :

$$Q = C_w.L.h^{1.5} \ldots\ldots (5.7)$$

Table 5.2, gives values for this modified coefficient C_w for variations in head against the ratio of weir height **H** to head **h**.

	Head h in metres						
H/h	**0.2**	**0.4**	**0.6**	**0.8**	**1.0**	**2.0**	**5.0**
0.5	2.3	2.28	2.28	2.27	2.27	2.26	2.26
1.0	2.07	2.05	2.04	2.03	2.03	2.02	2.02
2.0	1.95	1.93	1.92	1.92	1.91	1.91	1.9
10.0	1.85	1.83	1.82	1.82	1.81	1.81	1.8
∞	1.83	1.81	1.8	1.8	1.8	1.8	1.79

Table 5.2 Coefficient C_w for rectangular sharp-crested weirs.[137].

For example, for *RanDun* weir, if *Rannoch* reservoir level is at 204 m.a.s.l. and the *RanDun* weir height is 203.5 m.a.s.l. then:

h is (204-203.5) = 0.5 metre,
H is 0.61 metre
H/h is (0.61/0.5) = 1.22

extrapolating from table 5.2 : C_w is 2.08 approximately

therefore the discharge is $2.08 \times 10 \times 0.5^{1.5} = 7.35$ m³/sec = 26,473 m³/hour.

Finally, being a hydraulic link between two reservoirs, a weir flow is considered in the same manner as a power station throughput during the simulation process, i.e. each is converted to a simple water volume per hour and the change in reservoir storage can be computed with no associated generation.

5.8 Summary

The hydrological and hydraulic features of an individual storage reservoir are described and the main variables are specified. The various inflow/outflow causes and effects are described and the additional influences of linked cascade reservoirs and stations are discussed. The visual and conceptual representation of schemes, reservoirs and weirs is described in detail. Finally the arrangement of the Water Manager environment is described in terms of its open architecture to permit entry, access and scope for the alteration of all associated reservoir and weir variables.

CHAPTER 6 KNOWLEDGE & RULE BASE

6.1. Knowledge Engineering.

6.1.1 Introduction

Luger & Stubblefield[136] describe expert systems thus :

> "Expert knowledge is a combination of theoretical understanding of a problem and a collection of heuristic problem solving rules that experience has shown to be effective in the specific domain. Expert systems are constructed by obtaining this knowledge from a human expert and from reference material and coding [engineering] it into a form that a computer may apply to similar problems."

Thus the art of developing an expert system, known as knowledge engineering, requires two key personnel, the knowledge engineer (or system developer) who creates the software program and the expert whose expertise is modelled within the program. Although the transfer of knowledge from the expert to the expert system, via the knowledge engineer, seems to be relatively straightforward, in practice there are many potential problems that must be addressed.

This chapter describes the knowledge gathering process and discusses these problems, the methods used to overcome them and the capture of knowledge for an expert system. The description illustrates the implementation of Kappa-PC for this particular application and uses examples taken from the Water Manager to both illustrate the knowledge engineering process and the construction of the "intelligent" portion of the software.

6.1.2 Expert System Suitability

The development of an expert system becomes a major undertaking as the incorporation of all aspects of the subject domain and rules are converted into software. Therefore prior to development it is prudent to ensure the applicability of an expert system to the particular problem domain. This can be achieved by comparing the characteristics of the problem domain with a number of criteria.

Pfeifer & Lüthi[137] declare that those suggested by Davis[138] in 1982, remain valid as guidance for all proposed expert system developments. These criteria are:

- *Limited Domains*: All domains should be clearly delineated, have well-defined inputs and outputs[139] and be sufficiently narrow to allow the development of a manageable Expert System (ES) structure and rule base.
- *Recognised Experts*: ESs are often used where there are no prior criteria for appraising a solution, being evaluated and solved instead by recognised human experts. These experts must be available to provide the heuristic knowledge associated with the problem domain. Moreover, this knowledge must be "private knowledge" that is acquired essentially through personal experience as opposed to "public knowledge" extracted from text books, technical manuals, seminars, etc.
- *Duration*: Tasks that normally take an expert minutes to hours to perform are ideally suited for an ES. A task taking any longer, i.e. measured in days or weeks, is almost certainly too complex, while tasks requiring only a few seconds of expert time to complete are likely to be too trivial to justify the development and use of an ES.
- *High pay-off*: The task must be repetitive and the ES used frequently, otherwise developing an ES is not worth the effort. In effect, the cost of development should be recouped by either freeing the expert for other more difficult tasks or providing scope for improved decisions that save more money.
- *No Common-sense*: Common-sense is difficult to capture since it usually involves highly intuitive, instinctive and emotional judgements which draw on knowledge from many different domains. Furthermore, common-sense reasoning is implicit and highly automated making it usually inaccessible to conscious inspection or knowledge capture.

Meeting the last of these can render almost any problem domain unsuitable, however much of the expertise in engineering, although originally derived from the experts' common-sense, usually has evolved into thought processes that can be captured.

In addition to Davis' criteria, the following are specific reasons why anyone would wish to invest the time and financial commitment to develop an ES in the first place:

- *Consistency*: An ES would introduce a level of repeatability where several experts are involved in solving a problem using their own peculiar methods and interpretation of data.
- *Optimality*: In situations where the complexity of the problem to be solved, in terms of the number of factors (data and rules) which must be considered, the optimal solution can be missed and a sub-optimal alternative selected.
- *Training*: Where experts are unavailable to teach new personnel, an ES can assist by providing non-experts with the opportunity to learn the skills, by assuming the role of the expert within an off-line computer simulation.

In the case of the Water Manager the latter three criteria were the principal reasons for development, whilst, the task itself satisfies all of the initial criteria in that it is well defined; currently undertaken by experienced engineers; takes several minutes to an hour to perform; and is required to be repeated on a regular basis (at least daily).

6.1.3 Knowledge Gathering

Once the applicability of an expert system had been established, an appropriate shell was chosen, and both energy and hydraulic knowledge databases were defined and created in program resident or accessible data files (Chapters 4 and 5). The next step in the evolution of the Water Manager was to develop the expert system knowledge rulebase. A rulebase can normally be constructed by drawing information from a number of sources including: written material, computer based acquisition[140,141] or the generation of rules from existing software.[142] However, these sources tend to rapidly become out-of-date in a rapidly changing commercial environment, uninterpretable by the knowledge engineer, or simply fail to fully describe the situation. Therefore, the best method of knowledge gathering was to conduct an extended series of interviews with the expert (or a group of experts) in the particular field, i.e. the hydro controllers themselves. An alternative approach, not used in this instance, would be to job-shadow the expert, however, such an approach requires a great deal of time on behalf of the knowledge engineer and can be disruptive to the expert.

This rule gathering process is the most difficult operation to address during expert system development, since it relies on establishing a rapport with the expert(s) and translating their problem solving procedures, strategies and automatic thought processes into executable coded rules. Hence, the knowledge engineering process can be separated into four distinct serial tasks: preparation, acceptance, communication and capture.

6.1.3.1 Preparation

Prior to the knowledge acquisition process, known as elucidation of expert heuristics[143] (i.e. establishing the rules of thumb), the knowledge engineer must first attain a general understanding of both the problem domain and the appropriate expert system development tool. This initial information gathered by the knowledge engineer himself, must include a reasonable level of technical competence in the subject matter and, as far as the software is concerned, a good understanding of the methods of rule and data representation. Furthermore, the knowledge engineer must establish basic details on the areas of communication between the expert system, the user (e.g. graphical interface) and any propriety data sources (e.g. spreadsheet databases). By attaining this level of expertise, the knowledge engineer can ensure that the experts' knowledge can be incorporated within the expert system; be satisfied that the chosen ES development tool is suitable for the task ahead and avoid asking the expert for information that could have been obtained elsewhere.

6.1.3.2 Acceptance

The preparation stage is essential to help the knowledge engineer to overcome a number of hurdles to ensure acceptance of the expert system[144]. The most important of these hurdles is to overcome the emotional and psychological barriers that the expert(s) may create, consciously or sub-consciously, to resist the introduction of an expert system into their workplace. These barriers normally appear for two simple reasons:

- The human experts can often view an expert system as a threat to their job security, i.e. they foresee themselves eventually being replaced by a computer.
- The experts may fear the prospect of the software becoming a better expert than they are, revealing errors or shortcomings in their own methods.

At the outset these problems or fears can be allayed in a number of ways:

- Initially reassuring the experts that they are not about to be replaced, by describing an expert system as a representation of only a fraction of their expertise. (Refer to Section 6.1.3.3)
- Encouraging the expert to view the system as being under his/her ownership.
- Advising the experts that they will be testing, appraising and updating the new expert system, both during and after development is complete, thereby assuring them that they control the system.
- Clearly indicating that an expert system is not infallible and can make mistakes (usually due to gaps in communicated expertise)[145], and that the only people that can judge and offer correction are the experts.
- Selling the idea of the expert system as a useful tool for the expert and offering as an incentive, the idea that the expert system will remove some of the more mundane and repetitive aspects of the job, thus releasing the expert to pursue the more complex and interesting activities associated with the job.

6.1.3.3 Communication

Having gained acceptance of the expert system, the next major hurdle for the knowledge engineer is to extract the knowledge from the expert. However since expert systems are constructed and operate in a way that is usually unfamiliar to most computer users, it can be difficult for an expert to grasp the nature of the knowledge that is required and the form in which it needs to be presented. Therefore, to ease the transfer of knowledge, the knowledge engineer must provide the experts with appropriate background information on what the expert system is going to do, how it will do this and why it is being used. In addition, the expert must be provided with a basic understanding of expert system concepts and techniques so that he/she is able to comprehend the representation of his/her expertise within the developing software.

This pre-development preparation (described in sections 6.1.3.1 and 6.1.3.2) greatly assists in overcoming the third hurdle, extracting the facts and rules from the expert. However, again a number of problems can arise due to the difficulties of transferring all the knowledge from the expert to the expert system. Figure 6.1 illustrates this problem by showing that, during the evolution of the knowledge gathering process, information is lost at every stage.

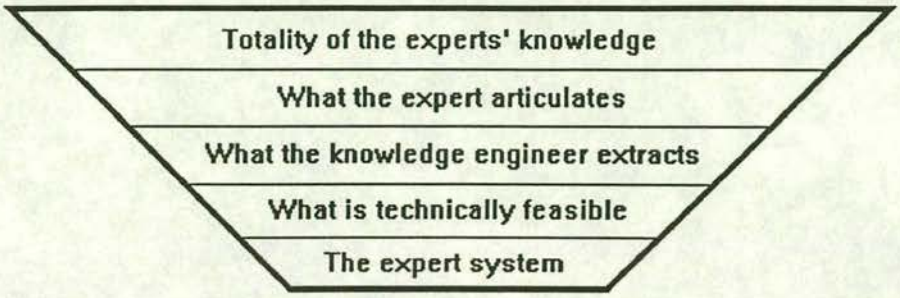


Figure 6.1 Knowledge Gathering[146]

These information losses are due to:

- The experts' familiarity with their own area of expertise, i.e. when asked to articulate their expertise they cannot differentiate between that which is common knowledge and that which is genuine expertise.
- The experts may be unable to convert their automatic thought processes into words such that they find it difficult to define what it is that they do which constitutes expertise. Consequently, they would find it difficult to write down their expertise in a form that is useful to the knowledge engineer.
- Having captured the knowledge, the knowledge engineer is not always able to translate this into coding for the expert system.

In addition to the above problems, in areas where several experts are involved, each may employ conflicting methods to achieve the same aims, thereby introducing parallel paths and conflicts within the expert system.

6.1.3.4 Capture

Capturing the knowledge from the experts for incorporation into the software broadly followed three steps: discussion, translation and implementation.

Discussion usually entails an initial general meeting with the experts to ensure that they are comfortable with the idea and gauge if they have any thoughts as to how the system will develop. In this case, several visits of a few days duration were made to the Scottish Hydro-Electric CCR, where general discussions and interviews were held with a wide range of managerial staff. During this time the engineers engaged in controlling the transmission network and scheduling generation were also observed. More particularly, the methods of water control and hydro scheduling were analysed and appraised. From these early meetings a working relationship with the engineers was established and the general remit of the expert system was conceived.

Over the course of subsequent visits the experts began to elucidate their general experiences, and impart details of the source and nature of available data. Thus the knowledge database began to expand while simple data relationships were established.

This process continued over four years, initially at CCR, but, half-way through the assembly of the ES, the scheduling of hydro was passed to the control engineers at the Hydro Group control centres at Dingwall and Clunie. Thus further discussions took place at Clunie where a slightly different approach to hydro scheduling was taken but the general knowledge remained the same.

Gradually, the experts began to narrow down the discussion to the root knowledge ready for capture, thus initiating the formation of rules. However, the knowledge drawn from the experts was not entirely converted into rules, since the majority of the gathered information formed the basis for other coded structures and user interface configurations. For example, much of the engineers thought processes were concerned with allocating priority to the reservoirs and stations or laying specific conditions on particular items, i.e. running priorities, runoff percentages, etc. Consequently, the resulting Water Manager had to incorporate a comprehensive user interface to permit the engineers to allocate their own preferences or system constraints.

Some of these preferences were simply personal choices with no rule basis at all, for example, when asked to explain a specific target level, each engineer declared their own personal targets "because that is where I like to see the reservoir", or "just because !".

The system constraints involved such things as station outages, set availability and generation time priority, each of which were determined explicitly by others with no reference to the engineers, although, they had to use this knowledge to formulate their ideas for system operation.

However, the intelligent portion containing the rules was formulated as part of the operational aspects, i.e. once the system was running a series of decisions need to be made the avert problems in reservoir operation. These were mainly concerned with how to avoid extreme levels at a reservoir without upsetting the balance elsewhere.

6.2. Water Manager rules

6.2.1 Introduction

The rule gathering focused on the action of engineers to save the integrity of the water system. Two rule trees were produced which form the basis of their thought processes and were used as a foundation for constructing the rule base for the Water Manager. The structure of each, given below, set out the various questions to be answered by the engineers as they pursue a solution to a spilling or draining reservoir.

Spilling Reservoir Rule Tree

If a reservoir in the cascade is approaching the maximum level the following possibilities exist to prevent spilling:

A.1 Increase generation flow to a lower reservoir.

- **A.1.1** Can the generation be increased?
  - **A.1.1.1** Is the station at maximum sets available or on an outage?
  - **A.1.1.2** Will the increase of one set be sufficient?
  - **A.1.1.3** Is the station on a Priority Run (i.e. no change permitted)?
- **A.1.2** Will the lower reservoir spill as a consequence?
  - **A.1.2.1** What is the extra available storage?
  - **A.1.2.2** Is reservoir on a lower or higher priority?
  - **A.1.2.3** Can a lower station let the water through- Priority?

A.2 Decrease the generation flow from an upper reservoir.

- **A.2.1** Can the generation decrease?
  - **A.2.1.1** Is the station at zero sets available or on an outage?
  - **A.2.1.2** Will the decrease of one set be sufficient?
  - **A.2.1.3** Is the station on a Priority Run?
- **A.2.2** Will the upper reservoir spill?
  - **A.2.2.1** What is the additional available storage?
  - **A.2.2.2** Is reservoir on a lower or higher priority?

A.2.2.3 Can an upper station be shut down - Priority?

A.3 Reduce the height of a lower weir.

A.3.1 Can the weir be lowered?

A.3.1.1 Is the weir at minimum height ?

A.3.1.2 Will the decrease be sufficient?

A.3.2 Will the lower reservoir spill?

A.3.2.1 What is the additional available storage?

A.3.2.2 Is reservoir on a lower or higher priority?

A.3.2.3 Can an lower station let the water through?

A.4 Increase the height of an upper weir.

A.4.1 Can the weir be raised?

A.4.1.1 Is the weir at maximum height ?

A.4.1.2 Will the increase be sufficient?

A.4.2 Will the upper reservoir spill as a consequence?

A.4.2.1 What is the extra available storage?

A.4.2.2 Is reservoir on a lower or higher priority?

A.4.2.3 Can an upper station shut down?

A.5 No changes possible

Draining Reservoir Rule Tree

If a reservoir within a cascade is approaching the minimum level the following possibilities exist to avert draining :

B.1 Reduce the generation flow to a lower reservoir.

B.1.1 Can the generation be reduced?

B.1.1.1 Is the station at zero sets available or on an outage?

B.1.1.2 Will the reduction of one set be sufficient?

B.1.1.3 Is the station on a Priority Run (i.e. no change permitted)?

B.1.2 Will the lower reservoir drain as a consequence?

B.1.2.1 What is the minimum available storage?

B.1.2.2 Is reservoir on a lower or higher priority?

B.1.2.3 Can a lower station be reduced to minimise loss of water?

B.2 Increase the generation flow from an upper reservoir.

B.2.1 Can the generation increase?

B.2.1.1 Is the station at maximum sets available or on an outage?

B.2.1.2 Will the increase of one set be sufficient?

B.2.1.3 Is the station on a Priority Run ?

B.2.2 Will the upper reservoir drain?

B.2.2.1 What is the minimum available storage?

B.2.2.2 Is reservoir on a lower or higher priority?

B.2.2.3 Can an upper station let the water through?

B.3 Reduce the height of an upper weir.

B.3.1 Can the weir be raised?

B.3.1.1 Is the weir at maximum height ?

B.3.1.2 Will the increase be sufficient?

B.3.2 Will the upper reservoir drain?

B.3.2.1 What is the minimum available storage?

B.3.2.2 Is reservoir on a lower or higher priority?

B.3.2.3 Can an upper station let the water through?

B.4 Increase the height of a lower weir.

B.4.1 Can the weir be lowered?

B.4.1.1 Is the weir at minimum height ?

B.4.1.2 Will the decrease be sufficient?

B.4.2 Will the lower reservoir drain as a consequence?

B.4.2.1 What is the minimum available storage?

B.4.2.2 Is reservoir on a lower or higher priority?

B.4.2.3 Can a lower station reduce to hold the water-Priority?

B.5 No changes possible

Thus using these rule trees, a general rulebase was designed which can apply to any reservoir where the number of upper and lower stations or weirs can be zero or any positive integer. This obviated the requirement for a set of rules to be attached to each reservoir and consequently reduced the overall size of the rulebase. Hence by adopting this approach the rulebase was designed to be called upon when required to assist the engineers to solve the reservoir level problems as quickly and as consistently as possible. The following sections describe the operation of the rules.

6.2.2 Initiation

The Water Manager expert system "rulebook" comprises more than fifty general rules which are designed to reason towards the "goal" of preventing one or several reservoir(s) spilling or drawing down to minimum level, i.e. draining. The rulebook remains idle for most of the time only being accessed when a reservoir problem is about to occur. The reasoning then follows the Forward Chaining process (see Section 3.2.2.4) which proceeds from the assertion of a fact and evaluates premises toward the Goal, *IsProblemSolved?*, i.e. can the reservoir problem be eliminated?

By way of an example, the sequence of events begins during a scenario run (see Chapter 7) when a warning is generated stating that a reservoir was about to reach one of the two unacceptable extreme levels. The warning would cause the problem reservoir status to be asserted, triggering the inference engine and activating the rules.

For example, if *Loch Rannoch* reservoir was about to spill, and the Goal name is *IsProblemSolved?*, the coding within Kappa-PC would be:

> *Rannoch:Status* = Spill;
> *RuleWorks:TRStatus* = *Rannoch:Status*;
> Assert(*Ruleworks:TRStatus*);
> ForwardChain(*IsProblemSolved?*);

This function extract also shows an intermediate transfer of information from *Rannoch:Status* to *RuleWorks:TRStatus* (where *TR* represents ***T**he **R**eservoir* and later *TOR* ***T**he **O**ther **R**eservoir* will be introduced). *RuleWorks* is a specially created object that provides the Water Manager with the inherent flexibility for applying the rules to any configuration of hydro cascade. When forward chaining is initiated, all applicable information associated with the reservoir under consideration is immediately drawn into *RuleWorks*. Sequentially, all rule control statements, also residing as slots within *RuleWorks*, are initialised. Finally, the rule processing begins by acting only on information contained within *RuleWorks*.

The *RuleWorks* object became necessary for two specific reasons:

- to allow the rulebook to apply to any reservoir, rather that have a set of rules for each reservoir. Unfortunately an individual reservoir system has several possible arrangements depending on its mode of interconnection with adjacent reservoirs (see Figure 6.2 below). Consequently each unique arrangement would require a different set of rules where all of the attached stations or weirs are explicitly named and their associated data incorporated. Therefore, *RuleWorks* is configured to temporarily normalise the arrangement while the rules seek a solution to a problem, i.e. the reservoir system is reduced and focused each time to the problem reservoir, one associated reservoir and the connecting station or weir. All data associated with these three scheme components is transferred into the *RuleWorks* object in slots identified by the prefix *TR* (the reservoir), *TOR* (the other reservoir) or *ThePSorW* (the power station or weir). Hence the rules need only recognise and operate on these three temporary "objects" allowing the rulebook to apply to any portion of a cascade scheme.

- during processing some data may be changed temporarily to assess its likely effect on the overall system. For example, a change to a station output would result in a change to the total MWhs and volume changes to the attached reservoirs, but, if this result causes another problem, the rules would cancel the action. However, if the changes were done directly, alternative corrective actions may be triggered unnecessarily, possibly unleashing a chain of events and data changes that could never be retrieved. Thus all actions and results are held within the *RuleWorks* object until the WM is satisfied that the changes are acceptable, and only then is the revised information released to update the "real" objects.

Figure 6.2 illustrates the general arrangement of a cascaded (problem) reservoir, which can be considered as a central reservoir being fed from one or more upper reservoirs via one or more upper "flow regulators" (stations or weirs), and feeding one or more lower reservoirs via one or more lower "flow regulators".

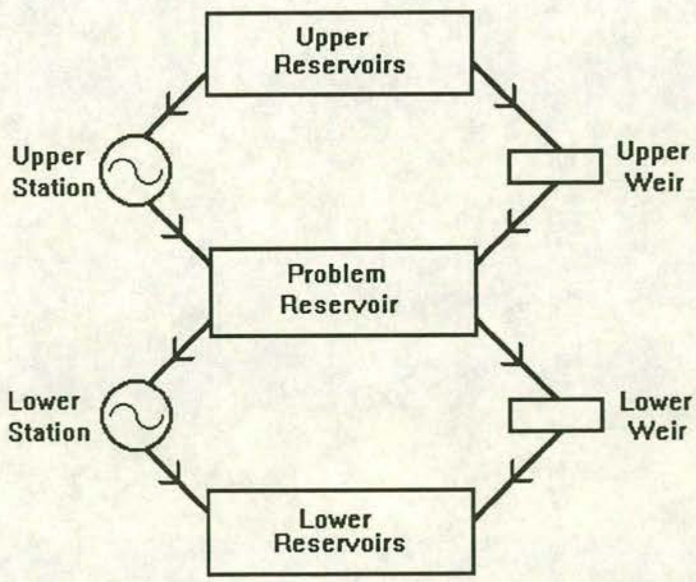


Figure 6.2 General Cascade Model

Thus for the particular problem of a spilling reservoir there are five possible actions:

- Reduce generation from an upper station.
- Increase generation at a lower station.
- Raise an upper weir.
- Drop a lower weir.
- No change.

The sample rule *TheProblemSpill* in Figure 6.3 illustrates these options, e.g. *RuleWorks:PosRaiseUpperWeir* points to the next rule which investigates the possibility of raising the upper weir subject to other conditions. The fifth option, "No change", does not appear in the rule since this is a default condition if all other routes yield an unsatisfactory conclusion. The rule also indicates a priority of 50 which along with *TheProblemDry* is the highest among the Water Manager rules. This ensures that these are the first rules investigated by the inference engine (see BestFirst evaluation in section 3.5.4).

RULE: TheProblemSpill	RulePriority 50
If RuleWorks:TRStatus #= Spill,	
Then RuleWorks:PosRaiseUpperWeir = yes; RuleWorks:PosIncLowerGen = yes; RuleWorks:PosDecUpperGen = yes; RuleWorks:PosDropLowerWeir = yes;	

Figure 6.3 RULE: *TheProblemSpill*

All five actions are prioritised to retain water at the highest level of the cascade and/or save revenue where possible. The priorities in order of highest to lowest are:

1. *Raise the upper weir*: keeping the storage at a higher level while reducing the flow into the spilling reservoir.
2. *Increase lower generation*: to obtain revenue from the water before it is wasted as spillage.

3. *Decrease upper generation*: losing current revenue but retaining the water for revenue generation at another time.
4. *Drop the lower weir*: losing the advantage of storing water at a higher reservoir level.
5. *No change*: default condition which is only likely if nothing else can be done to save the reservoir, resulting in a reservoir spill.

These actions and their relative priorities change for a draining reservoir although some of the reasoning is similar, the sequence becomes:

1. *Raise lower weir*: reduces draining by retaining water with no loss of revenue
2. *Increase upper generation*: to gain revenue from the inflow of water.
3. *Drop upper weir*: losing the advantage of storing water at a higher reservoir level
4. *Reduce lower generation*: losing current revenue but retaining the water for revenue generation at another time.
5. *No change*: default condition which is only likely if nothing else can be done to save the reservoir, thereby draining the reservoir.

Of course, all of these options are not applicable to every reservoir, since the number and variety of attached flow regulators will vary from reservoir to reservoir. Where more than one of the same type of flow regulator exists, (e.g. two or more upper stations) their relative priorities (see Section 4.4.6) are compared and that with the lowest priority would be altered if possible. This comparative action always ensures that the most flexible item is changed first. For example, a station under priority running (explained in Section 4.4.4) must operate at the same output over a set period of time and would therefore have a high priority to prevent a change to its operational status if an alternative lower priority station exists.

6.2.3 Strategy

The search strategy of the rules initially seeks the regulator with the lowest priority and changes its mode of operation first, if possible, e.g. for a spilling reservoir an upper weir (if it existed) would be raised. However, if the weir did not exist or was already at its full height, the rules proceed to seek out the next regulator on the priority list. Should the problem persist, once a regulators' operation had been changed, the rules determine the next appropriate action, and continuing until the problem is solved or no practical solution can be found, see Figure 6.4.

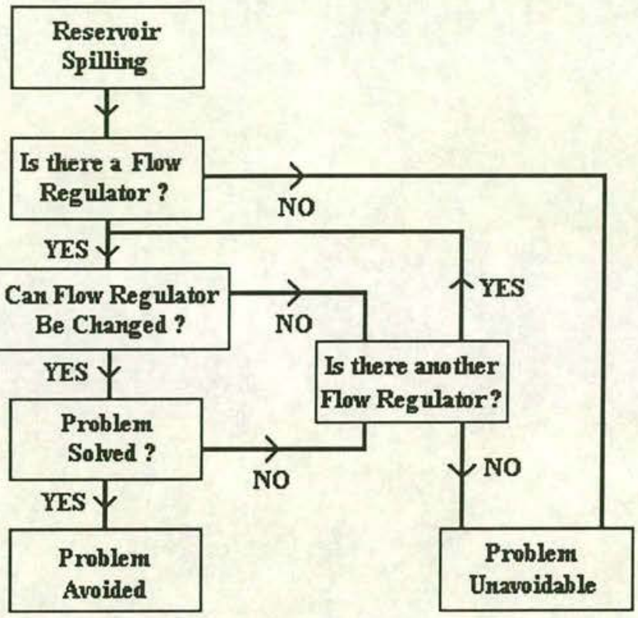


Figure 6.4 Search Strategy Flow Chart

The structure of the Goal, *IsProblemSolved?*, shown below, provides the necessary flexibility when seeking the solution to a reservoir problem which contains a number of possible solutions.

GOAL: IsProblemSolved?

```
(RuleWorks:AnswerToRules #= YesProbSolved )
Or (RuleWorks:AnswerToRules #= NoButTryAgain )
Or (RuleWorks:AnswerToRules #= NotYetTryAgain )
Or (RuleWorks:AnswerToRules #= NoButLast )
Or (RuleWorks:AnswerToRules #= NotYetButLast )
```

Figure 6.5 GOAL: *IsProblemSolved?*

The desired solution is the first, i.e. the *AnswerToRules* is ***Yes*** the ***Prob***lem is ***Solved***, but if the action taken does not solve the problem immediately, the rules assess the next regulator until the problem is solved or there are no regulators left. Thus the other solutions are:

NoButTryAgain: the regulator under investigation could not be altered, but there are other regulators to assess.

NotYetTryAgain: the regulator under investigation was altered but was insufficient to solve the problem, there are other regulators to assess.

NoButLast: the regulator under investigation could not be altered and there are no other regulators to assess.

NotYetButLast: the regulator under investigation was altered but was insufficient to solve the problem, but there are no other regulators to assess.

However, the consequences of a change to the operation of any regulator will obviously affect the dynamics of the connecting upper or lower reservoir(s). Therefore, the rules must investigate beyond the solution of the primary problem by investigating if there is a secondary effect on an attached reservoir. For example, if an upper reservoir is also heading towards spill, then any decision to hold back water to solve the primary problem, i.e. save the original problem reservoir from spilling, will create a secondary spill problem at this upper reservoir.

To react to such an event, reservoirs are also prioritised to the extent that the reservoir with the lower priority would be left to suffer the consequences. Although this situation rarely arises, in extreme cases the option has to be considered.

The primary, secondary and tertiary tiers of the spilling and draining rules are given in the rule trees in section 6.2.1. However, these only illustrate the initial possibilities that would be investigated, since the rules would repeat the operation until the Goal is met. Where a change in a regulator operation occurs the attached reservoirs must have their volumes and levels adjusted accordingly. Therefore, the reiteration process entails a mass of recalculations as well as possible adjustments to generation totals and the generation regime. This is illustrated by the sample rule in Figure 6.6:

This particular rule, *IncLowerGen*, shows the various premises that are necessary to establish whether a lower station can have the output increased and, if so, the conclusive action of calculating the change in flows, volumes and storages, together with trigger information to run a check on the effect on the lower reservoir, e.g. *RuleWorks:PosCheckTOR = WillLowerResSpill;*. Should this check be successful, the rule system would inform the user of the actions taken or proposed to save the problem reservoir (see Chapter 7, section 7.7.2 - Scenario Run).

```
RULE: IncLowerGen                                          RulePriority 40

If      (RuleWorks:PosIncLowerGen #= yes )
And ( RuleWorks:ThePSorWType #= Station )
And Member?( RuleWorks:LookatPSorWout, RuleWorks:ThePSorW )
And ( RuleWorks:ThePSorWOutage #= no )
And ( RuleWorks:ThePSorWPriorRun  #= no )
And ((RuleWorks:ThePSorWSNA * RuleWorks:ThePSorWCPS ) > RuleWorks:ThePSorWRO ),

Then
RuleWorks:ActionSetNosAvail = RuleWorks:ThePSorWSNA;
RuleWorks:ActionOutput = ( RuleWorks:ThePSorWSNA * RuleWorks:ThePSorWCPS );
RuleWorks:ActionVolume = ( RuleWorks:ActionOutput * RuleWorks:ThePSorWCMPU
                                        * 1000 * Global:ScenarioTimeIncrement );
RuleWorks:TRNewPDV = RuleWorks:TRPosDownVolume - RuleWorks:ThePSorWSSR
                                        + RuleWorks:ActionVolume;
RuleWorks:TORNewPUV = RuleWorks:TORPosUpVolume - RuleWorks:ThePSorWSSR
                                        + RuleWorks:ActionVolume;
RuleWorks:TRNewVolume = ( RuleWorks:TRVolume + RuleWorks:TRPosUpVolume
                                        - RuleWorks:TRNewPDV );
RuleWorks:TORNewVolume = ( RuleWorks:TORVolume + RuleWorks:TORNewPUV
                                        - RuleWorks:TORPosDownVolume );
RuleWorks:TRNewStorage = RuleWorks:TRNewVolume / RuleWorks:TRCubMetPerUnit;
RuleWorks:TORNewStorage = RuleWorks:TORNewVolume / RuleWorks:TORCubMetPerUnit;
RuleWorks:PSorWAction = Increased;
RuleWorks:PosCheckTOR = WillLowerResSpill;
```

Figure 6.6 RULE: *IncLowerGen*

6.3. Simulating the rules in Kappa-PC

Following the definition of the rules and their actions, the next stage was to install them within the Water Manager. As with other programming features, the Kappa-PC environment provides several development windows, editors and debugging facilities, for ease of installation, amendment and analysis of a rule base. Using examples from the Water Manager, the following sections illustrate each of these windows.

6.3.1 Installing a rule

Rules are created in the specially designed rule editor using the same easy to understand syntax KAL, as that used to create functions and methods. An example of a Kappa-PC rule editor, showing the Water Manager rule *TheProblemSpill*, appears in Figure 6.7 below:

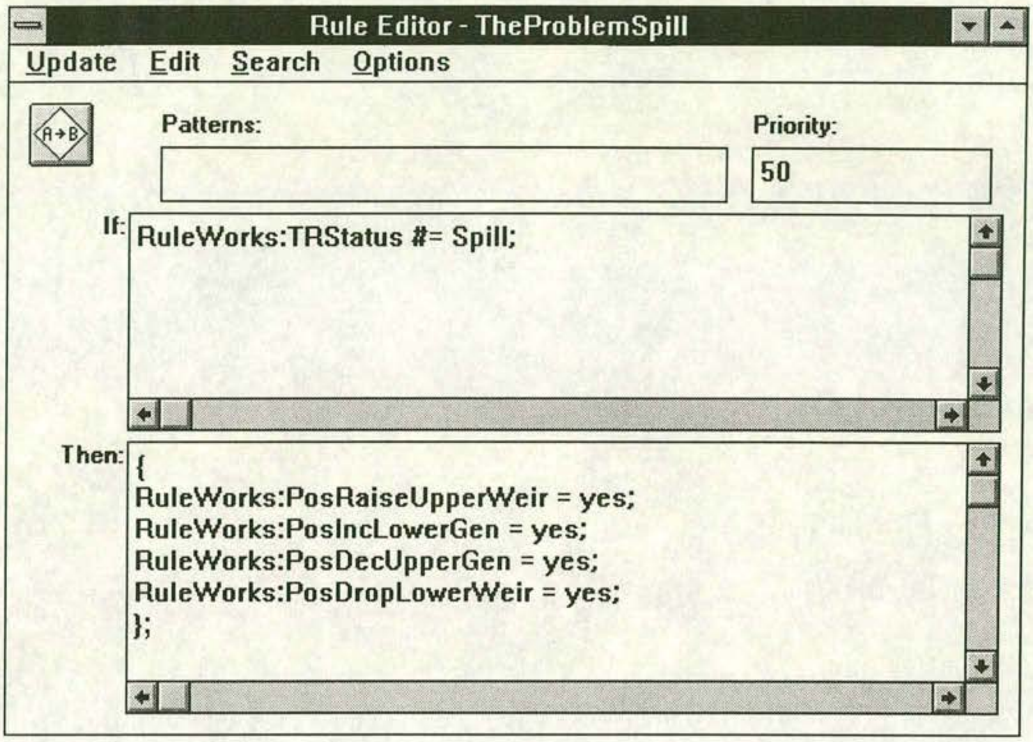


Figure 6.7 Rule Editor

Rules can be created using *patterns*, explained in section 3.5.3, to address a range of objects. However due to the non-uniform nature of cascades this particular facility could not be fully utilised in the Water Manager, instead the *RuleWorks* object (explained in section 6.3.2) allowed the generalisation of the rules.

6.3.2 Installing a Goal

A Goal is an expression or a number of expressions representing questions that need to be answered to achieve an end result. Like rules, goals are written in the KAL language in the form of a test expression that would return the answer TRUE if the Goal condition had been satisfied. The example below shows these test expressions in the Goal, *IsProblemSolved?*, where the reasoning process would be halted if *RuleWorks:AnswerToRules* equated to any of the stated answers, e.g. *YesProbSolved*.

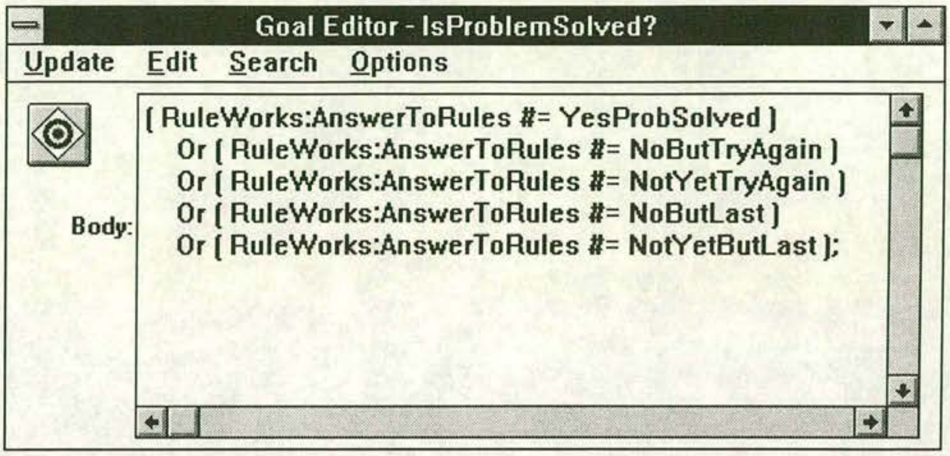


Figure 6.8 Goal Editor

As the rules and goals are created, a developer has access to three rule related development tools as part of the Kappa-PC environment (see section 3.5.2). These aid the developer to understand the operation of the rules by showing the actions of the inference engine during processing. Each of these tools is briefly explained in the following sections.

6.3.3 Rule Relations Window

Typically rules in a knowledge base have precedent (IF Dependencies) and dependent (THEN Dependencies) rules. The Rule Relations Window provides a graphical description of the relationship between rules in the knowledge base.

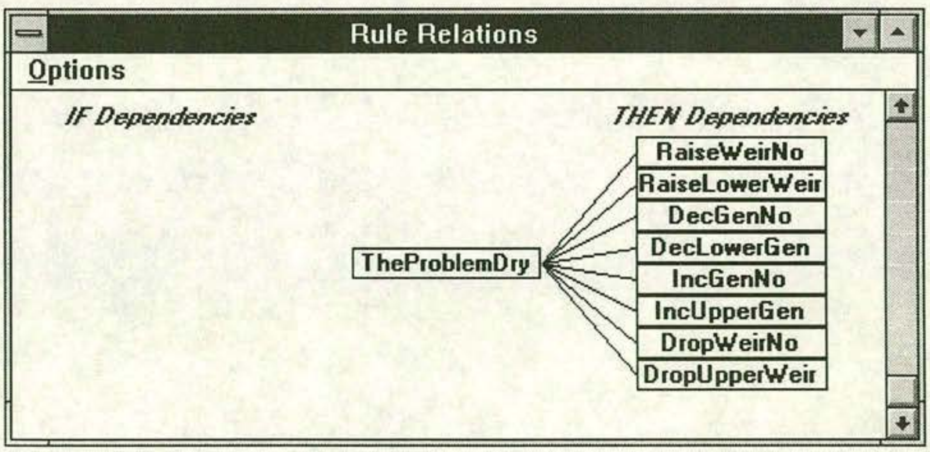


Figure 6.9 Rule Relations Window

The example above illustrates the rule *TheProblemSpill* which being top of the rule tree has no IF-dependencies but has a number of THEN-dependencies where the inference engine would seek out the next relevant rule during processing. Thus within the rule relations window each rule can be expanded in turn to display their dependencies and follow through the possible sequence of events.

6.3.4 The Inference Browser

The Inference Browser displays the inference process for a rule-based evaluation, displayed in the form of a graphical network of rules. Thus the developer can use the Inference Browser to trace through from start to finish the complete inference process. The information presented is similar to that of the Rule Trace Window, the main difference being that Kappa-PC does the work of identifying the chaining relationship whereas when using the Rule Trace Window the developer has to work harder to see the effective chain.

6.3.5 Rule Trace Window

During a forward (or backward) chaining cycle the inference engine of an expert system will invoke a number of rules from the knowledge base. The Rule Trace Window allows the developer to view this invocation in the form of a transcript. In addition, it allows the developer to trace the impact of the inference process on particular slots in the knowledge base. This allows the developer to see how the system generates conclusions and to trace the source of errors in the knowledge base.

6.4. Summary

The process of knowledge engineering is described and exemplified by the methods applied to capture the Water Manager knowledge base. The discussion provides an insight into the extraction, formulation and implementation of rules to assist hydro controllers avert spilling or draining reservoirs. The installation and analysis of this rulebase using Kappa-PC are described in detail. The discussion focuses on the rationale behind the use of a stand-alone general "rulebook" instead of the conventional approach of applying particular rules for individual reservoirs. Finally a description is given of the resulting arrangement, a generalised WM shell which allows the simulation of any cascaded schemes using the same rulebase.

CHAPTER 7 The WATER MANAGER

7.1 Introduction

The development of software to simulate the control processes involved in energy and water management of cascaded hydro could have taken either of two forms:

1. The simulation of an existing system, e.g. a SHE scheme, with predetermined data and set procedures.
2. The creation of a general system, i.e. an expert system environment, that can be used to simulate any cascade anywhere in the world.

The former has the advantage of a knowledge base that is rigid and any peculiarities of the system can be included within the software, although these may only appear in the particular system being modelled. The major disadvantage of this methodology is the inability to use the software for an alternative cascade without significant alterations. The latter provides the flexibility to imitate almost any system with minimal modifications. Unfortunately, to provide this level of flexibility, the software program must have the capability to accept a large amount of fundamental information at initial set-up, provide the means to access and amend this information and be able to arrange the information in the form required for the rules to act upon.

Originally, this research project followed the first route, developing a system to simulate an elementary serial cascade, the SHE Garry/Moriston scheme. However, when this model was applied to a larger system with series and parallel links, the modifications required, necessitated an almost universal program rewrite. The outcome of this initial exercise was to revert to the second approach, adding considerably to the remit of the software, which now required the following principal features:

- A method of assembling or deleting an entire scheme specification.
- A flexible simulation system that could apply to any shape or form of cascade scheme.
- A flexible user interface that could display and accept a wide variety of information associated with any scheme.

In addition, the system required to have the capability to assist the control engineers to fully utilise hydro resources by:

- determining the most advantageous operating regime,
- using and maintaining on-line up-to-date operational information,
- taking due account of all hydrological factors and variables,
- ensuring all environmental constraints are adhered to,
- calculating and testing the best course of action to take, when a change in the operating regime occurs,

This chapter describes how each of the above features were incorporated within the Water Manager expert system environment. For each requirement the Water Managers' structure, capabilities, salient features, mode of operation and overall appearance are discussed.

7.2 Structure

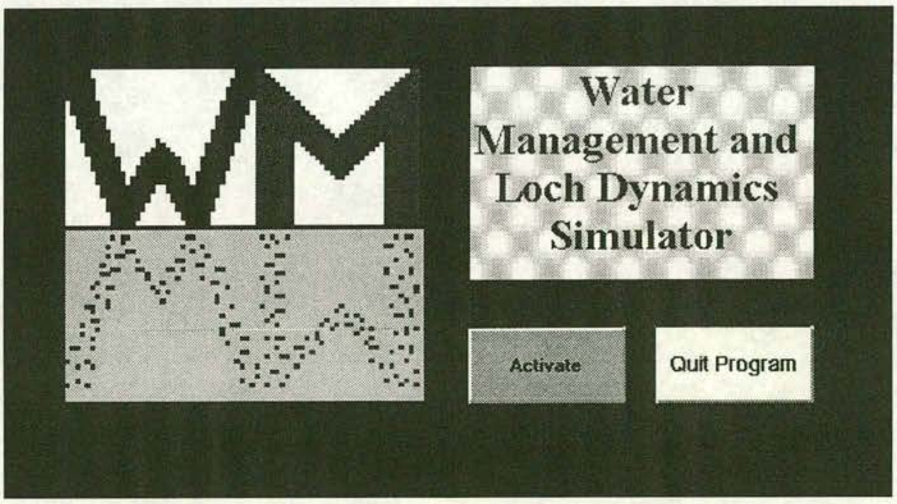


Figure 7.1 The Water Manager

The basic structure of the system can be separated into four modular parts:

- The Knowledge Database.
- The Decision Support Expert System.
- The External File Interface.
- The User Graphic Interface

Each of these modules consists of several sub-modules, illustrated in Figure 7.2., that are all linked together to form the overall program environment.

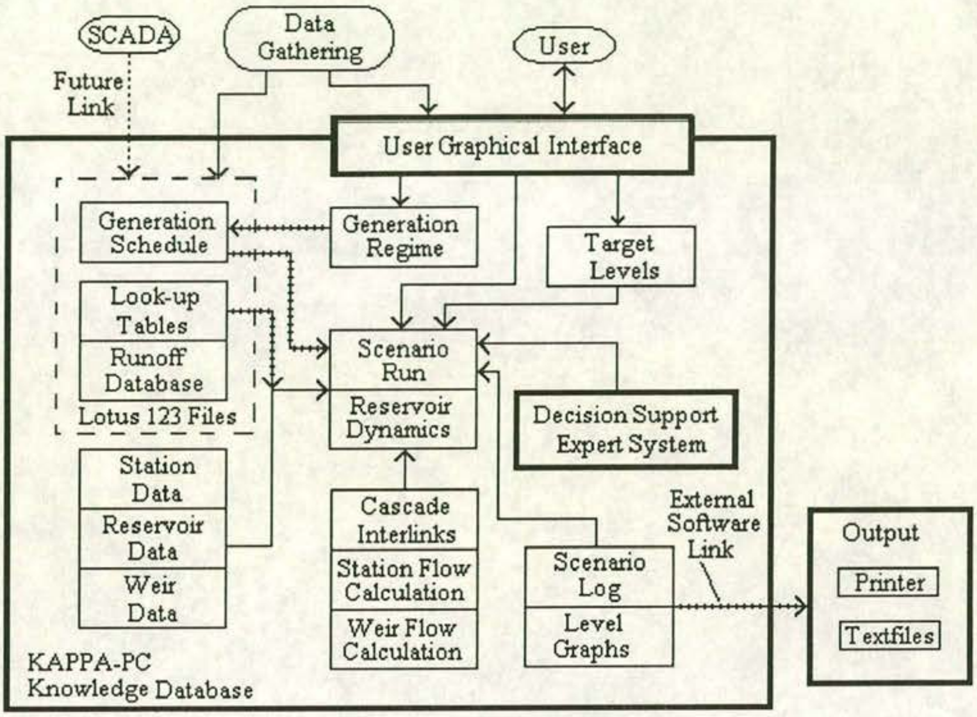


Figure 7.2 System Links

The knowledge database contains all objects and various procedurally coded sequences which process the object data. The objects would each represent the individual components within a cascaded hydro scheme (e.g. stations) together with peripheral information relating to the operation of the system (e.g. time priority slots, etc.). Many of these structural building blocks and operational procedures have been discussed in previous chapters where the data associated with stations, reservoirs, etc., have been described in detail.

The decision support expert system, comprising the rulebase and goals, has been described in chapter 6, however, its context and effect during a scenario run are now described in this chapter.

The external file interface consists of software DDE links that provide the bridge for the flow of information between the object database and other computer storage files. These external program or scheme specific files are described in Section 7.4.

The user interface provides operator access to the object databases, control of program operation and the data result screens. Many of these screens or windows have been described throughout chapters 3 to 6, the remainder are described later in this chapter.

7.3 System Overview

The Water Manager incorporates all of the functionality required under the remit, detailed in section 7.1, and has the following presentation and operational features:

❶ a user-friendly graphical interface.
❷ an on-line help system.
❸ the ability to assemble (or delete) and model any cascaded hydro scheme utilising a flexible serial/parallel hydraulic interlinking system.
❹ dialogue boxes within which the user can view and update reservoir, station and weir data attributes.
❺ easy access to the associated application software, i.e. Lotus 1-2-3 and Microsoft Write, as a means of data storage.
❻ the capability of determining the best generation profile by optimal scheduling of all hydro stations, taking account of priority time slots, target levels, station set availability and limiting conditions.
❼ the capability to run a scenario of operation for any scheme given the following information: start-time, duration, incremental time, weather conditions, percentage runoff, and data location (internally generated profile or Lotus database).

The environment can model the operation of any number of cascaded hydro-electric schemes comprising up to 12 reservoirs and 12 power stations or weirs. (This limitation is simply due to screen graphics space which may be overcome in due course by additional screen layering.) Each item within the cascade can be interconnected in any manner and is established during the creation of a scheme within the software environment, described in Section 7.4.1.

Running the Water Manager involves a sequence of events that ultimately demonstrates to the user whether a generation schedule will produce the desired energy while maintaining the reservoir levels within pre-specified limits. The sequence is as follows:

1. The user selects the scheme or group of schemes to be simulated.
2. The schedule of generation for the week ahead is either installed via a Lotus spreadsheet or the Generation Regime sequence is invoked. The latter operation was fully described in chapter 4, section 4.6.
3. A "fast" scenario can be run for the week ahead to establish if there are likely to be any problems with the water system due to the generation schedule.
4. A full scenario can be run over the day, week or for a customised period of time to establish a more detailed assessment of likely effects.
5. Identification of reservoir problems and suggested actions are highlighted.
6. The resulting reservoir level changes, the total generation output in MWh and any problem areas can be observed via an on-screen log or a generated text file. Graphs of the water levels over the scenario time period can also be viewed and printed to show the overall effect on the reservoir.

In addition to the above operational sequence, via a series of control screens, the user has the option of adjusting:

reservoir starting levels;
the weather effect by adjusting runoff percentages;
and the source and value of all data used.

On delivery, the Water Manager environment has no installed hydro schemes, but, requires the user to first assemble one or several schemes that are to be simulated. For this purpose, when the Water Manager environment is first run, a series of control buttons appears at the bottom of the screen as shown in Figure 7.3.

Figure 7.3 Control Buttons

The two buttons at the extreme left and right have singular functionality: HELP provides access to the WM help system and QUIT simply exits and returns to the Water Manager front screen (Figure 7.1). The other five buttons initiate the different aspects of the WM environment by either providing the user with serially presented windows or offering several optional features or windows. The operational flow chart in Figure 7.4 shows these series and parallel paths as they would be encountered by the user during normal operation.

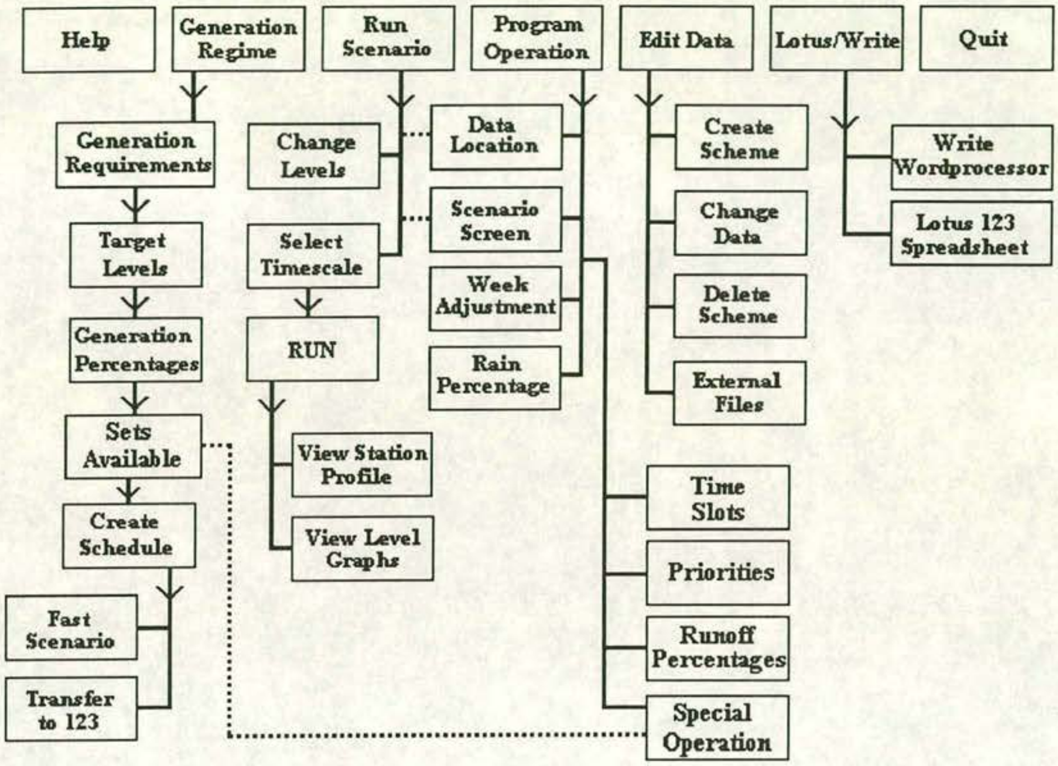


Figure 7.4 Operational Flow Chart

The dotted lines indicate features that can be accessed in other paths while the user is following a particular sequence. Once the user has quit from this side feature he is returned to the main specified path. For example, while following the "Generation Regime" path at the "Sets Available" feature the user can view and change the "Special Operation" of stations but would not be able to directly access the other features in the "Program Operation" path. Each of these controlled paths are described in more detail in the following sections.

7.4 Edit Data

The "Edit Data" facility must be the first button utilised in order to define and create the schemes. This feature also gives the user the ability to delete or edit the data associated with any pre-assembled scheme.

7.4.1. Create Scheme

A user can create a new scheme or part thereof, by entering all relevant information on the scheme, reservoirs, power stations and weirs together with appropriate interconnections. Prior to assembly all stations and weirs must be allocated numbers from 1 to the total number of components. The stations/weirs can be numbered in any order, since during the assembly procedure, the software automatically identifies their type and inter-relationship with the reservoirs. The user is initially presented with the edit window, shown in Figure 7.5, requesting details of the scheme name, group and the number of components within the scheme. The WM then proceeds by asking the user to provide the data for each of the components in turn, starting with the reservoirs (see also Figure 5.9 in chapter 5) then the stations and weirs, Figures 4.6 and 5.15 respectively.

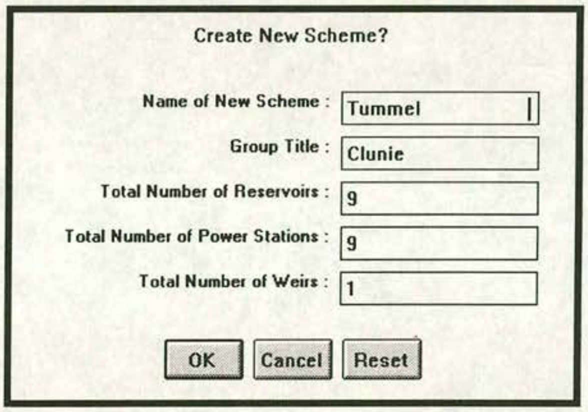


Figure 7.5 New Scheme

In addition to the specification of all data associated with a scheme, several software files must also be created and declared for use by the Water Manager, see Scheme Files below.

Once the scheme data entry is complete, the WM calculates a number of default values (necessary for the first operational run) and uses the numbering system specified above to organise and record all hydraulic links (including compensation flow) between each reservoir. The WM then creates the scheme and all its components within the software shell. Finally the scheme name is added to the program listing and appears at the left-hand side of the main system screen, shown in

Figure 7.10. Thus scheme assembly is complete and it is declared available to have simulation exercises performed on it.

7.4.2 External Files

When active, the Water Manager relies on several peripheral databases and text files to organise the storage of information and bitmap pictures to provide a suitable appearance, e.g. a company logo in place of the ***WM*** icon. However, in order to function properly and prevent software malfunction, all associated file names, directories and paths must be specified in advance. Thus a series of edit windows permits the user to specify these files and their directory location. While this particular feature can be accessed at any time, during the assembly procedure the specific scheme file names are requested. The names of these files must be specified although at the time of scheme assembly they may not necessarily exist, however, before proceeding too far with any simulation, the user will be prompted to rectify the situation.

There are three categories of file used by the WM:

- Application files and directories.
- Program files and directories.
- Scheme files and directories.

7.4.2.1 Application directories

These are associated with the pre-compiled applications used from within the Water Manager to access standard database and text files.

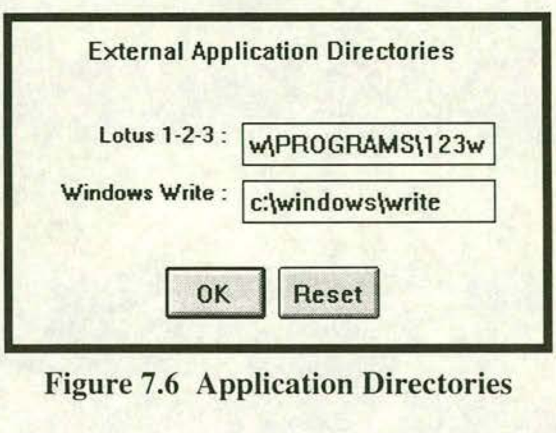


Figure 7.6 Application Directories

In this particular case, the WM only uses Lotus 1-2-3 for Windows and Microsoft-Write files. Therefore, if access is to be gained during program operation, the WM prompt window shown in Figure 7.6, allows the user to pre-specify the directory in which these application environments may be found.

7.4.2.2 Program Files

These are a series of files used directly by the software for graphic displays and data storage during processing. These are part of the suite of software that combine to form the WM, but on installation their directory location must be specified using the prompt window below.

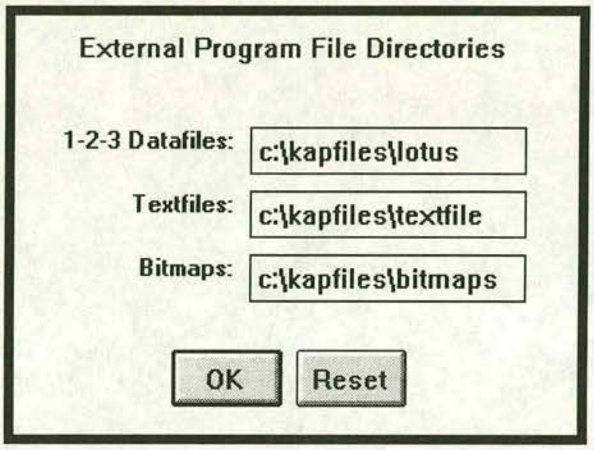


Figure 7.7 File Directories

The standard names and function of the management software files are as follows:

LoProDat.wk1 - The main storage file containing: the weekly generation profile for all stations in any scheme. Takes the form of MW per half-hourly increment; the weir heights per half-hour over the week and the reservoir start levels.
Runoff.wk1 - The runoff figures averaged over the last ten year period. This file is not necessary if a LTAA runoff figure is being used instead (see section 5.6.2).
scenar.txt - A storage text file into which the software downloads events from a fast scenario.
wmlogo.bmp - The main logo displayed periodically during program execution. This can be replaced by a company logo, if required.

mwr1.bmp - The front picture displayed while the program is loading. Again this can be replaced by any bitmap picture.

Each of these files is declared (using the full path name) in the prompt window shown in Figure 7.8.

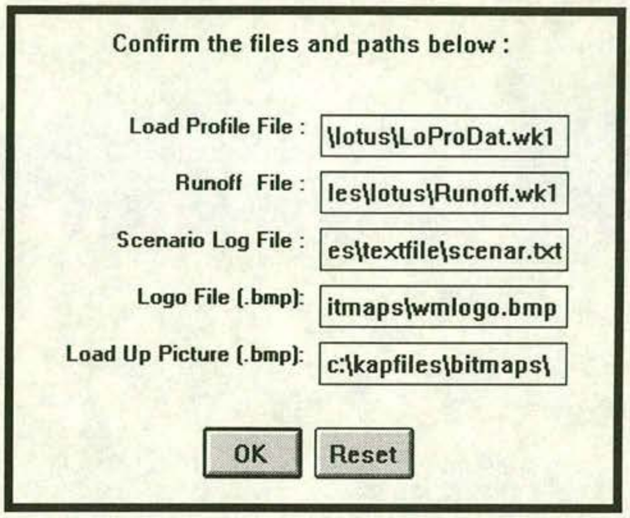


Figure 7.8 Program Files

The *LoProDat.wk1* and *runoff.wk1* files are intended for software access only since any alteration to these would cause the main software to malfunction. Unfortunately the WM writes to and reads from these files which renders them unsuitable to be fully write-protected, however, user accessible buffer files have been created to overcome this handicap (see below).

7.4.2.3 Scheme Files

Each cascade scheme should have their own specific associated files which may be used by the software if so directed, or are a means of accessing the protected program files above. The standard file names and their function are as follows:

A. *???LoPro.wk4* - Weekly generation profile for ??? scheme, specifically designed to permit the two-way transfer of information from *LoProDat.wk1* without direct user access to the program file.

B. *???10ro.wk4* - the runoff figures over the last ten year period, permitting the two-way transfer of information from *Runoff.wk1 as above.*

C. *???Look.wk1* - The look-up file containing storage versus level. This file is only used during the scheme assembly procedure to fill the *LookUpMCM* and *LookUpZeroLevel* slots for each reservoir (see Appendix 2).

D. *??specop.txt* - Storage file for information pertaining to station outages and priority running (see section 4.6.3).

E. *??????.bmp* - the bitmap picture used in a customised scenario-run window, to display the scheme geographic or hydraulic arrangement.

In each scheme the "???" would be replaced by a scheme identifier for all files, e.g. the Tummel files shown in the prompt window below. All files must be stored together in a directory that is attached to the scheme, e.g. for Tummel the directory name is tumfiles.

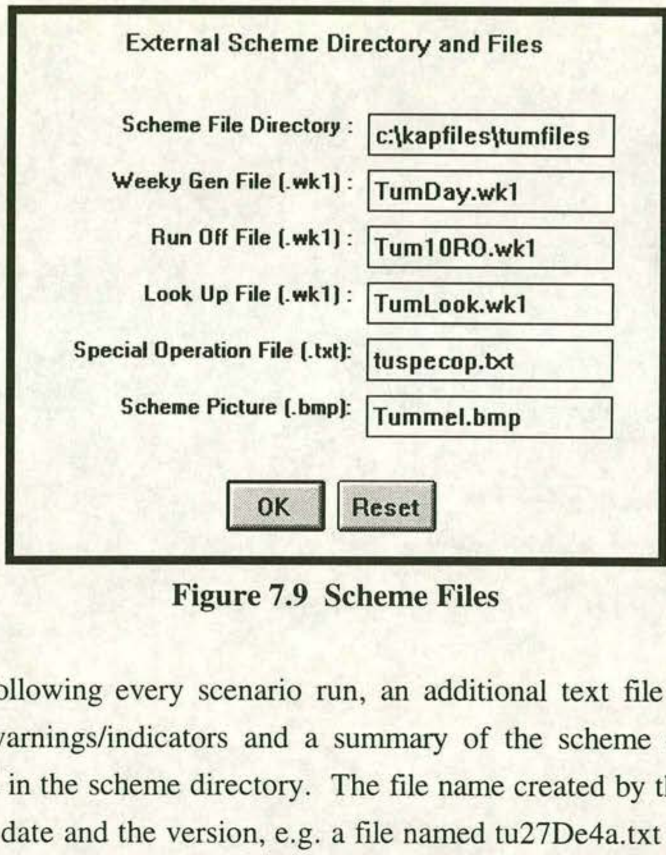


Figure 7.9 Scheme Files

Automatically following every scenario run, an additional text file will be created, containing all warnings/indicators and a summary of the scheme operation. This would be stored in the scheme directory. The file name created by the WM indicates the scheme, the date and the version, e.g. a file named tu27De4a.txt is a scenario run for Tummel on 27th December 94, version 'a' (i.e. first run of the day).

7.4.3. Delete Scheme

Should a scheme be altered, e.g. a new station incorporated, the original scheme must first be completely erased from the Water Manager and re-assembled. This Delete

Scheme function permits the removal of a complete scheme or group by simply specifying the name, however, the task is security protected to prevent accidental or unauthorised erasing.

7.4.4. Change Data

The Change Data function gives the user access to all data entered during the assembly process. It can be used either as a fast access database or to alter the installed data, e.g. where a seasonal compensation flow is altered. To access this function the user must select the scheme and then select the item to be viewed. The edit windows are similar to those used during the assembly process and were illustrated in chapters 4 and 5.

7.5 Program Control

Following the scheme assembly process described in Section 7.4.1, the user can then begin simulation of any cascade. At start-up the user is presented with the full main screen shown below.

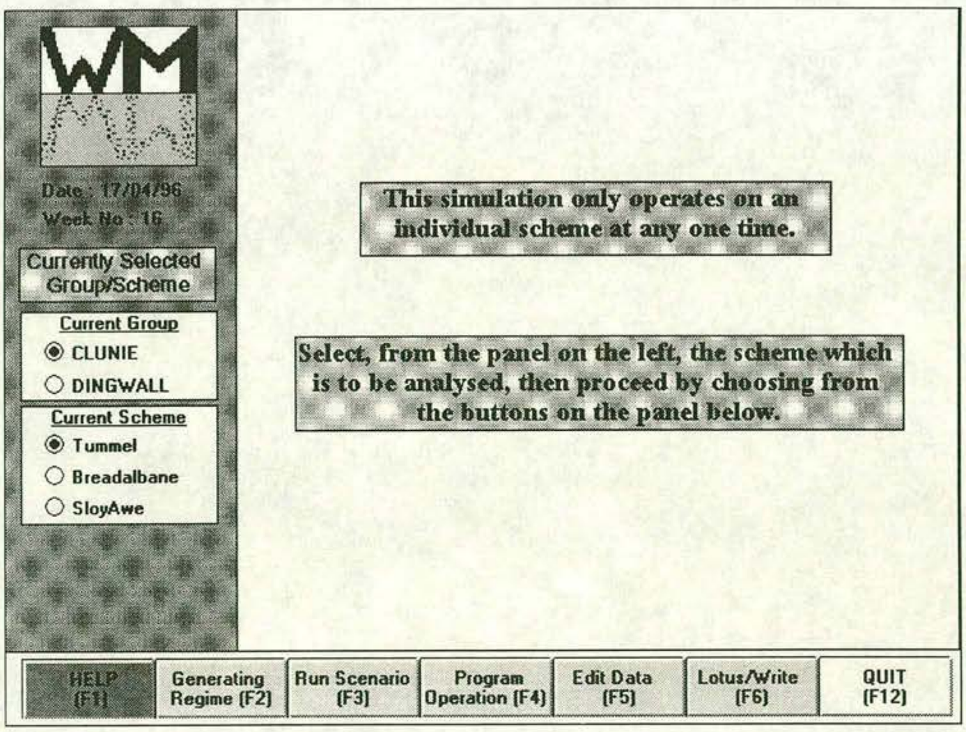


Figure 7.10 Main Screen

The radio buttons on the left-hand side automatically appear showing all group and scheme names entered by the user. The user can now select the group, and hence, the scheme that is to be analysed. All subsequent operations will only involve the selected scheme in particular, and the group in general. The example shows the names of SHE groups, Clunie and Dingwall, with the list of the selected Clunie group of schemes appearing below the "Current Group" window.

By choosing Program Operation, the user can call up the Control Screen shown below. Here the program operational parameters can be defined by the user. These parameters include: the source of data (internal or external); the time, power station or reservoir priorities; runoff percentages; the special operation of the stations; year offset and rain percentage. The control buttons at the bottom of the screen change number and appearance to suit the functionality of the operational path.

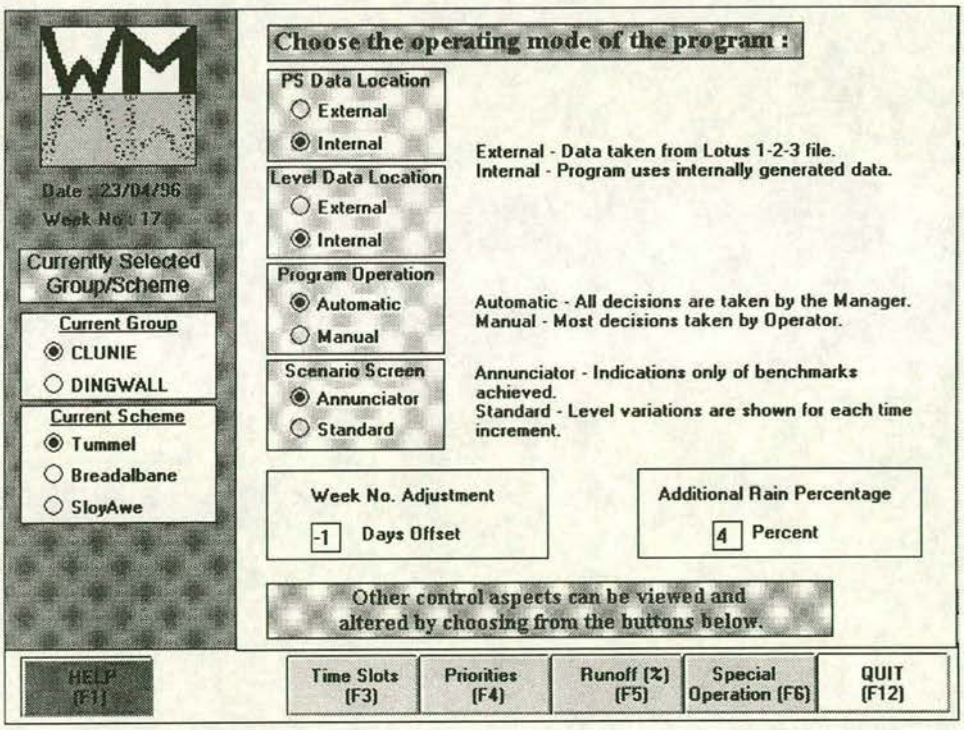


Figure 7.11 Program Control Screen

7.5.1 Source of Data

To run a scenario the program requires two sets of data over and above the permanent component data. These sets are the current reservoir levels and the weekly generation profile, which can be obtained from either of two sources:

Internal, where the required data is taken from within the program itself, the levels can be adjusted through the 'Levels Update' section of Program Operation, and the Generation profile is created by running 'Generation Regime'
External, where both the levels and generation profile can be drawn in from an external Lotus 1-2-3 file via the *LoProDat.wk1* program file.

7.5.2 Adjustments

Auto/Manual operation: At times of crisis decisions have to be taken to save a reservoir from spilling or draining. This entails the selection and adjustment of power station generation or weir height a task undertaken by the rules. Thus a scenario run in automatic mode would make the decisions and advise the user. Alternatively the system can run on manual as a training aid where the WM would prompt the user to make the major decisions.

Scenario Screen: A user is given the choice to display the results from a scenario run in a standard screen or an annunciator screen. The standard screen simply indicates the reservoir levels as they change during a scenario run, whereas the annunciator screen, shown in figure 7.14, acts more akin to a control panel.

Year: Most companies operate with each week being numbered either by calendar weeks or by financial year weeks. Therefore it was considered useful to include an indication of the week number, presented at the top right-hand corner of the main screen, immediately below the logo and date. However, since each year starts on a different day, while each week starts on the same day, a small adjustment is necessary to allow computation of the week number. Again for total flexibility this has been included as a user defined value.

Rain: For added authenticity during a fast scenario run, a minor adjustment can be made to increase or decrease the effect of rainfall/runoff to test possible worst cases. This rain percentage can be any integer value between 0 and 10.

7.6 Generation Regime

The function and operation of this feature have already been fully described in chapter 4, section 4.6.

7.7 Scenario Run

A scenario run describes the iteration process carried out by the software to determine the change in reservoir levels throughout the cascade over a set period of time. Within the WM there are two types of scenario, "fast" for rough guidance, and full for incremental detail. Each is described below:

7.7.1 Fast Scenario

The fast scenario is only used at the end of a "Generation Regime" run and follows a set sequence of events:

1. A weekly generation profile is created by averaging the half-hourly generation schedule into seven daily profiles.
2. This average profile is then used in a scenario run over seven days in daily increments.
3. The effect on reservoir levels and a summary of generation and levels is then displayed in on-screen log format.
4. If no spill or drying reservoirs are indicated then the generation profile may be considered hydraulically sound, although a quick analysis of the logged level changes may alert the user to possible problem areas.
5. If any warnings are given, or a possible problem is suspected, then a more accurate full scenario should be run. (see Run Scenario below.)

The use of a fast scenario run is intended to provide the user with a guide to the likely outcome of running a generation regime without the need for a full scenario run. However as indicated previously this has its drawbacks and if there is any doubt a full scenario run must be used.

7.7.2 Run Scenario

Run scenario is the major application feature of the WM. This is the hydraulic simulation of a cascade over a period of time to assess the changes and trends in the water level of all reservoirs. This draws together all relevant information associated with the dynamics of the reservoirs, and calls on the "rulebook" at critical moments in the analysis. A scenario run ultimately provides the user with a visual display of the changes to the main variables, level and generation output, and produces a summary of the cascade operation over the chosen timescale.

The user is initially presented by the scenario control screen below which allows the operational parameters or the reservoir initial levels to be altered and a scenario to be run over a choice of standard periods of time: Day; Two-Day and Week (buttons at the bottom of the screen). At this stage, the user is also prompted to confirm the location of the data to be used for the ensuing scenario run.

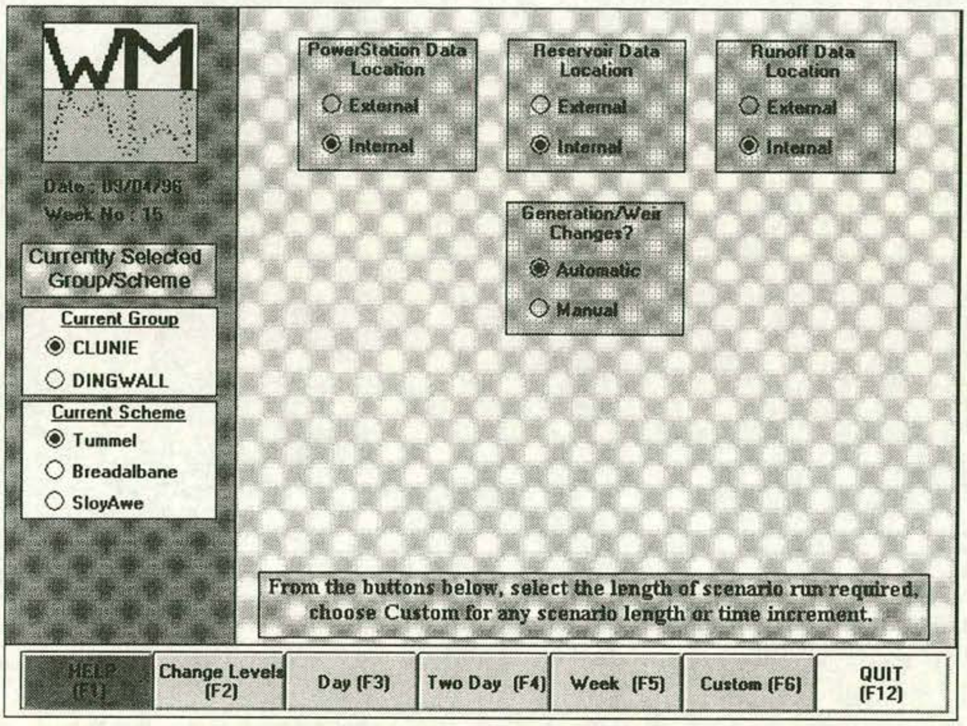


Figure 7.12 Scenario Control Screen

As an alternative to the pre-defined scenario timescales, a "custom" scenario can be run which initially prompts the user to declare certain details, Figure 7.13. Thus a scenario can run over any period of time, in various time increments (most accurately half-hours), starting at any time during the week.

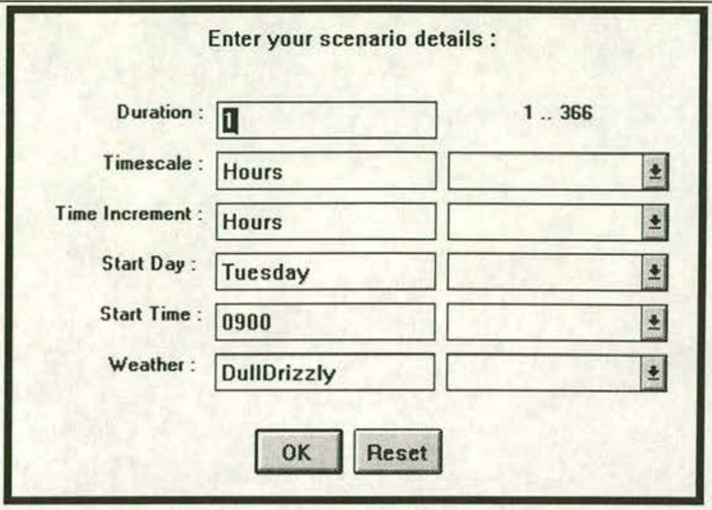


Figure 7.13 Custom Scenario Menu

The scenario sequence of events is:

1. The user states if the scenario is to be run over a standard (or user defined) period of time, in user defined time increments. The standard periods are a day, two-days or a week while the standard increments are half-hours, hours and days. Additionally a user can specify a custom period of a month or a set number of increments. For example, a user scenario run may be required to be run over a 10 hour period in half-hourly increments.
2. The WM determines the change in reservoir levels taking account of the weather conditions and generation profile. For each incremental time period the WM calculates the total volumes of water flowing into or out of each reservoir. The new reservoir volumes are then converted to a kWh storage and level. The new levels are compared with the benchmark levels and the current rate-of-rise is assessed.
3. The annunciator screen (if selected) prompts the user when any of the pre-defined limits is achieved, e.g. the particular time increment number will also be indicated.
4. In the event of a reservoir reaching the spill or dry condition the expert system automatically begins to assess the situation. By applying the rulebook and heeding any priorities the WM will initiate and advise of changes to the Generation Regime to relieve possible spill or draining problems.
5. All events are recorded in a screen log and stored in a text file. (see also External Files, section 7.4.2.3)

The screen below illustrates some of these features:

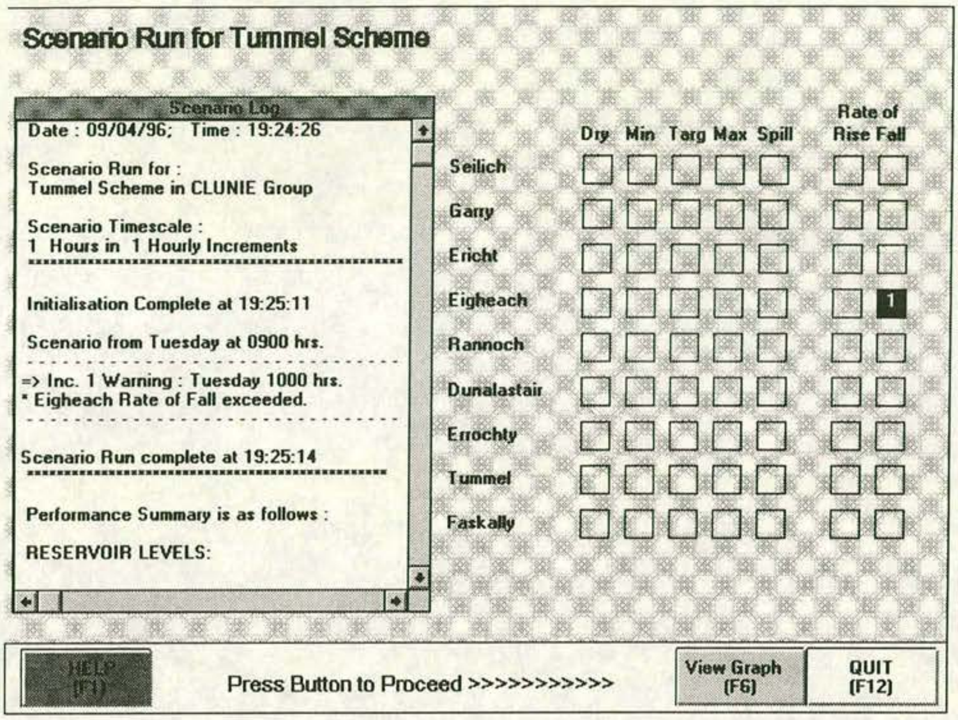


Figure 7.14 Scenario Annunciator Screen

Once a scenario run is completed the WM provides:

① a profile of the behaviour of each reservoir, in graphical form, outlining any possible problem that is likely to occur. Should any reservoir level reach the maximum or minimum limits, the decision support attempts to alleviate the situation together with an indication of the required aversive actions.

② a profile in graphical form of the power station output or weir height of all components associated with any selected reservoir (see graphs in section 7.8).

③ an annunciator screen to display the state of all reservoirs, indicating if and when a reservoir level reaches any of the benchmark levels or exceeds the maximum rate-of-rise or rate-of-fall.

④ a record and on-screen log display of all level indicators, support decisions and a summary of reservoir level and station generation. The contents of the log are automatically downloaded into a numbered/dated storage text file.

Thus during a scenario the decision support system indicates and records the appropriate action to take to prevent spillage or draining of reservoirs. It will also automatically change the generation profile if appropriate. These changes can then be reincorporated and the scenario rerun to ensure no further problems are likely to occur.

7.8 Graphs

At the end of a scenario run several graphs can be viewed providing the user with a quick visual display of the consequences of the scenario on an individual reservoir. The user can choose any reservoir and would typically be presented by the graphs below. A typical levels graph, shown in Figure 7.15, indicates the variation in reservoir level over the scenario run and compares it with the fixed Maximum, Minimum and Target levels.

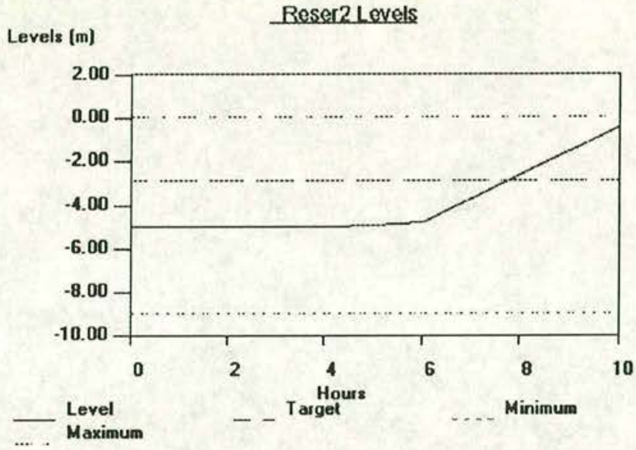


Figure 7.15 Typical graph of levels

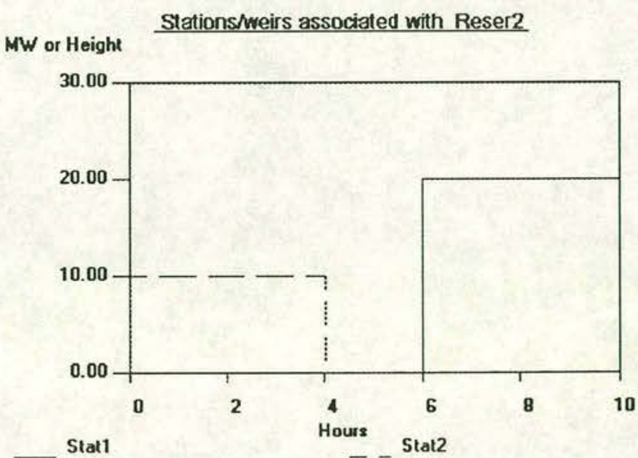


Figure 7.16 Typical graph of generation profile

The generation profile displays the MW output from all associated upper and lower stations linked directly to a chosen reservoir. Thus the user can easily see the effect each station has on the reservoir level by comparing the two graphs. Additionally the user can print-out any of the graphs.

7.9 Lotus/Write

The WM uses additional files for storing and retrieving generation profiles, historical runoff data and for downloading scenario logs and scheme status reports. These files are in a form that can be easily accessed by standard spreadsheet and wordprocessor packages. Whilst running the WM, if fast access to these files or applications is required, the Lotus/Write function produces the screen below.

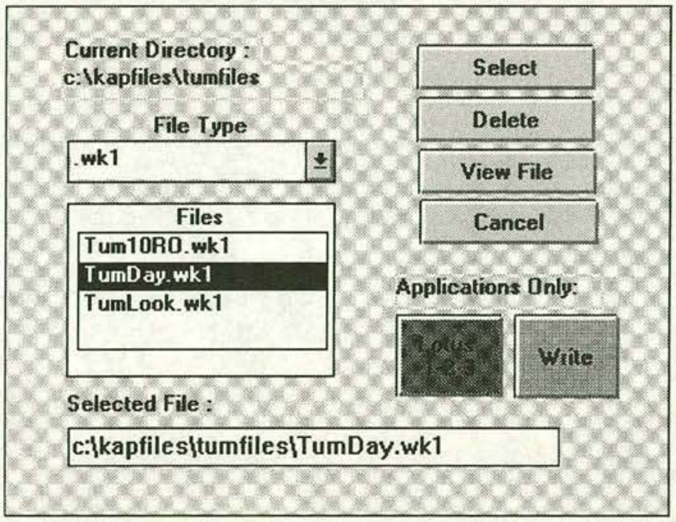


Figure 7.17 Lotus/Write screen

Here the user can call up or delete any file or simply transfer to either of the associated applications Lotus 123 or Microsoft Write.

7.10 Help

Help is available at any time during program operation, via the button continually displayed at the bottom left-hand corner of the screen. The help window and menu system have also been developed in KAPPA-PC and are resident within the main WM shell. Initially the user would be presented with the main Help screen below.

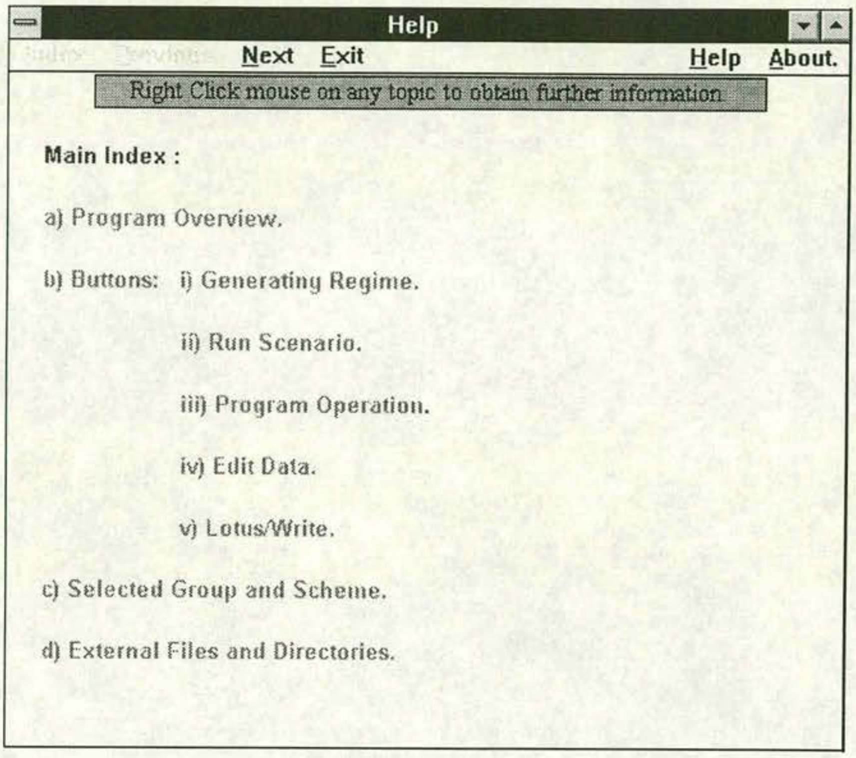


Figure 7.18 Help Main Screen

Details of all button functions and processes can thus be found by right-clicking with a mouse on any of the topics shown or by using the customised menu at the top.

7.11 Summary

The Water Manager is presented here as the user would see and operate it. Each of the facilities contained within it are discussed and the sequential actions of a scenario run are stepped through. Illustrations are given of the main features that sets the WM environment apart from other similar systems. These are:

- Its inherent flexibility, i.e. the data contained within it is not rigid, allowing new schemes to be added as required, whilst obsolete schemes can be erased.
- Accelerated scenarios starting at any time of a weekly generation schedule, running for any time period over selected time increments.

- The program can be used as a simple, fast access database for information on reservoirs, power stations and weirs within a scheme.
- The user-friendly software can operate on any PC with Microsoft Windows™ installed.

CHAPTER 8 PERFORMANCE STUDIES

8.1 Introduction

The performance of any software is normally measured by its reaction to changing variables and, in the case of an expert system, its ability to provide consistent practical solutions or advice. Therefore, evaluation of the flexibility, performance and accuracy of the Water Manager required the simulation of different scenarios on a number of scheme configurations. For each of the schemes, one or a number of facets were tested and verified by observing and recording the WM's responses to changes in the physical, environmental and user selected data. These verification tests can be separated into two categories: the creation of an optimum generation schedule; and the scenario run to establish the effect of the schedule on the water system.

Unfortunately, due to the sheer physical size of typical reservoirs, the complicated hydraulic interconnections within series and parallel schemes, and the large number of scheduled generation timeslots associated with an individual scheme, the accuracy of the WM operating on such cascades might be difficult to follow. Thus, in order to illustrate and verify the WM performing on schemes that might be visualised more easily, a series of simplified example schemes, involving both serial and series-parallel systems, were assembled within the software environment. This chapter describes the major features of each of these demonstration schemes and verifies the operation of the Water Manager. Finally some more complex results produced during extended analysis of the SHE Tummel Valley Scheme are given.

8.2 Demonstration Schemes.

8.2.1 Scheme Components

The demonstration schemes have been specifically designed with relatively low volume reservoirs, each having regular dimensions and fixed integer data, e.g. 100% daily Runoff volume is 20,000 m^3 and the volume-storage ratio for *Reser1* is 1 m^3/kWh. Similarly, the stations have been specified with easily identifiable capacities and flows, and a Weir with fixed dimensions has also been included. The main reasons for selecting these parameters are:

- to cause the reservoirs to rise and fall rapidly and display in reasonable timescales, the operation of simple systems.
- to show the effect of considerable runoff and compensation flow on small reservoirs.
- to provide simple calculation and assessment of generated energy to compare the required energy with the energy available from the stations.

The major details of each item used are given below:

Reservoirs:

Data	Reser1	Reser2
Drawdown (metres)	10	10
Volume (m^3)	1,000,000	200,000
Daily Runoff (100%)	20,000	20,000
Compensation (m^3/hr)	2,000	1,000
Storage (m^3/kWh)	1	0.2

Table 8.1 Demonstration Reservoirs

Data	Stat1	Stat2
Capacity	20	10
No.Sets	4	2
m3/kWh	1	0.2

Table 8.2 Demonstration Stations

Data	Weir
Height (m)	12
Max to min (m)	10
Length (m)	2

Table 8.3 Demonstration Weir

8.2.2 Scheme Arrangements

The basic serial cascade comprises a reservoir-station-reservoir-station arrangement, shown in Figure 8.1.

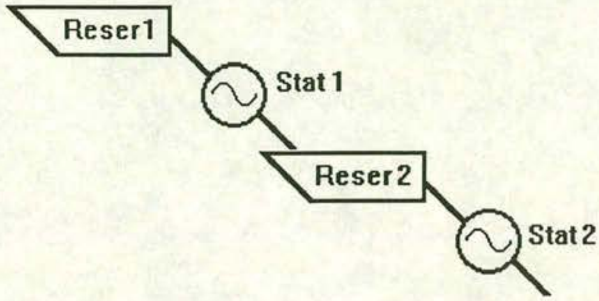


Figure 8.1 Scheme A

For the second arrangement a weir was introduced between the two reservoirs in place of the upper station, as shown in Figure 8.2.

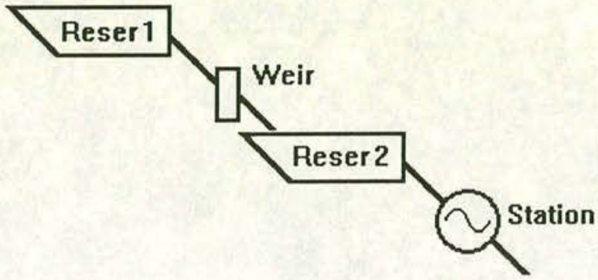


Figure 8.2 Scheme B

Figure 8.3 shows Scheme C, the simplest form of a series/parallel cascade. This arrangement was used during the software development to illustrate most of the effects likely to be encountered. The four reservoirs are also relatively small in volume to show rapid changes in level during the simulation exercises.

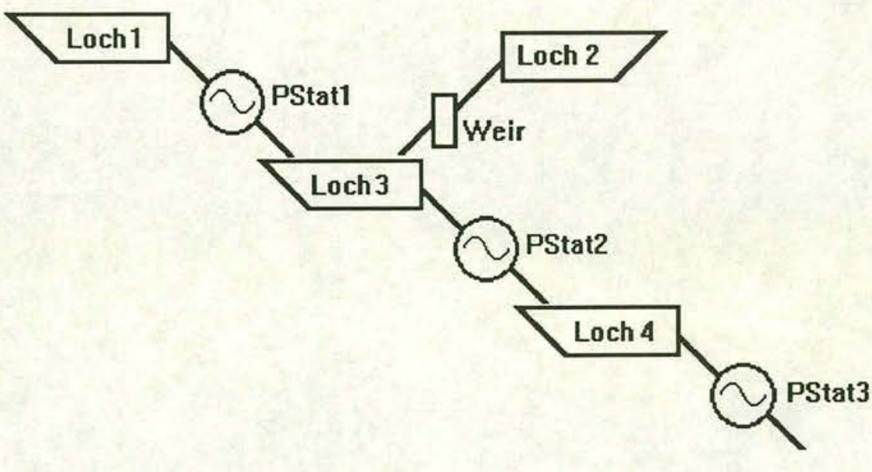


Figure 8.3 Scheme C

Finally the Tummel Valley Scheme (which is the most complex of SHE cascades) is used to confirm that the principles of generation scheduling and water system simulation embodied in the WM can be applied with some confidence to schemes of commercial proportions and complexity

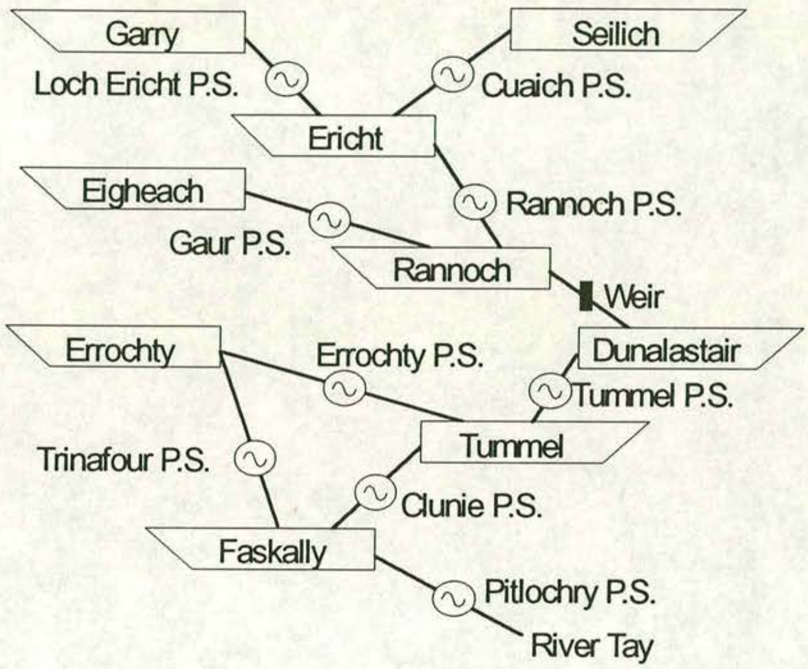


Figure 8.4 Tummel Valley Scheme

8.3 Generation Regime Results (Applied to Scheme A)

The procedures to establish an optimum generation schedule, used by the WM "Generation Regime" function, have been fully explained in chapter 4, section 4.6. However, to test and illustrate its operation, a series of simulations were performed initially using Scheme A above. This cascade has upper and lower stations rated 20 MW and 10 MW respectively: and with no station or set outages, the total maximum generation available is 720 MWh per day, giving a weekly total generation of 5040 MWh. Using these values as benchmarks, the Generation Regime was performed over different situations and the results are described below. Where appropriate, the profile produced can be observed to validate the WM operation. For all examples the time priorities were as shown in Figure 8.5. Normally these priority times would follow the demand curve but for demonstration purposes the top priority time slots have been clearly separated to exaggerate the effect of the WM.

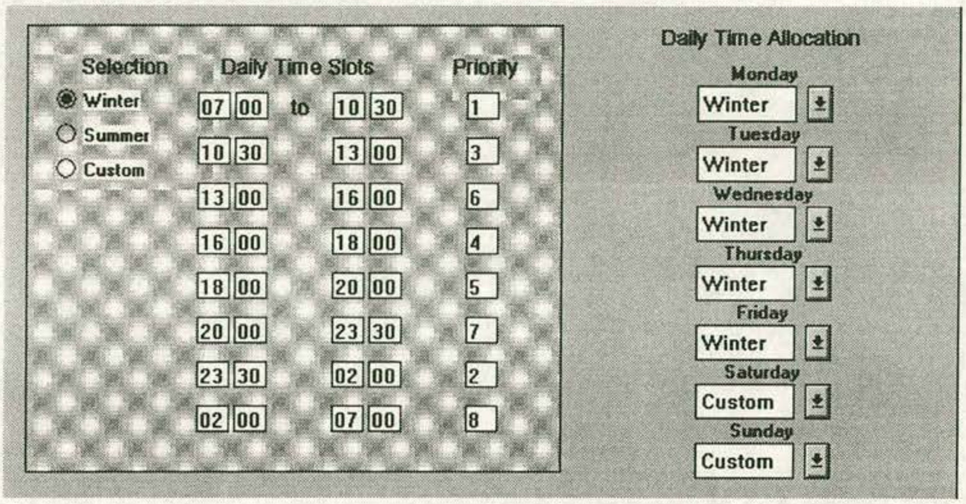


Figure 8.5. Time Priorities

There exist four possibilities when trying to match the supply and demand of electrical energy. The following sections demonstrate each of these and provide an analysis of the way in which the Water Manager addresses the situations.

8.3.1 Under-capacity (week)

Consider the situation where the total generation requirements are spread evenly throughout the week and the total energy requirement of the load exceeds the capacity of the scheme. The parameters entered for such an occasion would be:

Required MWh	Daily Percentages						
	Mon	Tue	Wed	Thur	Fri	Sat	Sun
6000	14.2	14.3	14.3	14.3	14.3	14.3	14.3

Table 8.4 Under-capacity Requirements

(Note: the percentage for Monday is slightly lower than the other days to ensure the total percentage requirement is 100%. Otherwise the WM would not allow the Generation Regime process to continue without correction.)

From the entered figures it is clear that the total generation is above the total capacity of the scheme. Additionally by spreading the load evenly across the seven days it follows that the capacity per day is also inadequate. Thus the WM issues the following warning:

Available Generation is too low on Mon, Tue, Wed, Thu, Fri, Sat, Sun - Change ?

Generation_Requirement
Sets_Available
Cancel

This alerts the user that there is insufficient capacity available for any day of the week and further prompts the user to reassess the generation requirement or to check the availability of generation plant.

8.3.2 Under-capacity (day)

It is not always the case that if the total generation requirement is less than the weekly capacity then the daily requirements can be met.

Required MWh	Daily Percentages						
	Mon	Tue	Wed	Thur	Fri	Sat	Sun
5000	12	12	24	12	16	12	12

Table 8.5 Under-capacity Requirements (day)

For example, if the required MWh were reduced to 5000 (marginally below the total capacity), and the daily percentage spread were changed to that shown above, the user would receive the following warning:

Available Generation is too low on Wed, Fri - Change ?

Generation_Requirement
Sets_Available
Cancel

This again alerts the user to undercapacity but also informs him where the problem exists (i.e. the higher percentage days of Wednesday and Friday) providing the opportunity to redistribute the daily percentages.

8.3.3 24-hour generation

The term "24-hour generation" describes the event when all available generation must operate over 24 hours to achieve the generation requirement for the day, e.g. in the case of Scheme A, 720 MWh. However, since most schemes are likely to have a variety of plants with different capacities, the likelihood of declaring the exact value for 24-hour generation can be remote. Consequently the WM assesses this situation to within -1 %, i.e. if the percentile was 714 MW, the WM would declare this as 24-hour generation simply to alert the user of this precarious condition where spare capacity is rather insignificant.

Required	Daily Percentages						
MWh	Mon	Tue	Wed	Thur	Fri	Sat	Sun
5000	14.2	14.3	14.3	14.3	14.3	14.3	14.3

Table 8.6 24-hour Generation Requirements

For example, using the evenly spread daily percentages with the reduced requirement of 5000 MWh as shown above. The user prompt now appears thus:

> **There is sufficient generation available to meet the MWh Requirements, but all sets must run 24 hrs on Tue, Wed, Thu, Fri, Sat, Sun. Create a Weekly Generation Profile accordingly ?**

(Note that in this instance Monday has not been declared as 24-hour generation since 14.2 % of 5000 = 710 MW and is outside the 1% margin.)

In this situation the generation profile can be produced. The WM initially creates the profile within KAPPA (in the station object slots *stationname:PSWeek*) before offering the facility to transfer the data to the Lotus database. Usually it is within the database that the user is then able to view the created profile. Unfortunately, since the whole database is too large to be shown here the infomation below has been extracted directly from the internally held station objects and arranged into easily read data tables.

Here each day has 48 half-hour slots read from left to right starting from the 0700-0730 hrs slot at the top left-hand corner of the first line of numbers, down to the final slot 0630-0700 hrs at the bottom right-hand corner of the second line.

Stat1:PSWeek	day starting at 0700 hrs																							
Mon	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Tue	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Wed	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Thur	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Fri	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Sat	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Sun	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20

Table 8.7a Scheme A, Stat1, Generation Schedule 1

Stat2:PSWeek	day starting at 0700 hrs																							
Mon	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	**0**	**0**
Tue	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	**0**
Wed	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	**0**
Thur	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	**0**
Fri	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	**0**
Sat	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	**0**
Sun	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	**0**

Table 8.7b Scheme A, Stat2, Generation Schedule 1

This slot information clearly shows that the priority station *Stat1* has had all 336 half-hour slots filled with 20 MW, whilst *Stat2* has a slot during the early morning trough (0630-7000 hrs) of each day with zero generation (shown in bold type). The Monday figures for *Stat2* also has the 0600-0630 slot at 0 MW which is the marginal difference between whether or not 24-hour generation is declared.

8.3.4 Over-capacity

In the more usual case where available capacity exceeds demand, the generation requirement would tend to be less than the total available. Thus the WM would allocate generation in order of priority station and time, i.e. the highest priority station would first be allocated to generate at the highest priority time, then the next station, then the next time and so on until the total generation requirements are met. To illustrate this mode of operation the following example data was entered:

Required	Daily Percentages						
MWh	Mon	Tue	Wed	Thur	Fri	Sat	Sun
2400	5	5	10	15	20	20	25

Table 8.8 Over-capacity

As all daily requirements are well within the available capacity, the user is prompted to create the Generation Profile, i.e. the weeky schedule.

There is sufficient generation available to meet the MWh Requirements.
Create a Weekly Generation Profile accordingly ?

The Water Manager would again allocate generation in order of priority, producing the following slot information.:

Stat1:PSWeek	day starting at 0700
Mon	20 20 20 20 20 20 20 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 20 20 0 0 0 0 0 0 0 0 0 0 0 0 0
Tues	20 20 20 20 20 20 20 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 20 20 0 0 0 0 0 0 0 0 0 0 0 0 0
Wed	20 20 20 20 20 20 20 20 20 20 20 20 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 20 20 20 20 20 0 0 0 0 0 0 0 0 0 0
Thur	20 20 20 20 20 20 20 20 20 20 20 20 0 0 0 0 0 0 20 20 20 20 20 20 20 20 0 0 0 0 0 0 0 20 20 20 20 20 0 0 0 0 0 0 0 0 0 0
Fri	20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 0 0 0 0 0 20 20 20 20 20 0 0 0 0 0 0 0 0 0 0
Sat	20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Sun	20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 0 0 0 0 0 0

Table 8.9a Scheme A, Stat1, Generation Schedule 2

Stat2:PSWeek day starting at 0700 hrs	
Mon	10 10 10 10 10 10 10 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Tues	10 10 10 10 10 10 10 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Wed	10 10 10 10 10 10 10 10 10 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 10 10 10 10 10 0 0 0 0 0 0 0 0 0 0
Thur	10 10 10 10 10 10 10 10 10 10 10 10 0 0 0 0 0 0 10 10 10 10 10 0 0 0 0 0 0 0 0 0 0 10 10 10 10 10 0 0 0 0 0 0 0 0 0 0
Fri	10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 0 0 0 0 0 0 0 10 10 10 10 10 0 0 0 0 0 0 0 0 0 0
Sat	10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Sun	10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 0 0 0 0 0 0 0 0 0 0 0 0

Table 8.9b Scheme A, Stat2, Generation Schedule 2

As both stations are fully available and flexible, the generation profile pattern is the same for each, i.e. the stations are allocated to generate during the same high priority times.

Detailed analysis of the profiles show the gradual filling-up of slots in accordance with the time priorities. For example on Monday and Tuesday where the requirement is low only the slots from 0700-1030 hrs are filled for *Stat2*. *Stat1*, being on first priority, covers the same time period but has also been allocated to the beginning of the second priority period of 2330-0200 hrs. As the requirement increases through the week the other time slots are filled. For the weekend days, which are on the custom time priority (not shown), the slot filling is slightly different to account for changes in the duration and priorities of the time periods. The effect of these changes is illustrated by comparing Friday and Saturday which have the same overall requirement, i.e. 20%, but the generation schedule is clearly different.

8.3.5 Over-capacity with special conditions

Using the same requirements but adding special conditions to the stations the generation profile for the these requirements would change accordingly. For example, if a station were about to go on outage for maintenance, the control engineers may declare it for priority running the day before to endsure the headwater level stays within safe limits. Thus consider the situation where *Stat2* is on priority running between 0900-1800 hrs on Wednesday and on outage for Thursday, see Figure 8.6.

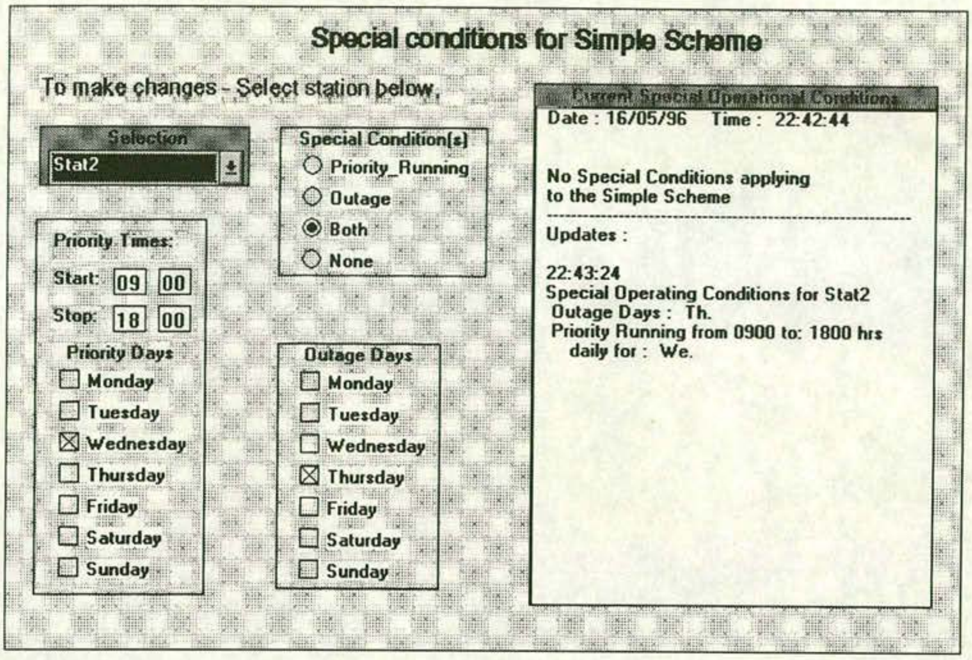


Figure 8.6. Special Conditions

The generation profiles produced by the WM now become:

Stat1:PSWeek	day starting at 0700 hrs
Mon	20 20 20 20 20 20 20 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 20 20 0 0 0 0 0 0 0 0 0 0 0 0 0
Tues	20 20 20 20 20 20 20 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 20 20 0 0 0 0 0 0 0 0 0 0 0 0 0
Wed	20 20 20 20 20 20 20 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 20 20 20 20 20 0 0 0 0 0 0 0 0 0 0
Thur	20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 0 0 20 20 20 20 20 0 0 0 0 0 0 0 0 0 0
Fri	20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 0 0 0 0 0 20 20 20 20 20 0 0 0 0 0 0 0 0 0 0
Sat	20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Sun	20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 0 0 0 0 0 0

Table 8.10a Scheme A, Stat1, Generation Schedule 3

Stat2:PSWeek day starting at 0700 hrs	
Mon	10 10 10 10 10 10 10 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Tues	10 10 10 10 10 10 10 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Wed	10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 0 0
	0 0 0 0 0 0 0 0 0 10 10 0 0 0 0 0 0 0 0 0 0 0 0 0
Thur	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Fri	10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
	10 10 0 0 0 0 0 0 0 10 10 10 10 10 0 0 0 0 0 0 0 0 0 0
Sat	10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
	10 10 10 10 10 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Sun	10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
	10 10 10 10 10 10 10 10 10 10 10 10 0 0 0 0 0 0 0 0 0 0 0 0

Table 8.10b Scheme A, Stat2, Generation Schedule 3

These generation profiles, when compared with those produced for the previous section clearly shows the effect of special conditions on Wednesday and Thursday. *Stat2* being on outage on Thursday has not been allocated any generation, instead all generation for the day has been given to *Stat1*. On Wednesday *Stat2* has been allocated generation essentially over the period of priority running, but, also in other priority time slots to make up the generation. On the other hand, the *Stat1* profile is reduced to compensate for the additional *Stat2* generation.

Section 8.3 illustrates different aspects of the scheduling process and for each situation demonstrates the scheduling response of the WM Generation Regime. However the creation of the generation schedule does not itself address its likely effect on the water system. Therefore to test the integrity of the water system, the WM "Scenario Run" function is implemented to simulate the water flows, caused by the generation regime and the local hydrology. Thus the changes in reservoir levels can be assessed over a pre-set period of time.

8.4 Scenario simulation results

This section provides results from several demonstration scenarios beginning with cascade reservoirs operating within acceptable limits, i.e. normal operation. These are followed by the more onerous situations when a spilling or draining problem occurs, thereby calling the rule system. In each scenario all reservoirs start at mid level: -5 m below spill level

8.4.1 Scenario 1 (scheme A normal operation)

The first simulation runs over 10 hours with following generation schedule:

Hour	1	2	3	4	5	6	7	8	9	10
Stat1 (MW)	0	0	0	10	20	20	10	0	0	0
Stat2 (MW)	10	10	10	10	10	10	10	10	10	10

Table 8.11 Scenario 1: Generation Profile

Within the WM the station generated outputs are displayed in graphical form as shown below:

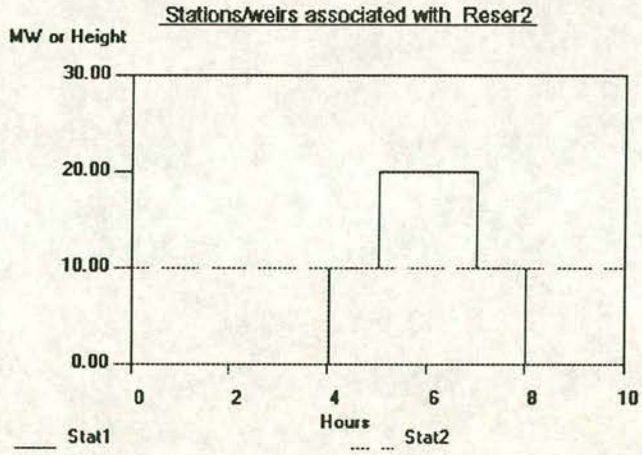


Figure 8.7 Station Generation Plot - Scenario1

Ignoring hydrological effects, *Reser1* level would expect to remain constant until the 4th hour when *Stat1* is despatched. The level would then be drawn down to a new constant level after the 8th hour when *Stat1* is switched-out. *Reser2* would be drawn down at a constant rate as *Stat2* operates continuously, however, as *Stat1* has a greater volume flow than *Stat2*, *Reser2* level will rise. The two graphs produced during the scenario run are shown below:

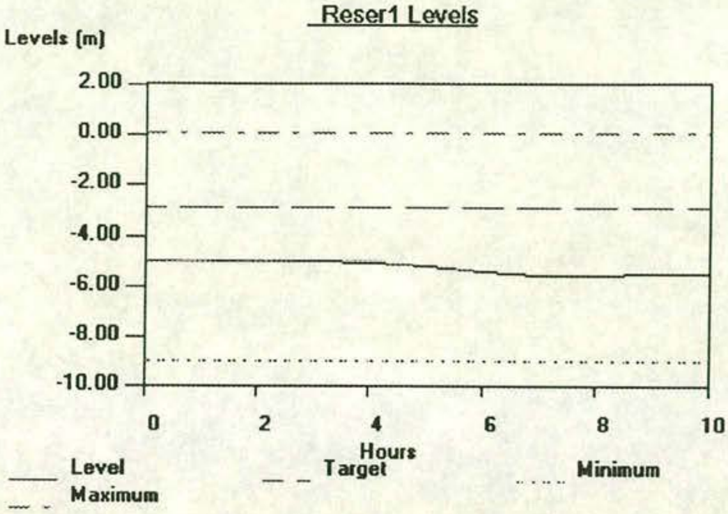


Figure 8.8 Large Reservoir (Reser1) Levels - Scenario1

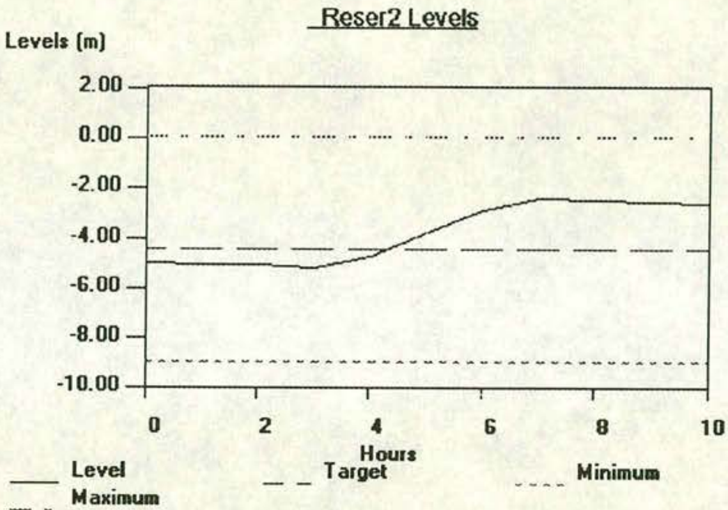


Figure 8.9 Small Reservoir (Reser2) Levels - Scenario1

The above provide the expected results showing that when the upper station *Stat1* is despatched the lower *Reser2* level rises rapidly due to a much larger volume of water being supplied than that being drawn. Also when *Stat1* is shut-down allowing Reser2 level to recover slowly when *Stat2* again controls the drawdown. Being much larger than *Reser2*, *Reser1* shows a lesser effect when *Stat1* is despatched. The additional effect of runoff is also illustrated in the graphs for *Reser1* where a marginal level increase is shown after *Stat2* has been shut down.

(Note: the two graphs seem to indicate both reservoir levels being affected by Stat1 ahead of it being despatched. However, this is purely a result of the graphics which

smooths-out the transition in level from the 3rd hour to the 4th. If the scenario was run over a longer period of time, in shorter time increments, this effect would be imperceptible.)

8.4.2 Scenario 2 (scheme A normal operation)

This scenario illustrates the reaction of the same cascade to an alternative generation schedule, but once again the reservoir levels remain within normal limits. Additional effects of runoff and compensation can also be observed since for this scheme these flows are large enough to be significant. The schedule used for this scenario is shown respectively in tabular and graphical form in Table 8.12 and Figure 8.11.

Hour	1	2	3	4	5	6	7	8	9	10
Stat1 (MW)	0	0	0	0	0	0	20	20	20	20
Stat2 (MW)	10	10	10	10	0	0	0	0	0	0

Table 8.12 Scenario 2: Generation Profile

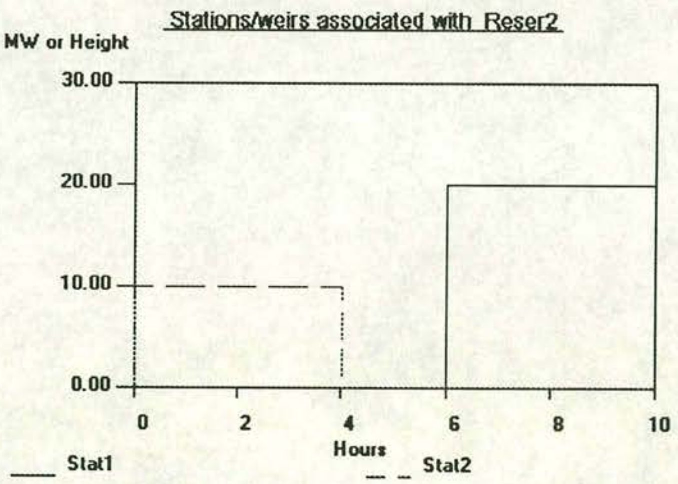


Figure 8.10 Station Generation Plot - Scenario2

Figures 8.11 and 8.12 show the resultant reservoir levels. Here the difference between the runoff into, and compensation outflow from, *Reser1* is relatively insignificant compared to the volume of the reservoir, therefore there is no apparent change in level at the begining of the scenario. Meanwhile *Reser2* is absorbing the compensation inflow and the difference between its own runoff and compensation outflow, by simply generating from *Stat2* which draws sufficient water to keep the reservoir level constant. However, a dramatic rise in *Reser2* begins when *Stat1* is despatched while *Stat2* is switched out.

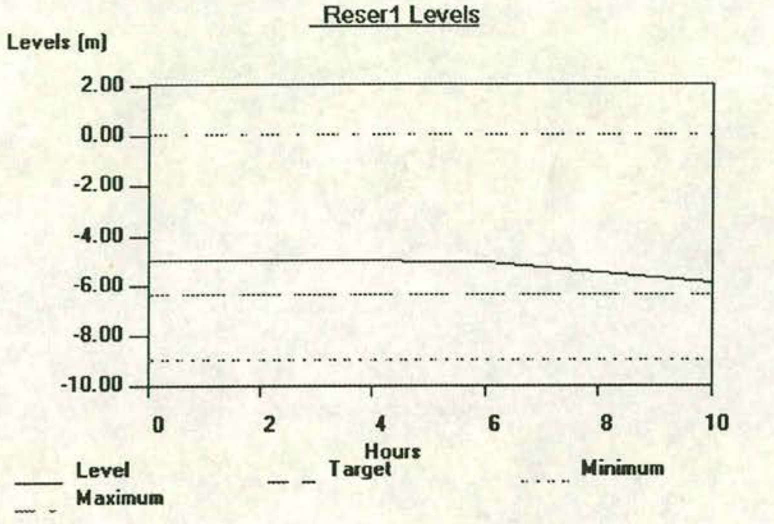


Figure 8.11 Large Reservoir (Reser1) Levels - Scenario2

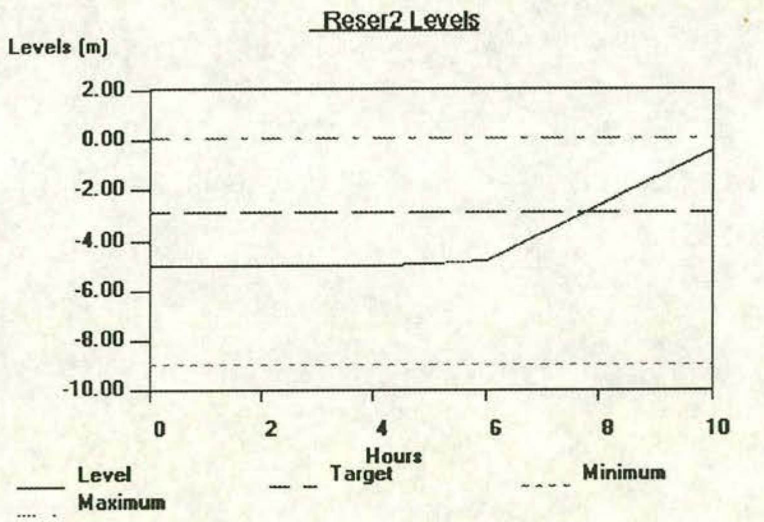


Figure 8.12 Small Reservoir (Reser2) Levels - Scenario2

This scenario illustrates two important aspects:

The first is when a station is used to "generate" the runoff while maintaining the reservoir level. This is a situation that normally occurs during periods of heavy or sustained rainfall where the hydro controllers endeavour to stabilise the water system by generating at all stations in a cascade thereby moving the runoff quickly down through the system.

The second is clearly shown by the operation of *Stat1*. This station has a profound influence on the lower reservoir and careful management is required to ensure *Reser2* remains within the operating level limits. However it also shows that in some instances a smaller lower reservoir controls the operation of the upper station. Although this may seem to be an extreme situation such a scheme exists within the Dingwall Group of SHE at Shin Hydro Scheme. The geography of the scheme is shown in Chapter 5, Figure 5.2 where releatively large Loch Shin feeds the much smaller Little Shin reservoir via Lairg Power station.

8.4.3 Scenario 3 (scheme A: Spill)

This example illustrates one extreme condition where the lower reservoir achieves the problematic spill situation. The generation regime is shown in Table 8.13.

Hour	1	2	3	4	5	6	7	8	9	10
Stat1 (MW)	20	20	20	20	20	20	20	0	0	0
Stat2 (MW)	0	0	0	0	0	0	0	10	10	10

Table 8.13 Scenario 3: Generation Profile

The level graphs are shown below:

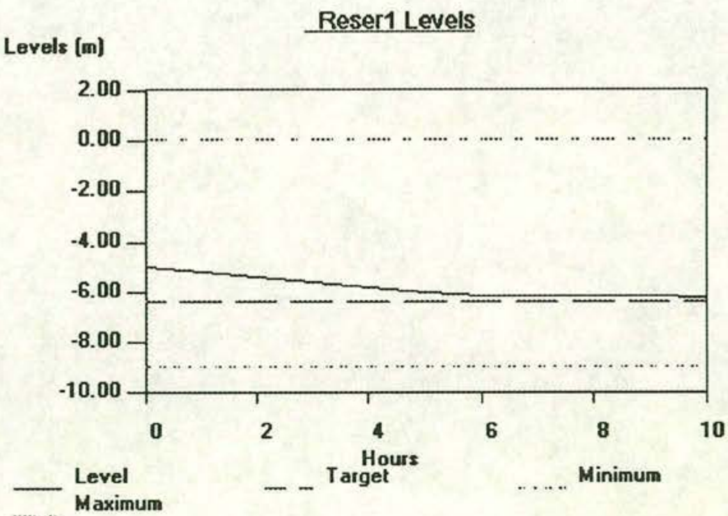


Figure 8.13 Large Reservoir (Reser1) Levels - Scenario3

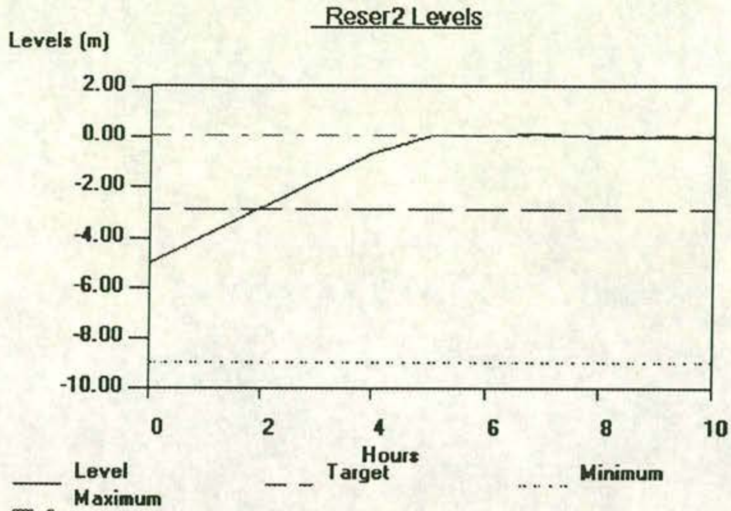


Figure 8.14 Small Reservoir (Reser2) Levels - Scenario3

The level graphs show the steady reduction in *Reser1* level in a similar manner to the previous scenarios. However as the generation from *Stat1* occurs at the beginning of the scenario while *Stat2* is switched out the rise in Reser2 reaches the spill limit by the 5th hour (see Figure 8.14). At this stage the WM triggers the rules in an attempt to prevent the spillage.

While the graphs show the level changes to the reservoirs, the information generated by the WM during a scenario run gives a better indication of what actually happened. Below is an extract from the scenario log for the above situation, which starts by noting the general information to describe the scenario itself including the date and time that the scenario was run and the timescale covered by the scenario. Several initialisation procedures are necessary to clear old data from previous scenarios and pull-in the desired generation profiles, the scenario log indicates that this has been completed before proceeding with a run. In the example, the scenario starts at 0700 hrs on Sunday and provides details when any of the reservoirs reach a benchmark level or when the rules are initiated.

Analysis of the log gives the user an insight into the behaviour of the cascade system and the WM itself. Two hours after initiation a warning is given that the lower reservoir level is rising and will achieve the high target level at 0900 hrs (high indicates the reservoir levels rising towards a target level that was initially set above the reservoir start level). At the fifth time increment *Reser2* reaches the spill level and the rules attempt to avert the problem. The first action is to shut down the upper station and despatch *Stat2*, unfortunately with runoff and compensation also filling the reservoir, the action does not quite solve the problem and some water will be spilled. However over the next two time increments the problem is cleared and the reservoir is saved. For the remainder of the scenario there were no further warnings.

```
Date : 21/05/96;   Time : 11:42:16
-----------------------------------------------------------
Scenario Run for :  SchemeA Scheme in DINGWALL Group
Scenario Timescale :  10  Hours in  10 Hourly Increments
Initialisation Complete at 11:42:31
-----------------------------------------------------------
 Scenario from Sunday at 0700 hrs.
-----------------------------------------------------------
=> Inc. 2 Warning : Sunday 0900 hrs.
* Reser2 high target level achieved.
-----------------------------------------------------------
=> Inc. 5 Warning : Sunday 1200 hrs.
* Reser2 is a spilling reservoir, attempts to
    prevent the problem are:
    1.Stat2 powerstation increased to 10 MW.
    2.Stat1 Station decreased to 0 MW.
     The problem is unavoidable.
* Reser2 Maximum Level reached.
-----------------------------------------------------------
=> Inc. 6 Warning : Sunday 1300 hrs.
* Reser2 is a spilling reservoir, attempts to
    prevent the problem are:
    1.Stat2 powerstation increased to 10 MW.
    2.Stat1 powerstation decreased to 0 MW.
     The problem has been avoided.
-----------------------------------------------------------
=> Inc. 7 Warning : Sunday 1400 hrs.
* Reser2 is a spilling reservoir, attempts to
    prevent the problem are:
    1.Stat2 powerstation increased to 10 MW.
     The problem has been avoided.
-----------------------------------------------------------
Scenario Run complete at 11:43:23
```

Figure 8.15 Scenario 3 Log of Events

A consequence of the rule action is to change the original generation schedule. Comparison of the generation plot above with Table 8.13 shows these changes where *Stat1* has been switched-off and *Stat2* despatched after the 4th hour.

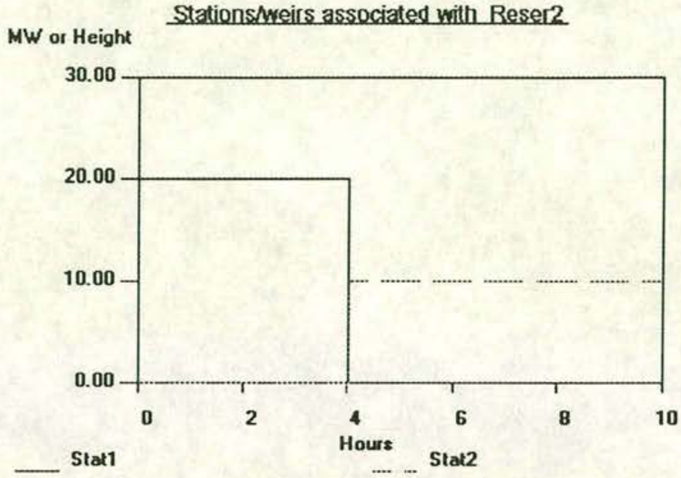


Figure 8.16 Station Generation Plot - Scenario3

In addition to the "events log" a summary (shown below) is produced at the end of a scenario which details the total generation from the scheme and some level information on all reservoirs.

Performance Summary is as follows :
RESERVOIR LEVELS: Reser1 levels : Minimum: -10.00m; Target: -6.36m Initial: -5.00m; Final: -6.22m Reser2 levels : Minimum: -10.00m; Target: -2.92m Initial: -5.00m; Final: -0.03m
GENERATION LEVELS: Individual PS generation: Stat1 share: 80 MWh Stat2 share: 60 MWh Generation for Simple Scheme: Total production : 140 MWh Production required : 197 MWh

Figure 8.17 Scenario 3 Log Summary

(Note: In the above case, the figures for "Total production" and "Production required" do not match. This is due to an averaging effect, i.e. the production required has been produced by calculating the hourly average for the day and multiplying it by the scenario timescale. Of course, this ten hour scenario has been run over a lighter loaded period and therefore does not achieve the requirement, thus this comparison is only applicable when a scenario has been run over a day or multiple thereof.)

8.4.4 Scenario 4 (scheme A: Dry)

This example illustrates the other extreme condition where the upper reservoir drains, it uses the same generation profile as scenario3 but *Reser1* initial level starts low.

Hour	1	2	3	4	5	6	7	8	9	10
Stat1 (MW)	20	20	20	20	20	20	0	0	0	0
Stat2 (MW)	0	0	0	0	0	0	0	10	10	10

Table 8.14 Scenario 4: Generation Profile

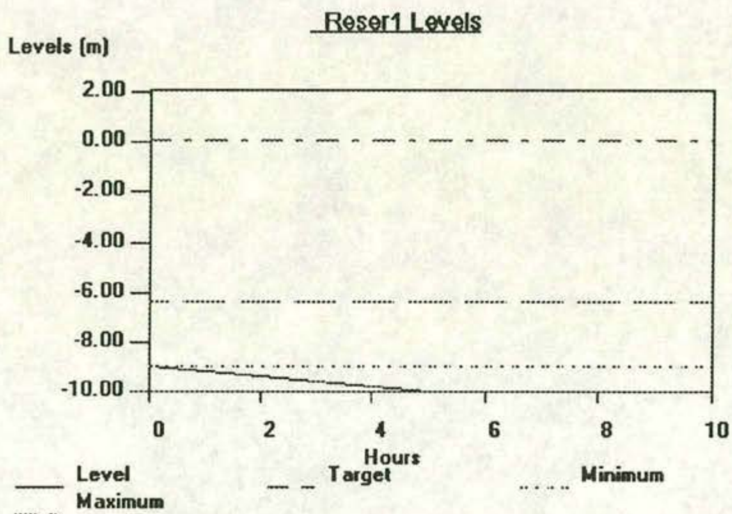


Figure 8.18 Large Reservoir (Reser1) Levels - Scenario4

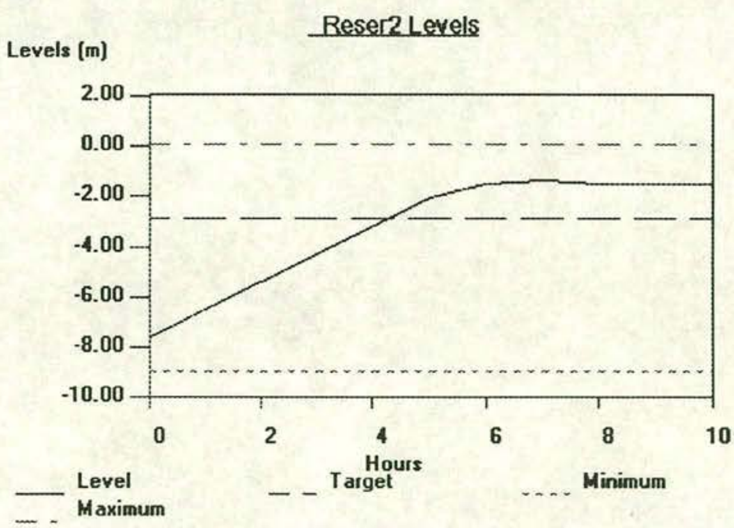


Figure 8.19 Small Reservoir (Reser2) Levels - Scenario4

The reservoir level graphs are given above and together with the scenario log below again the operation of the WM is clearly shown. However, in this instance the draining situation cannot be prevented since *Reser1* is unable to recover (once drained) due to the ongoing requirement for compensation water.

Date : 21/05/96; Time : 15:02:12
Scenario Run for : Simple Scheme in DINGWALL Group Scenario Timescale : 10 Hours in 10 Hourly Increments Initialisation Complete at 15:02:24
Scenario from Sunday at 0700 hrs.
=> Inc. 1 Warning : Sunday 0800 hrs. * Reser1 Minimum Level reached.
=> Inc. 5 Warning : Sunday 1200 hrs. * Reser1 is a drying reservoir, attempts to prevent the problem are: 1.Stat1 Station decreased to 0 MW. The problem is unavoidable. * Reser2 high target level achieved.
=> Inc. 6 Warning : Sunday 1300 hrs. * Reser1 is a drying reservoir, attempts to prevent the problem are: 1.Stat1 powerstation decreased to 0 MW. The problem is unavoidable.
=> Inc. 7 Warning : Sunday 1400 hrs. * Reser1 is a drying reservoir, attempts to prevent the problem are: 1.Stat1 Station cannot be changed. The problem is unavoidable.
=> Inc. 8 Warning : Sunday 1500 hrs. * Reser1 is a drying reservoir, attempts to prevent the problem are: 1.Stat1 Station cannot be changed. The problem is unavoidable.
=> Inc. 9 Warning : Sunday 1600 hrs. * Reser1 is a drying reservoir, attempts to prevent the problem are: 1.Stat1 Station cannot be changed. The problem is unavoidable.
=> Inc. 10 Warning : Sunday 1700 hrs. * Reser1 is a drying reservoir, attempts to prevent the problem are: 1.Stat1 Station cannot be changed. The problem is unavoidable.
Scenario Run complete at 15:03:22

Figure 8.20 Scenario 4 Log of Events

Performance Summary is as follows :
RESERVOIR LEVELS:
Reser1 levels :
Minimum: -10.00m; Target: -6.36m
Initial: -8.96m; Final: -10.00m
Reser2 levels :
Minimum: -10.00m; Target: -2.92m
Initial: -7.58m; Final: -1.54m
GENERATION LEVELS:
Individual PS generation:
Stat1 share: 80 MWh
Stat2 share: 30 MWh
Generation for Simple Scheme:
Total production : 110 MWh
Production required : 197 MWh

Figure 8.21 Scenario 4 Log Summary

8.4.5 Scenario 5 (scheme B weir action)

This scenario is used to illustrate the operation of a weir. In the example, the weir begins at a height of 6 m, i.e. higher than the reservoir level, but mid way through the scenario it drops to a height of 3m which is lower than the reservoir level, see Table 8.15.

Hour	1	2	3	4	5	6	7	8	9	10
Weir1 (m)	6	6	6	6	3	3	3	3	3	3
Stat2 (MW)	0	0	0	0	0	0	0	10	10	10

Table 8.15 Scenario 5: Generation Profile

The reservoir level graphs below clearly show the action of the weir. Here the upper reservoir level is constant until the weir is lowered, then it begins to draw down as would be expected. Meantime *res2B* rises slowly at first, due to high runoff in this instance, but when the flow over the weir enters *res2B* the level begins to rise faster. The rate-of-rise is high at first since the head of water above the weir is large (refer to section 5.7.3) but as the upper reservoir level falls the head falls, the flow reduces and hence the rate-of-rise decreases.

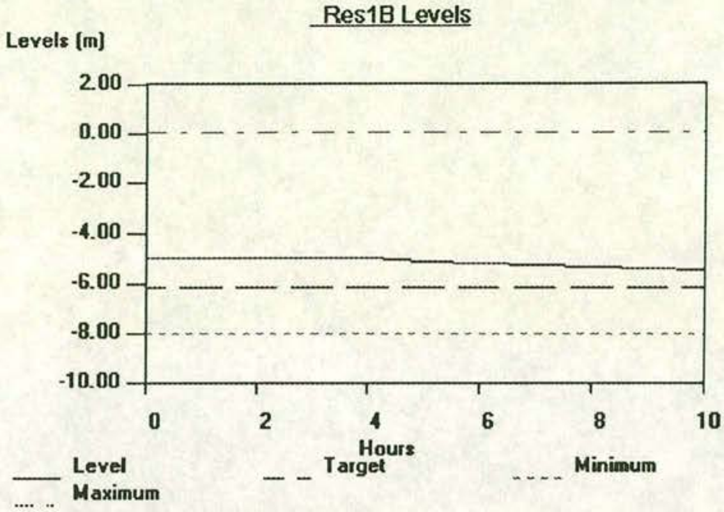


Figure 8.22 Large Reservoir (Res1B) Levels - Scenario5

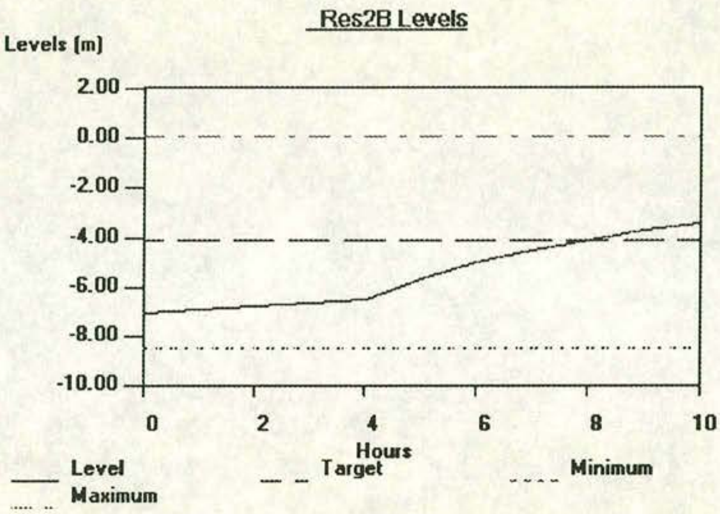


Figure 8.23 Small Reservoir (Res2B) Levels - Scenario5

8.4.6 Scenario 6 (scheme C serial/parallel cascade)

This scenario is used to illustrate the operation of the WM when applied to a serial/parallel cascade. The station generation profiles (Table 8.16) have been arbitrarily chosen and the weir has been arranged to momentarily drop below its upper reservoir level.

Hour	1	2	3	4	5	6	7	8	9	10
Weir 1 (m)	8	8	8	8	8	5.2	5.2	5.2	8	8
PStat1 (MW)	20	20	20	20	20	0	0	0	0	20
PStat2 (MW)	0	0	0	10	10	10	0	0	0	10
PStat3 (MW)	25	25	25	25	25	0	0	0	0	0

Table 8.16 Scenario 6: Generation Profile

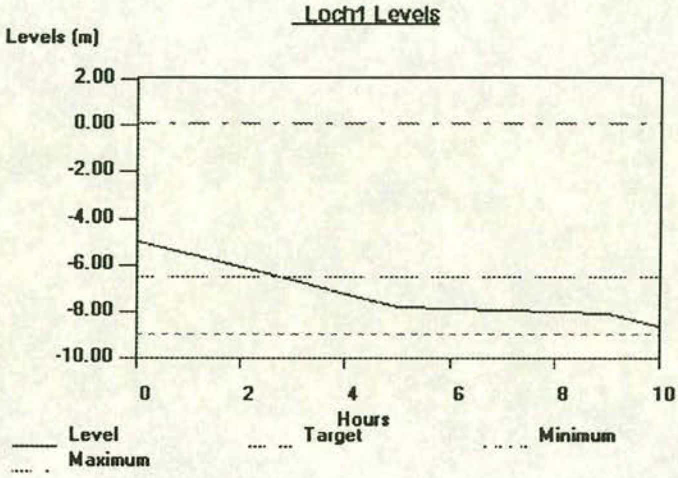


Figure 8.24 Loch1 Levels - Scenario6

Loch1 level falls at a contant rate while PStat1 generates, When the station is switched out the reservoir levels out until the station is once again despatched at the end of the scenario.

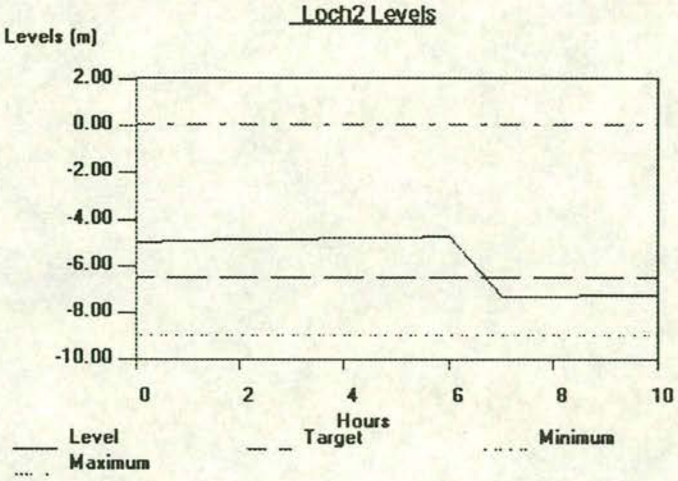


Figure 8.25 Loch2 Levels - Scenario6

Loch2 level initially rises slowly due to runoff, but it then dramatically falls when the weir is dropped. The reservoir then begins to recover when the weir is raised above *Loch2* level.

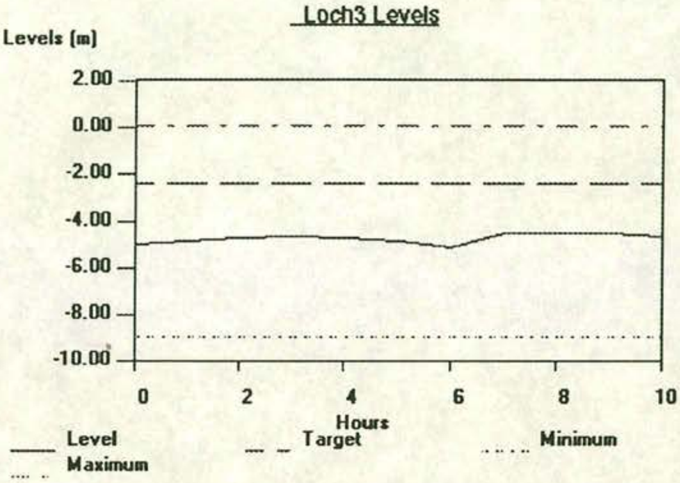


Figure 8.26 Loch3 Levels - Scenario6

At first *Loch3* level rises due to the flow from *Loch1*, but when PStat2 is despatched the combined effect is to reduce the reservoir level. The level rises again when the flow over the weir enters the reservoir, but then levels out when the weir is raised and all stations are switched out. Finally drawdown begins again when the stations are despatched at the end of the scenario.

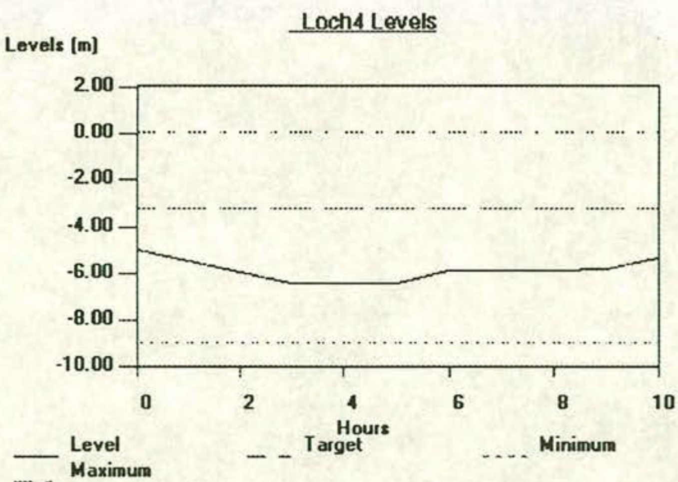


Figure 8.27 Loch4 Levels - Scenario6

The flow through *PStat2* is similar to that through *PStat3* as shown in the graph below. The levelof *Loch4* is initially drawn down by the action of *PStat3* but when *PStat2* is despatched the combined effect is to stabilise the level. At the 5th hour

PStat3 is switched out and the flow from *PStat2* causes the reservoir level to rise momentarily until it too is switched out. When *PStat2* is despatched at the end of the scenario the level begins to rise again.

8.5 SHE Scheme Run (Tummel Valley)

8.5.1 Generation Profile

The previous sections illustrate the principles behind the creation of an optimum generation profile to satisfy the energy requirement, at the economically beneficial times, with due regard to the state of the stations.

To test the application of the WM to a real system, operation of the Tummel Valley Scheme was simulated under the following conditions:

Required	Daily Percentages						
MWh	Mon	Tue	Wed	Thur	Fri	Sat	Sun
14000	14.2	14.3	14.3	14.3	14.3	14.3	14.3

Table 8.17 Tummel Valley Requirements

Table 8.18 shows a typical set of operational details that were applied to the stations within the scheme for a particular day, in this case Monday.

STATION	MW	Priority	Special Conditions (Monday)
Gaur	6.4	6	
Cuaich	2.5	8	Priority Running 1000-2300
Loch Ericht	2.2	7	
Rannoch	48	4	
Tummel	34	5	Outage
Errochty	75	2	
Trinafour	0.5	9	Priority Running 0300- 2330
Clunie	61.2	3	Only 2 sets available
Pitlochry	15	1	Priority Running 0400-2200

Table 8.18 Tummel Valley Conditions (Monday)

Table 8.19 shows the generation profile for Monday as created by the WM.

Monday	day starting at 0700 hrs																							
Gaur	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	6.4	6.4	6.4	6.4	6.4	0	0	0	0	0	0	0	0	0	0
Cuaich	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0	0	0	0	0	0	0	0	0	0
Loch Ericht	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	2.2	2.2	2.2	2.2	2.2	0	0	0	0	0	0	0	0	0	0
Rannoch	48	48	48	48	48	48	48	48	48	48	48	48	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	48	48	48	48	48	0	0	0	0	0	0	0	0	0	0
Tummel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Errochty	75	75	75	75	75	75	75	75	75	75	75	75	0	0	0	0	0	0	75	75	75	75	0	0
	0	0	0	0	0	0	0	0	0	75	75	75	75	75	0	0	0	0	0	0	0	0	0	0
Trinafour	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0	0	0	0	0	0	0	0	0	0
Clunie	41	41	41	41	41	41	41	41	41	41	41	41	0	0	0	0	0	0	41	41	41	0	0	0
	0	0	0	0	0	0	0	0	0	41	41	41	41	41	0	0	0	0	0	0	0	0	0	0
Pitlochry	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
	15	15	15	15	15	15	15	0	0	15	15	15	15	15	0	0	0	0	0	0	0	0	0	0

Table 8.19 Tummel Valley Generation Schedule (Monday)

Again this illustrates the same rules apply to a large scheme where station outages and priority running take precedence over meeting the peak demand. The following observations highlight this:

- No generation is allocated to Tummel during an outage.
- Generation has been allocated to the priority running stations Cuaich, Trinafour and Pitlochry for the duration of their priority period
- The time periods have had generation allocated in order of priority, e.g. 0700-1030, 2330-0200, etc.
- Generation of the higher priority stations has been allocated first. Ignoring the first priority station, Pitlochry (since Priority Running supersedes Priority order) this is best illustrated by looking at the fourth priority period of 1600-1800 hrs. Errochty the 2nd priority station is the only unconstrained station allocated to generate throughout this period, while Clunie (3rd) is assessed to run for three of the half-hour slots and all other stations are not scheduled.
- The Clunie generation profile indicates the allocation has been restricted to the available 2 out of 3 sets. Here the capacity is shown as 41 MW (rounded-up from 40.8) instead of full capacity of 61.2 MW.

This demonstrates the accurate operation of the WM, assessing the optimum scheduling of cascaded hydro but taking full account of the electricity day and station availability constraints.

8.5.2 Scenario Run

Using the above generation regime and with all reservoirs starting around mid level, a scenario was run for Tummel Valley Scheme over the same 24-hour period. The resulting log entries and the full set of reservoir level graphs are given in Appendix 8 and for reference the geographical arrangement of the scheme is given below.

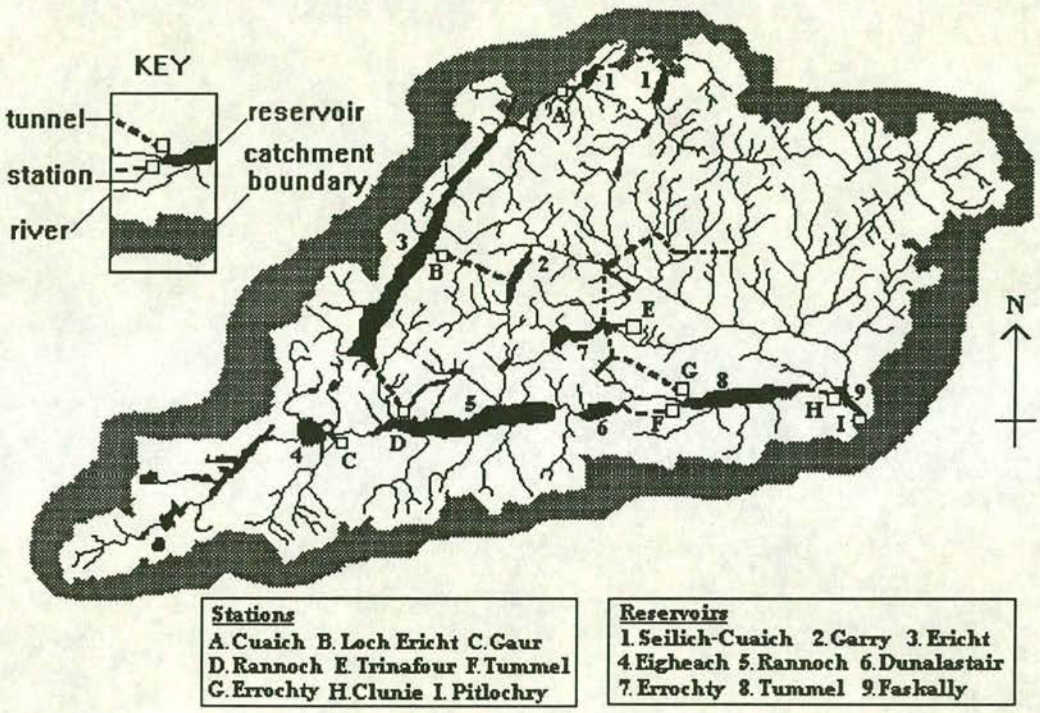


Figure 8.28 Tummel Valley catchment and physical arrangement

The graphs and scenario log display several aspects of system operation which were expected including the following:

- All reservoir levels vary at different rates and may rise or fall.
- Over the short period of time there were very few warnings given mainly due to the large volume of the reservoirs involved. The warning indicators are shown in

the annunciator below (The numbers indicate the particular time increment during which the warning first appeared).

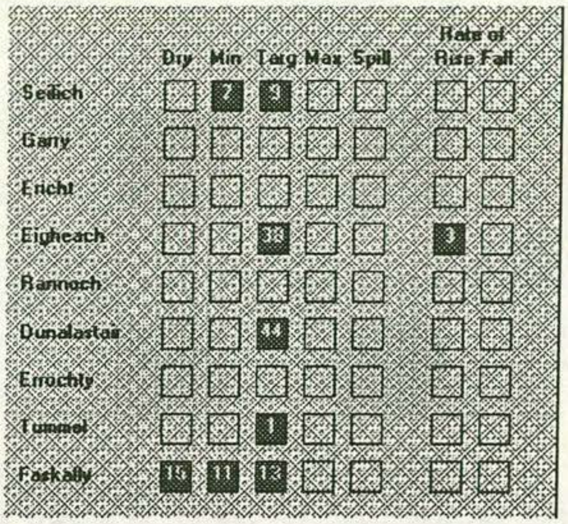


Figure 8.29 Scenario Annunciator

- Dunalastair reservoir level rose steadily since the lower station, Tummel was on outage.
- One reservoir, Faskally, dropped to dry level, due to the largest upper station being on outage (Tummel) and the lower station on priority running (Pitlochry). Unfortunately the attempts by the WM rulebase to prevent the drying problem were hindered by the uncompromising situations of these attached stations. Even when Clunie was despatched by the WM the flow was insufficient to supply Pitlochry, thus the problem persisted from the 15th time increment until the 38th when Pitlochry was finally switched-out.

This scenario run shows that the system does indeed simulate the operation of the water system and reacts to problems where it can. However, even if the WM is unable to solve the problem it does alert the hydro controllers to the possibility of such a situation allowing avertive action to be taken. For example, in this case: the Tummel outage could possibly be delayed until Faskally reservoir level was nearer to maximum level; the number of sets running at Pitlochry could be reduced; Clunie could be run continuously with all three sets.

8.6 Summary

This chapter illustrated the operation of the Water Manager over the two main areas, generation profile and scenario run. This operation was illustrated by a series of easily identifiable situations on simplified schemes. The chapter provides evidence that the WM can operate on a real scheme and uses Tummel Valley the largest and most complicated in the SHE area.

Throughout these simulations it became clear that there are many influences involved in a cascaded water system which make prediction difficult.

The results prove the applicability of the WM to scheduling and simulation of cascaded hydro-electric schemes. The illustrative scenarios demonstrate the effect of station turndown, outage or priority running on optimum generation schedules and reservoir levels. The reaction of the WM to extreme reservoir levels is also demonstrated in several of the scenario runs. The application of the WM to an authentic cascade confirms its value as a means to simulate compressed real-time scheduling operations and scenario runs for most cascaded hydro schemes.

CHAPTER 9 DISCUSSION and CONCLUSION

9.1 Introduction

The management of any hydro-electric scheme is described in this thesis as a combination of several key areas each of which must be addressed in order to formulate a strategy for the optimum control of all water and energy resources associated with a simple reservoir/power station system or an integrated hydro-electric cascade. These key areas are:

- Historical hydrological data.
- Hydro-plant and reservoir characteristics.
- Water flow control and storage.
- Electricity generation scheduling.
- Revenue maximisation.

In addition, interconnection of these five main areas is provided by the hydro control engineers who use their practical knowledge of the relationships within and between each area to control and plan the overall hydro-electric system. Essentially the engineers' expertise becomes the vital ingredient to ensure the integrity of the water system and to obtain the maximum revenue from generation.

Previously, and in relative isolation, each of the individual key areas has been investigated and analysed using improved procedures or simulation techniques to enhance the understanding of their situations or to provide faster utilisation of data. As detailed in section 2.4, this work has included:

- For most established catchments, hydrological data has been gathered for many years and, where sufficient data exists, extrapolation and trending are now being used to predict the hydrological effect on the reservoirs within a scheme. In the past this has involved written and manually calculated data although now computer databases of advancing sophistication are used to produce up-to-date practical information from pre-loaded or on-going recorded data.
- The observable, measurable and theoretical effect on a reservoir by the action of water throughput from upper or lower power stations has long been the subject of

computer simulation using various mathematical techniques each incorporating the simple characteristic relationships of individual system components.

- Computer modelling has also been widely applied to a variety of practical and hypothetical water system arrangements (including hydro) and are used to assess and predict the effect of changing flows and storages.
- Generation scheduling has been the subject of many investigations, involving both real and idealised power systems and using numerous mathematical and computational techniques to model the availability and allocation of generation to meet the variable electricity demand from a number of mixed-fuel sources.
- Revenue maximisation has been incorporated in many of the scheduling models, however, maximisation from hydro is a more recent development, particularly in the privatised UK ESI, where computer simulations are only now being developed to include the variable cost of water.
- In recent years, expert systems have emerged as an additional computational technique to incorporate and simulate an engineers' expertise. Consequently they are currently used, or are being developed, to provide the human element within various situations including hydro cascade control. However, the catchment topology and local climate define the unique physical arrangement of each hydro system which in turn determines the particular management strategy, thus causing most developments in the hydro expert system field to be site specific.

Hence this thesis discusses and describes an alternative approach to hydro management drawing all key areas together for the first time within one medium to simulate and integrate each of the fundamental controlling strategies that ultimately provide an overall management system that can be applied to scheduling and water control of any hydro cascade.

Therefore, throughout the duration of this five year project much knowledge of the control and operation of cascaded hydro and electricity power systems has been formalised. The resulting suite of software and thesis embodies this recently accumulated knowledge and realises the aims of the undertaking. This chapter concludes the thesis by recounting these aims and objectives, discussing the work involved, examining the knowledge and experience gained, and drawing together all interim observations and conclusions from Chapters 2-8. The technical novelty of the work is highlighted and finally extended to make suggestions for future work.

Therefore the main achievements of the work have been:

- The gathering together of a considerable body of source information and additional knowledge associated with the management of hydro cascades all retrieved from an assortment of media. This included: learned society papers; technical journals; written memoranda; computer data spreadsheets; historical hydrological tables; established theoretical techniques for the management of hydro stations and the determination of water conveyance and storage; industrial practices in the same; and new ideas for trading energy into the electricity pool.
- Extracting and assessing information that was not widely understood from the minds of the hydro controllers themselves. This produced phenomenon not previously simulated or recognised that required translation into tangible concepts and facts that form the basis of management rules associated with hydro scheduling and water control processes.
- Formulating both of the above into a single medium within a generalised system that simulates the overall management of energy and water resources in a rational and consistent style with the ability to be interrogated, enhanced and used by hydro engineers involved in the management of any hydro cascaded scheme.
- Producing a working system that not only enables more effective water management of today's resources, but can either be used: now to forecast the most appropriate water management techniques as resources reduce; or in the future to react to the changing distribution of rainfall and water resources.

9.2 Aims and Objectives

The processes described above entailed several initial aims and objectives including:

- establishing a sound understanding of all aspects of electrical energy and water management associated with cascaded hydro-electric systems.
- completion of a review of alternative methods of simulating the operation and control of cascaded hydro-electric schemes.
- elucidation of expert knowledge and subsequent incorporation into software.
- development of a decision support environment which is able to model any cascaded scheme incorporating a combination of reservoirs, power stations and weirs each hydraulically linked in any configuration.

- verification of the DSS system as a means of simulating and assisting the management of cascaded hydro.

All of the above were achieved during the course of the work and are fully detailed in the previous chapters. The following sections provide a summary discussion of each aspect and their relative importance in the context of cascade management is described. In each section, conclusive statements point to the significance of the work as a contribution to the body of knowledge which encapsulates water and energy management of cascaded hydro schemes using expert system decision support software.

9.3 Discussion

9.3.1 Energy and water management

The link between the production of electrical energy and the control of water within individual hydro-electric stations is already widely recognised. Similarly, the hydraulic interlinking of cascaded reservoirs, and the supply-demand nature of electricity grid networks are established bodies of knowledge. This study concerned itself with the development of a system that would encompass these three concepts, together with an element of human expertise, in the form of a software model that can assist hydro-plant control engineers on optimal generation scheduling and prudent water management.

This research resulted in the accumulation of a vast amount of information interrelating, directly or indirectly, the following considerable areas of the research: reservoir hydrology, hydraulics and dynamics; water-to-electrical energy transfer via water turbine-generator sets; generating station scheduling and the electricity day; hydro control strategies and electronic data storage/retrieval.

The major conclusions drawn from this area of research are:

- In recent years the water management of hydro has changed significantly due, mainly, to the revised operational nature of generation companies within a competitive ESI. This places more emphasis on the generation of hydro power during periods of high revenue, peak-time demand and necessitates a means of profiling the generation to meet with the requirements.

- Management of hydro resources must comply with two influential controlling functions: the supply of electrical energy to meet demand efficiently and economically and the storage and movement of water whilst maintaining the natural river flows and reservoir levels within a cascade system. Thus a means of linking the two tasks has become essential to optimise each with regard to the other.
- Water as a fuel is no longer considered to be "free" but has gained a monetary value that varies in time with electricity demand and reservoir level. Also, the movement of water has become time-dependent, determined by electricity demand, replacing the previous practice where the electrical energy supply was a consequence of the movement of water. The management of water has taken on a greater economic significance (especially when trading into the electricity pool) and now requires precise water management.
- The variation in demand characterised by the peak and trough periods during the "electricity day" has a major impact on the despatching of hydro stations and subsequent creation of an optimum generation schedule. Also these time periods within the electricity day are not fixed but vary according to changes in demand due to the seasonal differences in climate and uneven weekly requirements (i.e. holidays and weekends). This leads to the conclusion that any assessment of a generation profile must be sufficiently flexible to recognise this fundamental variation in demand.
- Stations can be prioritised depending on their supply reservoir level to ensure that demand is first met by those stations with an abundance of water. Thus hydro stations cannot be treated as infinitely variable sources of electricity generation but must be scheduled in order, according to the level of their supply reservoirs.
- Station outages and priority running have a major effect on scheduling and must be taken fully into account. The previous practice of assessing the probability of outage is no longer acceptable as a means of determining available generation, therefore any simulation exercise requires precise control of these features.
- Reservoir levels have many influences including the forces of nature, government laws and the hydro engineer. This gives rise to an infinitely variable system where the hydro engineer must control the reservoir level by station water throughput to compensate for the relative unpredictability of the weather and rigidity of government.

- A reservoir may have a correlated set of tables to link rainfall, runoff and generated output which allows runoff and water storage to be quantified in MWh which can then be converted to a monetary value. Where no tables exist a period of monitoring will be necessary to assess the water-energy relationship.
- Current changes in global climate can greatly affect the future operation of a reservoir. The assessment of the trends in rainfall and consequent runoff must be factored into any analysis of hydro operation.
- The volume/level relationship of a natural reservoir tends to be non-linear introducing an additional variable into any analysis of level changes.
- The influence of cascaded hydro on adjacent reservoir levels and mid station operation becomes significant especially when reservoirs are approaching extreme levels.
- Reservoirs within a cascade are not always linked via a power station, a situation which can present a problem when trying to simulate such a system. The representation of a weir provides the necessary means to control the water flow.

The above statements show the many important factors that affect the operation of hydro cascades. Each has to be addressed when determining the appropriate generation profile for a scheme whilst maintaining the integrity of the water system. Furthermore, when simulating cascaded hydro all these influences must be included in software in an accessible form to permit adjustments to be made, thus ensuring up-to-date realistic behaviour of the system being modelled.

9.3.2 Simulation methods

A comprehensive review of simulation methodologies revealed an array of mathematical and computational techniques previously used to model both hydro systems alone or mixed-fuel generation scheduling. Most were successful in achieving their own aims but none seemed to have sufficient breadth or depth to undertake the incorporation of all areas of particular interest in this study. The research revealed the following:

- Current areas of computer control of hydro involve data acquisition and automation of simple control functions, e.g. start-up sequences. Large systems have been developed to provide more sophisticated control but these are site specific and are therefore custom built making them expensive to install.

- For simplicity most simulations are either PU/territorial specific or standardised cascade model arrangements.
- A large proportion of hydro system simulation comprises logical procedural algorithms, however, water management requires additional intelligent decision making hence many previous simulations are idealised but unrealistic.
- Object-oriented programming is ideally suited for this type of application due to the hierarchical approach providing inheritance of similar characteristics to the four major components, i.e. schemes, stations, weirs and reservoirs.
- Using rule-based logic and a forward chaining search strategy, an expert system provides the best means of introducing intelligence into a sequential simulation.

These conclusions led to an investigation into application software to suit the project, and included a search among a number of programming languages and artificial intelligence techniques. The outcome of the research, eventually led to the selection of Kappa-PC, an expert system shell incorporating rule-based logic and object-oriented programming.

9.3.3 Expert knowledge

The investigation into the capture of expert knowledge from the hydro controllers themselves, involved a number of serial tasks primarily to overcome the experts' anxieties, establish a rapport and build-up a basic understanding of the issues involved in controlling hydro resources and generating electricity efficiently. The knowledge gathering exercise required the extraction of "expertise" from the engineers which itself required care when trying to translate human thought processes into computer procedural code or rules. A series of interviews ultimately produced a range of information which could either be classed as straightforward factual information associated with scheduling and water control or provided the "rules-of-thumb" used by the engineers while going about their everyday tasks.

The following conclusions were drawn from the knowledge gathering process:

- IF..THEN type rules are ideally suited to mimic human thought processes.
- Extraction of expert knowledge can produce much more information than the rules themselves providing details of the user requirements (i.e. the specification

of the user interface) and additional procedural/mathematical coding necessary to simulate a hydro cascade.

- The operation of one reservoir is very similar to another, suggesting one set of rules covering all aspects of water management can be applied to any reservoir. This significant contribution provided the basis for the development of a software environment that can simulate any cascade rather than a program to simulate a particular scheme.
- The priority order of stations and weirs is important to add authenticity to the allocation of generation to preferred stations. This differs from the usual simplistic methods of considering stations in order of capacity or position in the cascade.
- The priority order of reservoirs is also important to ensure protection of specific storages in the event of a spill or drawdown of adjacent reservoirs.

The major contribution of this area of research was to indicate that although much of the information gleaned was specific to SHE, the features could apply to any PU or cascaded hydro scheme.

9.3.4 Software development

The incorporation of all aspects discussed previously involved the development of a large suite of software to produce the required operational characteristics of cascade hydro and provide full user access to most of the variables. The initial idea of basing the software on a particular cascade which could then be expanded to represent other schemes proved difficult to achieve and almost impossible to maintain. However, the alternative approach, a universal water management environment with the capability of modelling any cascade arrangement, offered the most flexible solution. This led to the following conclusions:

- Kappa-PC was the most convenient and suitable application software available which incorporates both OOP and rule-based reasoning within a user-friendly development environment.
- An extensive set of user interface "windows" is necessary to provide full access to all variables and databases.
- A universal simulation environment was preferable to a PU specific system.

The resulting software suite, the Water Manager, has proved successful as a template which permits any user to easily assemble a cascaded scheme within it and then provide the facilities for a user to perform a number of simulation exercises on the scheme.

9.3.5 Verification

The verification initially comprised several tests on simplified schemes with easily identifiable and understood data. These tests established the authenticity of the actions of the Water Manager by achieving the desired and predicted results against known situations or strategies. When applied to an actual scheme the test results again proved the operation of the software to be both accurate and useful as a decision support tool. The conclusions are:

- The inherent unpredictability of a cascade situation can be reduced to pseudo real time with accelerated scenarios that indicate the exact time that a reservoir problem will occur under the user set conditions.
- When a reservoir reaches an extreme level the rule system does not only investigate primary solutions (by adjusting water flow regulators) but also assesses secondary problems, i.e. the knock-on effect to connected reservoirs.
- The results prove the applicability of the WM to the scheduling and simulation of cascaded hydro schemes.

9.4 Contribution

The theme throughout this thesis shows that the operation of a cascaded hydro scheme can be separated into two distinct domains: energy management and water management. Each of these domains has been investigated and simulated separately (described in Chapters 4 and 5) however their results, respectively the generation schedule and scenario run, can have a bearing on the other domain. This work has shown that the simulation of these domains and their linked effect is possible using an integrated suite of software. This is particularly evident when the expert system rules are called upon and applied (described in Chapter 6) to situations where the generation schedule causes reservoir level limits to be breached. As a result of extensive simulation work carried out using typical, similar and identical configurations much novel experience and knowledge has been gained of cascade systems operation. This new experience includes:

- understanding the processes involved in the preparation and creation of optimum generation schedules.
- acknowledging the effect of local hydrology and weather on individual reservoirs.
- understanding the effect of various generating regimes on simple cascade schemes.
- an awareness of the control strategies used by the hydro controllers to prevent the extreme operation of a reservoir, i.e. spilling, draining and rate-of-change of level.

In particular the following additional details have emerged from extensive scenario runs on the Water Manager:

- Reservoir behaviour in a large cascade can be very unpredictable due to the diverse nature of the various inflows and outflows.
- The size of a reservoir has no bearing on its stability. Large and small reservoirs are equally liable to spill or drain in a very short period of time depending on the relative volume of inflows and outflows.
- Reservoirs at the upper and lower extremities of a cascade are not always the most critical. Indeed a mid level reservoir may become the controlling feature of the whole system.
- In extreme weather conditions there is little the hydro controllers can do to prevent spillage unless they had been warned in advance and had time to draw down the storages.

All of the general contributions are summarily described in the following sections:

9.4.1 Generation Schedules

The Water Manager incorporates a routine, Generation Regime, which provides the user with a means to schedule generation effectively to meet the projected demand, create the most economic "best fit" over the troughs and peaks of the electricity day, and take due consideration of the availability and priority of multiple stations in a group of schemes. The resulting optimum schedule is then accessible to the user to permit small personal alterations, if required, providing total flexibility in the creation of a generation schedule or operating regime. The design and development of the

WM proved that all factors involved in scheduling a large number of generating stations can be drawn together, prioritised to suit and be quickly assessed and arranged to produce a full weekly schedule in half-hourly increments for all stations. More importantly a small change to any of the data can cause a great deal of alterations to the schedule but Generation Regime is able the re-appraise the situation almost instantly to update the schedule.

9.4.2 Weather effects

The weather effect on a reservoir can be significant especially at the two extremes: heavy rainfall and continuous sunshine, where the outcome of prolonged heavy rainfall and runoff can cause even a large reservoir to spill in a relatively short period of time. The WM proves this fact and displays the importance of the weather by permitting the user to vary the runoff volume or weather factor (described in Chapters 4 and 7) and observe the consequent effect on reservoir levels. Thus the possibility of such events can be simulated in association with the proposed generation schedule to anticipate and subsequently prevent any possible adverse effects. This again highlights the value of the Water Manager as a predictive aid to hydro controllers.

9.4.3 Effect of a generation regime

Whereas the action of a single station is obvious, the compound effect of two or more power stations feeding water into or being fed from an individual reservoir can have a mixed influence on a reservoir level. Furthermore, in a complicated serial-parallel cascade, trying to anticipate the results of generation over a prolonged period of time is almost impossible. The development of the Scenario Run routine has illustrated that these effects can be assessed for any generation regime and for any ensuing weather conditions. Furthermore, given the initial starting levels simulation can be achieved over any length of time in any incremental time period (shown in Chapter 8). Thus the WM provides hydro controllers with the ability to accurately predict the outcome of their scheduling actions and its effect on any individual reservoir thereby proving its worth as a decision support tool.

9.4.4 Extreme conditions

Fast rate-of-change, draining and spilling conditions are the extreme limits which a hydro controller must always try to avoid. However knowing what is likely to happen over the next few hours may be predicted reasonably accurately but over a day or week the movement in the relative reservoir levels can become difficult to foresee due to the circumstances described in 9.4.2 and 9.4.3 above. The likelihood and occurrence time of these extremes are detected and highlighted during a WM scenario run. Furthermore, the rulebase within the WM decides the best action to take to prevent spilling or drying. Thus this enhanced feature of the WM provides the hydro controllers with an additional aid in their efforts to prevent extreme circumstances arising.

9.5 Future Work

Several recommended courses for future work have emerged from this research. All involve the enhancement of the basic model software and are:

- To link the software to a SCADA system to obtain true up-to-date, on-line information requiring limited user involvement.
- To refine station representation to account for part-load operation and the consequences of head variation.
- To incorporate a means of water extraction from individual reservoirs, for non-generation purposes.
- To fine-tune the weather representation.
- To assess the value of water.
- To include additional models of alternative water systems, e.g. canals or irrigation.

9.5.1 SCADA

Since most Power Utilities or large-hydro controllers tend to monitor their systems using some form of SCADA, it would be beneficial to incorporate a data capture system within the WM. There are programming difficulties in mapping data directly into the WM software however one possible approach would involve downloading the SCADA information into a spreadsheet which can in turn be linked into the WM. This would have the benefit of drawing in any appropriate data and ensuring that any information used during a simulation was the most recent available. A further advantage would be to reduce the amount of information which must be checked by the user prior to a simulation, e.g. reservoir levels.

9.5.2 Station representation

For authenticity, the simulation of each hydro-electric power station should include additional modelling information. This includes the ability for an individual generating set to operate at part-load, whereas presently the WM only allows for two extreme conditions, full-load or off. At part-load, the water flow/energy characteristic would have to be modified by an appropriate efficiency variation associated with the particular load condition. Thus the relationship between efficiency and load must be incorporated for each TG set, possibly in the form of a look-up table.

In addition, as the upper reservoir level falls and the lower reservoir level rises, the head and hence output of a turbine would change. Although this is relatively small and in many cases insignificant, in a competitive electricity market where the profit margins on energy are continually reducing, a small variation in energy production over a long period of time can produce an increase or reduction in revenue.

9.5.3 Water abstraction

Currently the assumption made is that water from each reservoir is either passed through a power station, is released as compensation river flow towards the next reservoir or in extreme cases spills over the dam. However, when used as a potable water supply system some water will be completely removed from the cascade system. To account for this extraction and consequent reduction in reservoir volume, a small change to the WM is all that is necessary to incorporate this feature. Unfortunately, the rule system would also need to be altered in order that the priority of this action is considered in the event of a draining reservoir.

9.5.4 Weather refinement

The vagaries of seasonal and daily weather and its subsequent effect on reservoir water levels have been incorporated within the WM by the action of the 10-year runoff database, the runoff percentage and the extra weather percentage. However, while this allows the user to tune the WM response to take full account of the ensuing climatic conditions, it does not allow changes in localised weather over a scenario run. This is generally acceptable since only prolonged rainfall or drought can have a significant effect over a short period of time, whereas extreme changes are averaged out over the course of a scenario. However, a means of allowing the user to set the predicted weather patterns over a scenario period would give the WM a much more realistic quality.

Beyond the weather variations over a short scenario, a more important effect is the present trend in climatic conditions. This has major implications on any hydro system as expressed by McVeigh[148] discussing the world-wide effect:

> "Due to global warming precipitation levels may fall in many countries lessening the effectiveness of hydro power."

Whittington & Gundry[149] took this a stage further by quantifying the effect and citing specific locations in Africa and Russia where major changes are currently happening while D. Lee[150], Manager of CLUNIE Hydro-group, described the situation in the Scotland over the last few years thus:

> "Dry spells are longer, wet spells are wetter, there is 40% more rain, less snow, there is too much water at one time"

These trends over recent years can be taken into account by using a rolling 10-year runoff database, which should be able to reflect the current changes in the global conditions. Should these changes become accelerated an additional factor may be necessary to compensate for the effect on predicted runoff. Predictions of these trends and the resultant effects on real hydro systems could then be investigated with additional modelling using the WM.

9.5.5 Value of water

Since the WM schedules generation to occur mainly during times of peak demand, it can be said that the water in the supply reservoir is valued at a price determined by the cost of electricity during these periods. Also spillage or inopportune generation during periods of low demand are varying losses which must be minimised to gain the optimum revenue. In a way prioritising the stations and reservoirs implies the differences in each station but cannot be relied upon to convert straight into a cost. Thus an added feature of the WM would be a means of evaluating this cost and relating it to the need to generate, i.e. the lower stations of a spilling reservoir must generate thereby reducing the value of the water in the reservoir.

9.5.6 Alternative water systems

Current water management includes the movement and storage of water in a number of related areas, potable water, canal networks, irrigation schemes, sewerage systems, flood/drought management and recreational facilities. Also future water resource management will incorporate reclamation of more waste water, weather effect modification, land management to improve water yield and new water saving techniques in all areas of water use. As each of these topics become more intermeshed the requirement for a suitable management system becomes apparent. Therefore, the techniques and basic understanding gained during the development of the WM could be turned towards the simulation of any of these systems. Although this goes well beyond the enhancement of the WM it does provide a springboard to a host of similar problems which could be tackled in the same way.

9.6 Concluding Remark

Effective water and energy management is already important for the sound hydrological operation of cascade hydro plants in the forum of world-wide ESIs. As a result of climate change and other global issues water management may become critical in the efficient use of a diminishing renewable energy resource.

Hence this thesis discusses and describes an alternative approach to hydro management, drawing all key areas together for the first time within one medium to simulate and integrate each of the fundamental controlling strategies that ultimately provide an overall management system that can be applied to scheduling and water control of any hydro cascade.

The author has assembled and assimilated an extensive body of knowledge in water and energy management and this has been combined in the Water Manager software. Through experience of its use the author has contributed to the greater understanding of complex cascade systems, as they are used today and likely to be used in the future.

APPENDIX 1 Energy Trading

A1.1 Bid preparation

One of the responsibilities of the day-ahead engineer (DAE) within a generation company is to prepare and submit to the England & Wales Pool, bids for energy trading. The structure and operation of the pool is such that at any one time the DAE prepares two bids for submission.

To do this the DAE sets generating plant conditions to meet the forecast of domestic demand and the additional contractual commitments to other large consumer companies or PUs. Once these commitments have been satisfied, the DAE profiles the excess capacity, if any, and decides whether or not to offer it to the E & W pool in the form of a bid. It is of course possible that system demand seen by the DAE may exceed the available capacity due to outage and therefore it may be necessary to purchase power from the pool rather than to sell. In this instance, the DAE will prepare the documentation for submission which shows a demand for energy. It is also possible to buy and sell energy within the same schedule day but it is forbidden to buy and sell within the same half-hourly settlement period.

The preparation of the bid in spreadsheet form details the demand and generation availability profile to meet this demand at each half-hour of the day. For each half hour, demand will be made up of domestic demand plus any contractual commitments plus any offer to supply to the pool. In addition details of prices and system constraints are entered into the spreadsheet which completes the bid ready for forwarding by facsimile to NGC.

In addition to day ahead trading into the pool, the generating companies can also trade on 'spot', a responsibility of the LE. The day ahead bidding process produces a constrained schedule which is the basis for trading during the schedule day. During the schedule day adjustments may need to be made to this schedule which may result in the opportunity to sell electricity to the pool for immediate or short-term despatch. There are two methods to facilitate this process:

- The pool can ask the generators if they have any excess capacity to sell and if they do and a price can be agreed upon. The generators then sell the power to the Pool, providing there is transmission capacity availability.
- NGC can also ask the generators to move to maxgen generation at a price which will have been quoted in the original bid.

A1.2 Schedule day

Bids are submitted each day, just before 1000 hrs, for the schedule day beginning at 0500 hrs the next morning. Thus the plan for the schedule day 0500 hrs on Wednesday to 0500 hrs on Thursday is first decided upon on the preceding Monday. This plan is updated in response to changes in plant availability and weather conditions, between 0800 hrs and 1000 hrs on Tuesday morning before submission. The DAE submits an offer which shows generator availability, energy prices (e.g. £20.00 per MWh), start-up prices and any constraints on the supply. Each offer covers a period of time known as the 'Availability Declaration Period' which runs from 2100 hrs on the day the bid is submitted to midnight after the end of the schedule day.

A1.3 Pool Operation And Rules

The pool is effectively a spot market for electricity which operates in two distinct stages. Subsequent to submission of bids, NGC run their scheduling program, known as GOAL (Generator Ordering And Loading) to produce an 'unconstrained schedule'. This schedule, as the name suggests, takes no account of system considerations such as transmission outages and capacity limitations, i.e. the schedule is an "ideal" order-of-merit listing the PU stations in the rank order that they would be despatched if no transmission constraints existed. It is issued to generators subsequent to the schedule day. System Marginal Prices (SMP) are calculated on the basis of this unconstrained schedule and reflect the total cost (including start-up and no-load costs) of the marginal set in each half hour during what are known as Table A periods and the incremental cost of the marginal set during Table B periods. Broadly speaking, Table B periods represent troughs in the demand curve whilst Table A periods represent the remainder of the day.

Subsequent to the first GOAL run, another version is run which produces the constrained schedule. This is issued to generators by 1500 hrs on the day of bid submission. The constrained schedule indicates when generators will be required to supply power but not the required load levels.

At about 1600 hrs the day ahead pool payment prices (PPPs) are issued which comprise the SMPs plus capacity payments made to generators. The capacity payment is determined thus :

Capacity Payment = LOLP(VOLL - SMP)

where **LOLP** (Loss of Load Probability) is the calculated probability for each half hour that there will be insufficient capacity to meet demand, based upon forecast demand and plant availability over the schedule day and the preceding seven days.

VOLL represents the price that pool members would be prepared to pay in order to avoid a loss of supply. VOLL is set at approximately £2000.00.

The price received by the generators varies depending on a station's position in the two GOAL run schedues and whether it actual contributed to the pool. The four types of payment are:

- Generation in the unconstrained schedule, which is despatched, receives the PPP.
- Generation in the unconstrained schedule which is not despatched receives the PPP minus the generator's bid price (i.e. lost profit, providing the original bid was made at cost).
- Any plant not shown in the unconstrained schedule, but which may appear in the constrained schedule, that is despatched is paid at bid price plus any availability payment.
- Any plant not in the unconstrained schedule and not despatched but nevertheless available receives the availability payment. The availability payment is set at **LOLP x (VOLL - Bid Price)**.

To avoid the volatile situation inherent in such a system it is common for contracts to be struck between generators and customers (such as RECs) which undertake to pay the difference between agreed contract prices and actual pool prices. This operates for most of the power supplied and purchased at present with short term changes in forecast demand being covered by 'spot' purchases from the pool.

To prevent/solve any problems with the above system operation, the government body, **OFFER (Office of Electricity Regulation)** oversees the industry to ensure fair play in the energy trading process and to protect the consumer interest.

APPENDIX 2 Typical Reservoir Object

INSTANCE: Rannoch
ROOT: TummelLochs
METHOD: CalcDefault2;
SLOTS: (Showing typical values)

```
Rannoch:Name = Rannoch;
Rannoch:Scheme = Tummel;
Rannoch:MaxLevel = 204.83;
SlotOption(Rannoch:MaxLevel, AFTER_CHANGE, CalcDefault2 );
Rannoch:MaxLevelZero = 0;
Rannoch:MinLevel = 202.39;
SlotOption( Rannoch:MinLevel, AFTER_CHANGE, CalcDefault2 );
Rannoch:MinLevelZero = -2.44;
Rannoch:MaxVolume = 45492000;
Rannoch:MaxStorage = 5100000;
Rannoch:LTAArunoff = 14350000;
Rannoch:AveStorePerMetre = 2145000;
Rannoch:CubicMetresPerUnit = 8.92;
Rannoch:TimeConstant = 0;
Rannoch:CompOutflow = 0.0008;
Rannoch:CompInflow = 0.0008;
Rannoch:IdentityNo = 5;
Rannoch:MaxDrawdown = 2.44000000000003;
Rannoch:DefaultLevel = 203.61;
Rannoch:InitialLevel = 203.97;
Rannoch:PrevLevel = 203.97;
Rannoch:InitialStore = 3389100.00000003;
Rannoch:InitialVol = 30230772.0000002;
Rannoch:PSinNo = 2;
Rannoch:PSoutNo = 0;
Rannoch:WinNo = 0;
Rannoch:WoutNo = 1;
Rannoch:PSinflow = 3, 4;
Rannoch:PSoutflow = 10;
Rannoch:Winflow = 10;
```

SLOTS(continued): (Showing typical values)

```
Rannoch:Woutflow = 10;
Rannoch:AveDailyRunoff = 36169.8630136986;
Rannoch:CheckStorage = 0;
Rannoch:PrevVolume = 30230772.0000002;
Rannoch:PrevStorage = 3389100.00000003;
Rannoch:Volume = 30230772.0000002;
Rannoch:TotalInflow = 86160.0004;
Rannoch:TotalOutflow = 3969.3604;
Rannoch:Storage = 3389100.00000003;
Rannoch:Level = 203.97;
Rannoch:LevelBelowSpill = -0.860000000000014;
Rannoch:LevelAboveDry = 1.58000000000001;
Rannoch:OpTimeIn = 1;
Rannoch:Warning = NULL;
SlotOption( Rannoch:TargetLevel, MINIMUM_VALUE, 202.39 );
SlotOption( Rannoch:TargetLevel, MAXIMUM_VALUE, 204.83 );
Rannoch:TargetLevel = 204.33;
Rannoch:PriorityStatus = 1;
Rannoch:UpdateLevel = -0.860000000000014;
Rannoch:PSinList = (PS_Rannoch, Gaur );
Rannoch:WoutList = RanDun;
Rannoch:ScenarioData = -0.860000000000014;
SlotOption(Rannoch:TargetLevelZero, MINIMUM_VALUE, -
2.44000000000003 );
SlotOption(Rannoch:TargetLevelZero, MAXIMUM_VALUE, 0 );
Rannoch:TargetLevelZero = -0.50;
Rannoch:RateOfRiseMax = 0.15;
Rannoch:RateOfFallMax = 0.15;
Rannoch:WarnMinLevel = -1.2;
Rannoch:WeekRunoff123 = 405;
Rannoch:DayRunOffFrom123 = 346287.426523298;
Rannoch:RateOfRise = 0;
Rannoch:RateOfFall = 0;
Rannoch:RoRsampleNo = 24;
Rannoch:RunoffVolume = 1507.07762557078;
```

SLOTS(continued): (Showing typical values)

Rannoch:LookupLevelZero = (-5.4864, -2.4384, -2.40792, -2.37744, -2.34696, -2.31648, -2.286, -2.25552, -2.22504, -2.19456, -2.16408, -2.1336, -2.10312, -2.07264, -2.04216, -2.01168, -1.9812, -1.95072, -1.92024, -1.88976, -1.85928, -1.8288, -1.79832, -1.76784, -1.73736, -1.70688, -1.6764, -1.64592, -1.61544, -1.58496, -1.55448, -1.524, -1.49352, -1.46304, -1.43256, -1.40208, -1.3716, -1.34112, -1.31064, -1.28016, -1.24968, -1.2192, -1.18872, -1.15824, -1.12776, -1.09728, -1.0668, -1.03632, -1.00584, -0.97536, -0.94488, -0.9144, -0.88392, -0.85344, -0.82296, -0.79248, -0.762, -0.73152, -0.70104, -0.67056, -0.64008, -0.6096, -0.57912, -0.54864, -0.51816, -0.48768, -0.4572, -0.42672, -0.39624, -0.36576, -0.33528, -0.3048, -0.27432, -0.24384, -0.21336, -0.18288, -0.1524, -0.12192, -0.09144, -0.06096, -0.03048, 0);

Rannoch:LookupMCM = (0, 0, 0.566336, 1.132672, 1.7273248, 2.2936608, 2.8599968, 3.4263328, 3.9926688, 4.5873216, 5.1536576, 5.7199936, 6.2863296, 6.8809824, 7.4473184, 8.0419712, 8.6083072, 9.1746432, 9.7409792, 10.335632, 10.901968, 11.468304, 12.03464, 12.6292928, 13.1956288, 13.7902816, 14.3566176, 14.9229536, 15.5176064, 16.0839424, 16.6785952, 17.2449312, 17.8112672, 18.40592, 18.972256, 19.5669088, 20.1332448, 20.7278976, 21.2942336, 21.8888864, 22.4552224, 23.0498752, 23.6162112, 24.210864, 24.7772, 25.3718528, 25.9381888, 26.5045248, 27.0991776, 27.6655136, 28.2601664, 28.8265024, 29.4211552, 29.9874912, 30.582144, 31.14848, 31.7431328, 32.3377856, 32.9041216, 33.4987744, 34.0651104, 34.6597632, 35.254416, 35.820752, 36.4154048, 36.9817408, 37.5763936, 38.1710464, 38.7373824, 39.3320352, 39.8983712, 40.493024, 41.0876768, 41.7106464, 42.3052992, 42.9282688, 43.5229216, 44.0892576, 44.6555936, 45.2219296, 45.7882656, 46.3546016);

Rannoch:LookupAvailable = yes;

Rannoch:GraphTargData = -0.50;

Rannoch:GraphMinData = -1.2;

Rannoch:PosDownVolume = 7915.68;

Rannoch:PosUpVolume = 172320;

Rannoch:VolumeHold = 30396683.3976258;

Rannoch:StorageHold = 3407699.93246926;

Rannoch:LevelHold = 203.978671297188;

SLOTS(continued): (Showing typical values)

Rannoch:StorageDiff = 1022.07;

Rannoch:StorageTarget = 2326.08832362316;

Rannoch:StorageCurrent = 3348.1617278109;

Rannoch:HoldLevel = -0.5;

APPENDIX 3 Typical Station Object

INSTANCE: Pitlochry

SUBCLASS: TummelStations

CLASS: Stations

SLOTS: (Showing typical values only)

Pitlochry:Name = Pitlochry;
Pitlochry:Scheme = Tummel;
Pitlochry:Type = Station;
Pitlochry:Capacity = 15;
Method(Pitlochry:Capacity, AFTER_CHANGE, CalcDefault1);
Pitlochry:NoofSets = 3;
Pitlochry:CubicMetresPerUnit = 30.9;
Pitlochry:StoreSpaceRequirement = 15450;
Pitlochry:DefaultOutput = 5;
Pitlochry:RequiredOutput = 0.5;
Method(Pitlochry:RequiredOutput, AFTER_CHANGE, WaterThroughput);
Pitlochry:CurrentOutput = 15;
Pitlochry:IdentityNo = 9;
Pitlochry:CapacityperSet = 5;
Pitlochry:MaxGenAvail = 360;
Method(Pitlochry:SetNosAvail, ALLOWABLE_VALUES, 0, 1, 2, 3);
Pitlochry:SetNosAvail = 3;
Pitlochry:UpperLoch = Faskally;
Pitlochry:LowerLoch = NULL;
Pitlochry:PriorityStatus = 1;
List(Pitlochry:SetNos, 0, 1, 2, 3);
Pitlochry:ScenarioData =15;
Pitlochry:TotalScenarioGeneration = 0;
Pitlochry:AllScenData = 15, 15, 15, 15, 15, 15, 15, 0, 0, 0 etc for 336 slots.
Pitlochry:PSWeek = 15, 15, 15, 15, 15, 15, 15, 0, 0, 0, 0, 0 etc for 336 slots.

APPENDIX 4 Typical Weir Object

INSTANCE: RanDun

ROOT: TummelWeirs;

SLOTS : (Showing typical values)

RanDun:Name = RanDun;
RanDun:Scheme = Tummel;
RanDun:Type = Weir;
RanDun:MaxWLevel = 204.85;
SlotOption(RanDun:MaxWLevel, AFTER_CHANGE, CalcDefaultHeight);
RanDun:MinWLevel = 202;
SlotOption(RanDun:MinWLevel, AFTER_CHANGE, CalcDefaultHeight);
RanDun:RequiredWLevel = 203.425;
RanDun:CurrentWLevel = 203.425;
RanDun:Length = 10;
RanDun:DefaultLevel = 203.425;
SlotOption(RanDun:TargetWLevel, MINIMUM_VALUE, 203);
SlotOption(RanDun:TargetWLevel, MAXIMUM_VALUE, 204.85);
RanDun:TargetWLevel = 203.9;
RanDun:IdentityNo = 10;
RanDun:Starttime = NULL;
RanDun:Stoptime = NULL;
RanDun:LowerLoch = Dunalastair;
RanDun:UpperLoch = Rannoch;
RanDun:PriorityStatus = 4;
RanDun:ScenarioData, = 203.425, 203.425, 203.425, etc for 336 timeslots.
RanDun:AllScenData, = 203.425, 203.425, 203.425, etc for 336 timeslots.
RanDun:WeirWeek, = 203.425, 203.425, 203.425, etc for 336 timeslots.
RanDun:Height = 5;
RanDun:UpperLevel = 204.02;
RanDun:Head = 0.594999999999999;
RanDun:HhRatio = 6.00840336134458;
RanDun:HhRatioNo = 4;

RanDun:CurrentHeight = 3.57500000000002;

RanDun:VolumeFlow = 30071.1015561318;

RanDun:HeadNo = 3;

RanDun:CWCoeff = 1.82;

RanDun:GraphData, 0, 0.5249, 0.5349, 0.5349, etc for 336 timeslots.

APPENDIX 5 Typical Scheme Object

INSTANCE: Tummel

ROOT: Cascades

SLOTS: (Showing typical values)

Tummel:Title = Tummel;
Tummel:Group = CLUNIE;
Tummel:LNo = 9;
Tummel:PSNo = 10;
Tummel:TotalInstances = 19;
Tummel:PSNoInput = 9;
Tummel:WeirNo = 1;
Tummel:PictureFileName = Tummel.bmp;
Tummel:TextFileName = tuspecop.txt;
Tummel:WeeklyLoadFileName = TumDay.wk1;
Tummel:RO10FileName = Tum10RO.wk1;
Tummel:LookUpFileName = TumLook.wk1;
Tummel:LochLocation = TummelLochs;
Tummel:PSLocation = TummelStations;
Tummel:WeirLocation = TummelWeirs;
Tummel:InstanceList = Seilich, Garry, Ericht, Eigheach, Rannoch, Dunalastair, Errochty, Loch_Tummel, Faskally, Cuaich, LochEricht, PS_Rannoch, Gaur, PS_Tummel, PS_Errochty, Trinafour, Clunie, Pitlochry, RanDun;
Tummel:PSWeirPriorityOrder = Pitlochry, PS_Tummel, PS_Errochty, Clunie, PS_Rannoch, LochEricht, RanDun, Gaur, Cuaich, Trinafour;
Tummel:LochPriorityOrder = Dunalastair, Loch_Tummel, Faskally, Errochty, Rannoch, Ericht, Garry, Seilich, Eigheach;
Tummel:WeirList = RanDun;
Tummel:PSList: = Cuaich, LochEricht, PS_Rannoch, Gaur, PS_Tummel, PS_Errochty, Trinafour, Clunie, Pitlochry;
Tummel:LochList = Seilich, Garry, Ericht, Eigheach, Rannoch, Dunalastair, Errochty, Loch_Tummel, Faskally;
Tummel:GenerationShare = 16.5;
Tummel:GenerationShareMWh = 5662.63;

SLOTS (continued): (Showing typical values)

Tummel:DayMWh1 = 1037;

Tummel:DayMWh2 = 663;

Tummel:DayMWh3 = 187;

Tummel:DayMWh4 = 663;

Tummel:DayMWh5 = 1042;

Tummel:DayMWh6 = 1037;

Tummel:DayMWh7 = 1037;

Tummel:FileNameList = TumDay.wk1, Tum10RO.wk1, TumLook.wk1, tuspecop.txt, Tummel.bmp;

Tummel:FileDirectory = "c:\kapfiles\tumfiles";

Tummel:ScenarioRunFiles = Tu26Ma5A.txt, Tu26Ma5B.txt, Tu26Ma5C.txt, Tu09Ap6A.txt;

Tummel:SpecCondList = Pitlochry;

Tummel:PSPriorRunning = Pitlochry;

Tummel:SchemeTotalMWh = 5676.83;

APPENDIX 6 Scottish Hydro-Electric Schemes (Stations)

All information taken directly from the Scottish Hydro-Electric plc, "Power From The Glens" publicity brochure 1991.

CONON	MW
Achanalt	3
Grudie Bridge	24
Mossford	24
Luichart	34
Orrin	18
Torr Achilty	15

AFFRIC/BEAULY	MW
Mullardoch	2.4
Fasnakyle	66
Deanie	38
Culligran	24
Aigas	20
Kilmorack	20

SLOY/AWE	MW
Sloy	130
Sron Mor	5
Clachan	40
Allt-na-Lairige	6
Nant	15
Inverawe	25
Kilmelfort	2
Loch Gair	6
Striven	8
Lussa	2.4
Tralaig	1

TUMMEL	MW
Gaur	6.4
Cuaich	2.5
Loch Ericht	2.2
Rannoch	48
Tummel	34
Errochty	75
Trinafour	0.5
Clunie	61.2
Pitlochry	15

GARRY/MORISTON	MW
Ceannacroc	20
Livshie	15
Glemmoriston	36
Quioch	22
Invergarry	20

BREADALBANE	MW
Lubreoch	4
Cashlie	11
Lochay	47
Finlarig	30
Lednock	3
St.Fillans	21
Dalchonzie	4

FOYERS	MW
Foyers	300
Foyers Falls	5
Mucomir	1.95

SHIN	MW
Cassely	10
Lairg	3.5
Shin	24

SMALL SCHEMES	MW	LOCATION
Chliostair	1	Isle of Harris
Gisla	0.54	Isle of Lewis
Kerry Falls	1.25	Gairloch
Loch Dubh	1.2	Ullapool
Morar	0.75	Mallaig
Nostie Bridge	1.25	Kyle Of Lochalsh
Storr Lochs	2.85	Isle of Skye
Other small Stations	6.148	

Scheme Capacities	MW
Conon	118
Affric/Beauly	170.4
Sloy/Awe	239.4
Tummel	244.8
Garry/Moriston	113
Breadalbane	120
Foyers	306.95
Shin	37.5
Small Schemes	14.98
TOTAL	1365.03

APPENDIX 7 Scottish Hydro-Electric Schemes (Reservoirs)

All information taken directly from the Scottish Hydro-Electric plc, "Power From The Glens" publicity brochure 1991. Only the main reservoirs have been included.

CONON	Elevation
Glascarnoch	252
Fannich	256
Achnalt	111
Luichart	88
Orrin	256
Achonachie	30

AFFRIC/BEAULY	Elevation
Mullardoch	249
Beinn a'Mheadoin	224
Beannacharan	113
Aigas	44
Kilmorack	27

SLOY/AWE	Elevation
Sloy	285
Sron Mor	296
Shira	338
Allt-na-Lairige	303
Nant	207
Awe	37

TUMMEL	Elevation
an-t-Seilich	427
Cuaich	397
Ericht	359
Garry	415
Eigheach	259
Rannoch	205
Errochty	329
Dunalastair	198
Tummel	144
Faskally	91

GARRY/MORISTON	Elevation
Loyne	227
Cluanie	214
Dundreggan	110
Quioch	201
Garry	85

BREADALBANE	Elevation
Lyon	343
an Daimh	433
Stronuich	292
na Lairige	521
Lednock	352
Earn	97
Breaclaich	443

FOYERS	Elevation
Mhor	194

SHIN	Elevation
Shin	93

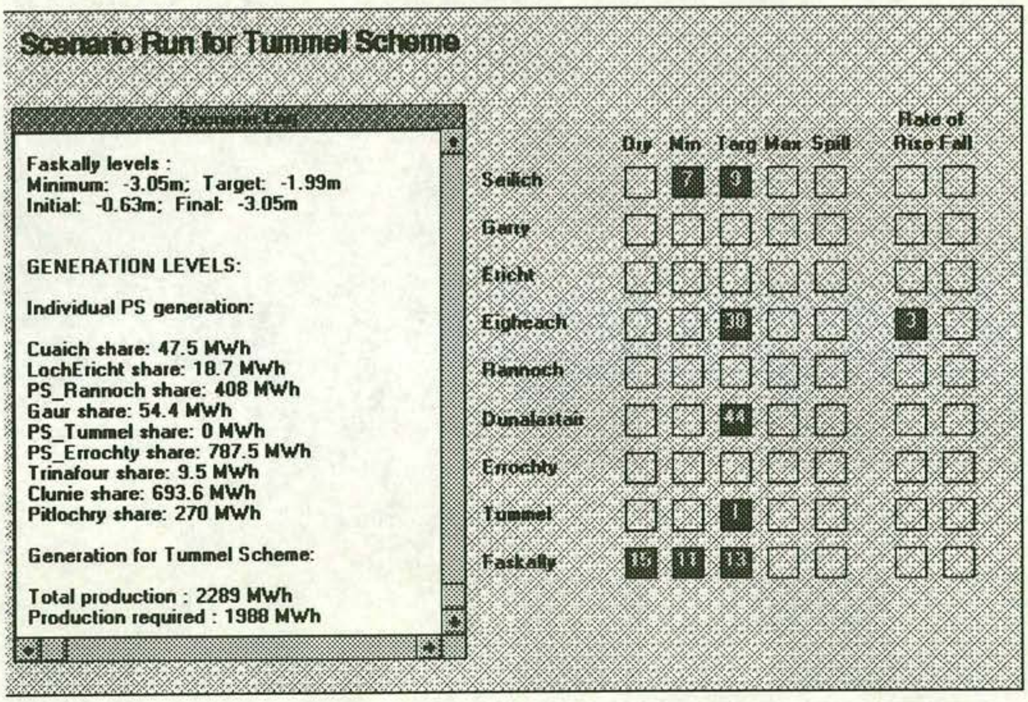
APPENDIX 8 Tummel Valley Scenario Run

A8.1 Scenario Run

The results of a scenario run for the Tummel Valley Scheme using the Generation schedule in Table 8.18 in Chapter 8. The scenario is performed over 24 hrs starting from 0700 hrs on a Monday morning and is assessed in half-hourly increments. Discussion of the results is given in Chapter 8.

A8.1.1 Scenario Annunciator Screen

The final scenario screen with all annunciated warnings is shown below.

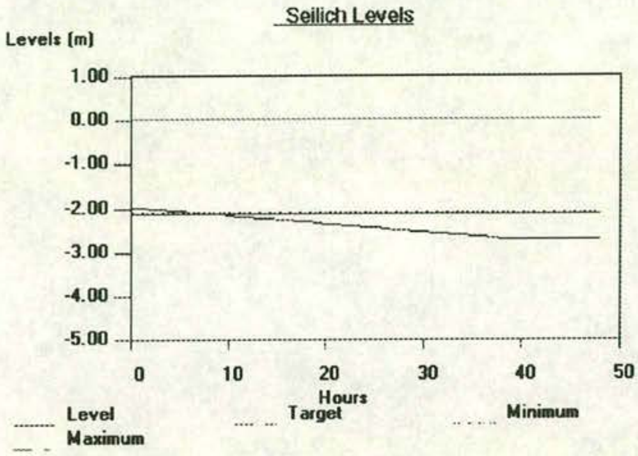


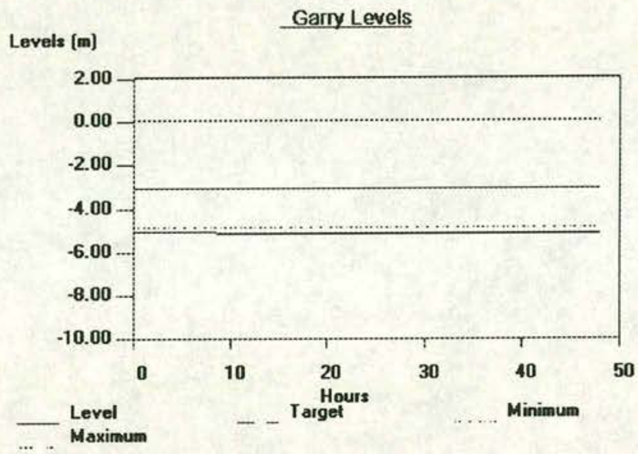
The full scenario log of events and summary are given in sections A9.1.3 and A9.1.4. and the variation in all reservoir levels are shown in the next section.

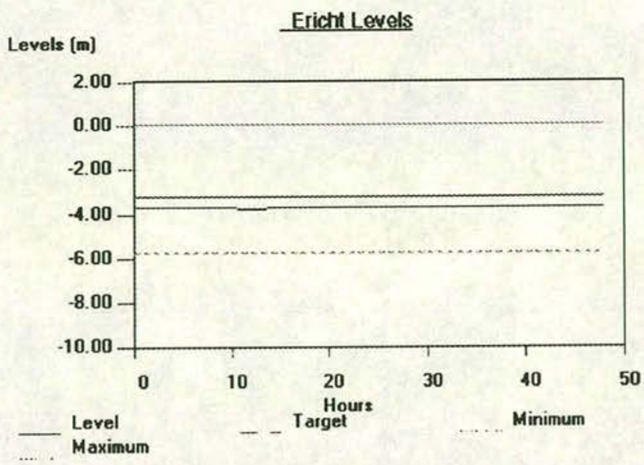
A8.1.2 Reservoir Level Graphs

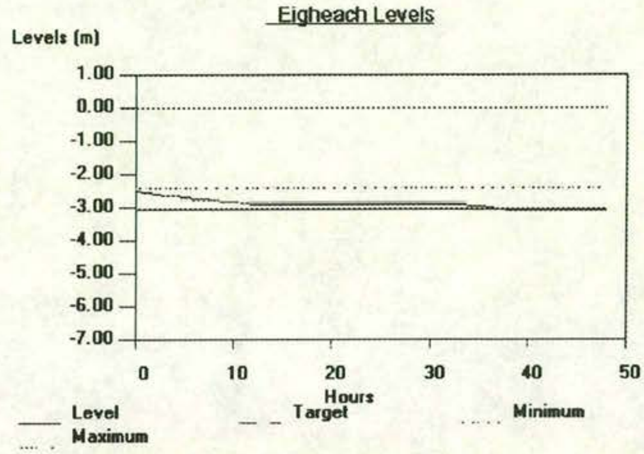
All reservoir graphs are shown on the following pages:

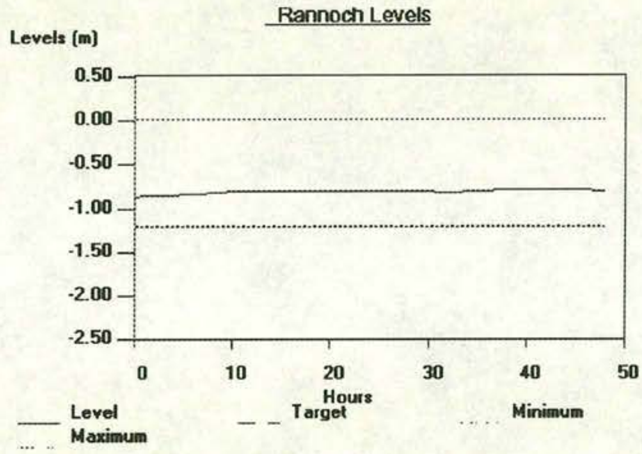
Page 2 Loch Seilich; Loch Garry; Loch Ericht.
Page 3 Loch Eigheach; Loch Rannoch; Dunalastair Reservoir.
Page 4 Loch Errochty; Loch Tummel; Loch Faskally.

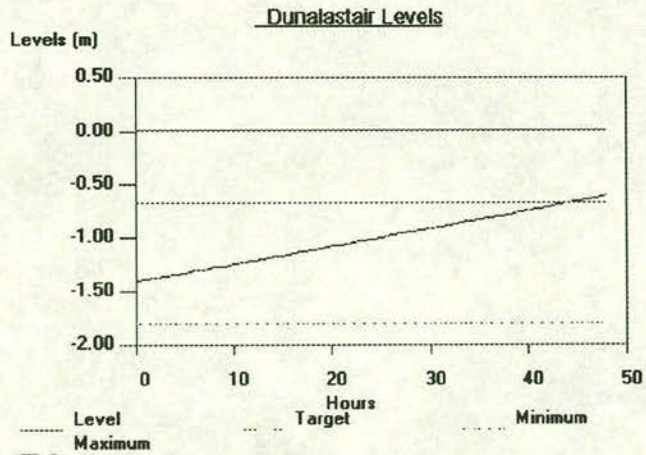

Seilich Levels
Levels (m)
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
0
10
20
30
40
50
Hours
Level
Target
Minimum
Maximum

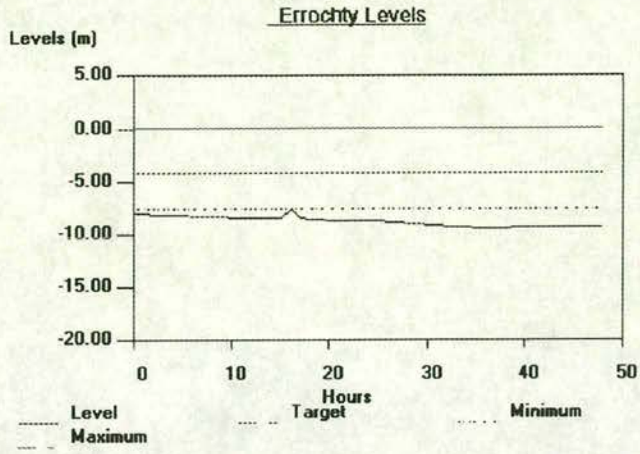

Garry Levels
Levels (m)
2.00
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
0
10
20
30
40
50
Hours
Level
Target
Minimum
Maximum

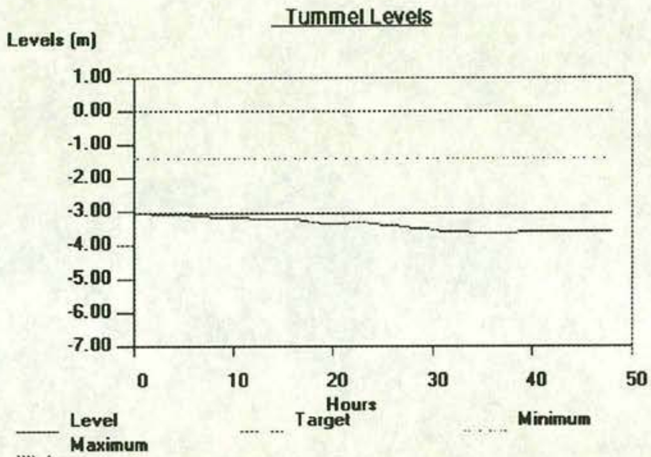

Ericht Levels
Levels (m)
2.00
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
0
10
20
30
40
50
Hours
Level
Target
Minimum
Maximum

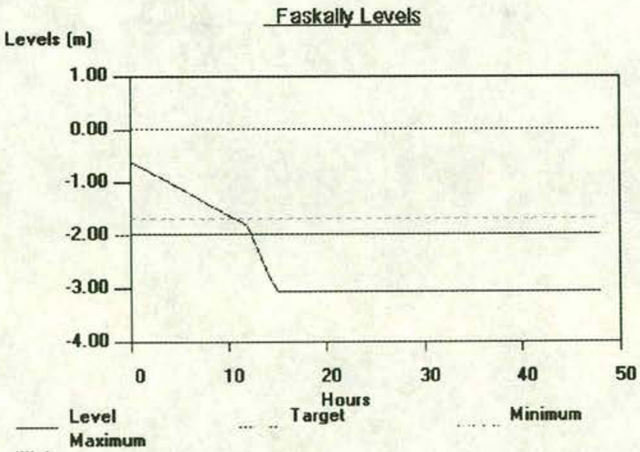

Eigheach Levels
Levels (m)
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
0
10
20
30
40
50
Hours
Level
Target
Minimum
Maximum


Rannoch Levels
Levels (m)
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
0
10
20
30
40
50
Hours
Level
Target
Minimum
Maximum


Dunalastair Levels
Levels (m)
0.50
0.00
-0.50
-1.00
-1.50
-2.00
0
10
20
30
40
50
Hours
Level
Target
Minimum
Maximum


Errochty Levels
Levels (m)
5.00
0.00
-5.00
-10.00
-15.00
-20.00
0
10
20
30
40
50
Hours
Level
Target
Minimum
Maximum


Tummel Levels
Levels (m)
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
0
10
20
30
40
50
Hours
Level
Target
Minimum
Maximum


Faskally Levels
Levels (m)
1.00
0.00
-1.00
-2.00
-3.00
-4.00
0
10
20
30
40
50
Hours
Level
Target
Minimum
Maximum

A8.1.3 Scenario Log

Date : 19/06/96; Time : 13:33:05
Scenario Run for : Tummel Scheme in CLUNIE Group Tummel Scheme in CLUNIE Group Scenario Timescale : 24 Hours in 48 Half_Hourly Increments Initialisation Complete at 13:33:58
Scenario from Monday at 0700 hrs.
=> Inc. 1 Warning : Monday 0730 hrs. * Loch_Tummel low target level achieved.
=> Inc. 3 Warning : Monday 0830 hrs. * Eigheach Rate of Rise exceeded.
=> Inc. 4 Warning : Monday 0900 hrs. * Eigheach Rate of Rise exceeded.
=> Inc. 5 Warning : Monday 0930 hrs. * Eigheach Rate of Rise exceeded.
=> Inc. 6 Warning : Monday 1000 hrs. * Eigheach Rate of Rise exceeded.
=> Inc. 7 Warning : Monday 1030 hrs. * Seilich Minimum Level reached. * Eigheach Rate of Rise exceeded.
=> Inc. 8 Warning : Monday 1100 hrs. * Eigheach Rate of Rise exceeded.
=> Inc. 9 Warning : Monday 1130 hrs. * Seilich low target level achieved. * Eigheach Rate of Rise exceeded.
=> Inc. 10 Warning : Monday 1200 hrs. * Eigheach Rate of Rise exceeded.
=> Inc. 11 Warning : Monday 1230 hrs. * Eigheach Rate of Rise exceeded. * Faskally Minimum Level reached.
=> Inc. 12 Warning : Monday 1300 hrs. * Eigheach Rate of Rise exceeded.
=> Inc. 13 Warning : Monday 1330 hrs. * Eigheach Rate of Rise exceeded. * Faskally low target level achieved.
=> Inc. 15 Warning : Monday 1430 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. (On priority running.) 2.Clunie Station increased to 40.8 MW. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable.
=> Inc. 16 Warning : Monday 1500 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. (On priority running.) 2.Clunie Station increased to 40.8 MW. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable.

Scenario (continued)
=> Inc. 17 Warning : Monday 1530 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. (On priority running.) 2.Clunie Station increased to 40.8 MW. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable.
=> Inc. 18 Warning : Monday 1600 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. (On priority running.) 2.Clunie Station increased to 40.8 MW. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable.
=> Inc. 19 Warning : Monday 1630 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. (On priority running.) 2.Clunie Station cannot be changed. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable.
=> Inc. 20 Warning : Monday 1700 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. (On priority running.) 2.Clunie Station cannot be changed. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable.
=> Inc. 21 Warning : Monday 1730 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. (On priority running.) 2.Clunie Station cannot be changed. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable.
=> Inc. 22 Warning : Monday 1800 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. (On priority running.) 2.Clunie Station increased to 40.8 MW. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable.

Scenario (continued)
=> Inc. 23 Warning : Monday 1830 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. (On priority running.) 2.Clunie Station increased to 40.8 MW. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable.
=> Inc. 24 Warning : Monday 1900 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. (On priority running.) 2.Clunie Station increased to 40.8 MW. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable.
=> Inc. 25 Warning : Monday 1930 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. (On priority running.) 2.Clunie Station increased to 40.8 MW. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable.
=> Inc. 26 Warning : Monday 2000 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. (On priority running.) 2.Clunie Station increased to 40.8 MW. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable.
=> Inc. 27 Warning : Monday 2030 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. (On priority running.) 2.Clunie Station increased to 40.8 MW. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable.
=> Inc. 28 Warning : Monday 2100 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. (On priority running.) 2.Clunie Station increased to 40.8 MW. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable.

Scenario (continued)
=> Inc. 29 Warning : Monday 2130 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. (On priority running.) 2.Clunie Station increased to 40.8 MW. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable.
=> Inc. 30 Warning : Monday 2200 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. (On priority running.) 2.Clunie Station increased to 40.8 MW. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable.
=> Inc. 31 Warning : Monday 2230 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. (On priority running.) 2.Clunie Station increased to 40.8 MW. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable.
=> Inc. 34 Warning : Tuesday 0000 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. 2.Clunie Station cannot be changed. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable.
=> Inc. 35 Warning : Tuesday 0030 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. 2.Clunie Station cannot be changed. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable. * Eigheach Rate of Rise exceeded.
=> Inc. 36 Warning : Tuesday 0100 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. 2.Clunie Station cannot be changed. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable. * Eigheach Rate of Rise exceeded.

Scenario (continued)
=> Inc. 37 Warning : Tuesday 0130 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. 2.Clunie Station cannot be changed. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable. * Eigheach Rate of Rise exceeded.
=> Inc. 38 Warning : Tuesday 0200 hrs. * Faskally is a drying reservoir, attempts to prevent the problem are: 1.Trinafour Station cannot be changed. 2.Clunie Station cannot be changed. 3.Pitlochry Station cannot be changed. (On priority running.) The problem is unavoidable. * Eigheach low target level achieved. * Eigheach Rate of Rise exceeded.
=> Inc. 39 Warning : Tuesday 0230 hrs. * Eigheach Rate of Rise exceeded.
=> Inc. 44 Warning : Tuesday 0500 hrs. * Dunalastair high target level achieved.
Scenario Run complete at 13:38:14

A8.1.4 Scenario Log Summary

Performance Summary is as follows :
RESERVOIR LEVELS:
Seilich levels :
Minimum: -4.27m; Target: -2.14m
Initial: -1.97m; Final: -2.69m
Garry levels :
Minimum: -9.14m; Target: -3.14m
Initial: -5.04m; Final: -5.13m
Ericht levels :
Minimum: -9.45m; Target: -3.25m
Initial: -3.75m; Final: -3.75m
Eigheach levels :
Minimum: -6.10m; Target: -3.05m
Initial: -2.52m; Final: -3.07m
Rannoch levels :
Minimum: -2.44m; Target: -1.22m
Initial: -0.88m; Final: -0.81m
Dunalastair levels :
Minimum: -2.00m; Target: -0.68m
Initial: -1.40m; Final: -0.61m
Errochty levels :
Minimum: -15.24m; Target: -4.20m
Initial: -8.14m; Final: -9.37m
Loch_Tummel levels :
Minimum: -6.10m; Target: -3.05m
Initial: -3.04m; Final: -3.61m
Faskally levels :
Minimum: -3.05m; Target: -1.99m
Initial: -0.63m; Final: -3.05m
GENERATION LEVELS:
Individual PS generation:
Cuaich share: 47.5 MWh
LochEricht share: 18.7 MWh
PS_Rannoch share: 408 MWh
Gaur share: 54.4 MWh
PS_Tummel share: 0 MWh
PS_Errochty share: 787.5 MWh
Trinafour share: 9.5 MWh
Clunie share: 693.6 MWh
Pitlochry share: 270 MWh
Generation for Tummel Scheme:
Total production : 2289 MWh
Production required : 1988 MWh

GLOSSARY

(Entries are in the order that they first appear in the text.)

OTEC - Ocean Thermal Energy Conversion........20
MW - Megawatt (1 million Watts)........20
GWh - GigawattHour (1000 million Watt-hours)........20
EdF - Electricité de France........20
PU - Power Utility........20
kW - kilowatt (1000 Watts)........22
CEGB - Central Electricity Generating Board........27
SSEB - South of Scotland Electricity Board........27
NSHEB - North of Scotland Hydro-Electric Board........27
ESI - Electricity Supply Industry........28
WM - The Water Manager........29
SHE - Scottish Hydro-Electric plc........29
SP - ScottishPower........32
NP - National Power........32
PG - PowerGen........32
NGC - National Grid Company........32
RECs - Regional Electricity Companies........32
CCR - Central control room........34
OFFER - Office of Electricity Regulation........34
CE - Control Engineer........34
LE - Loading Engineer........34
DAE - Day Ahead Engineer........34
OIC - Official in Charge........34
SCADA - System Control And Data Acquisition........34
MVAr - MegaVolt-Amperes (reactive)........35
LF - Load Factor........38
LDC - Load Duration Curve........39
PE - Potential Energy........45
KE - Kinetic Energy........45
PS - Power Station........50
PLC - Programmable Logic Controller........51
PDF - Probability Density Functions........52

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EXPERT SYSTEM MANAGEMENT of CASCADED HYDRO-ELECTRIC SCHEMES

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ABSTRACT

The presence of large-scale hydro electric plant in mixed-fuel generation systems provides electricity generators and regional electricity companies with a flexible low-cost energy resource. Potential energy may be stored in the impounded water and converted to electrical energy at short notice. Unfortunately the utility of the stored energy reserve is reduced by the effects of climate, the hydrology of the catchment, the commercially established demand for electricity and the competing price of strategically attractive fuels. Further, since the availability of hydro resources varies daily and seasonally, while the demand for power varies hourly, careful water resource management is required to ensure optimum operation of the system.

This paper describes the development of an expert system which assists in the optimal scheduling of hydro plant based on water and energy management of complex cascaded systems.

1. INTRODUCTION

Scottish Hydro-Electric plc (SHE) is one of six major UK power companies. Being vertically integrated, SHE generates, transmits, and distributes electrical energy in the North and Central regions of Scotland. The operation covers a total area of approximately 54,400 square kilometres of predominately rural countryside. Within this area, SHE has over 49,000 kilometres of transmission and distribution circuits normally supplying a demand of around 1500 MW of electricity to almost 600,000 customers[1][2]. In order to meet the consumer energy demand SHE, either through direct ownership of generating stations or under contract, has access to a mix of nuclear, coal fired, dual oil/gas fired, conventional hydro and pumped storage generation up to a total capacity of 3240 MW. Up to 40% of Scotland's energy requirements are met by the conventional hydro-electricity generation, provided by 33 hydro systems mostly within 8 major schemes, consisting of 76 reservoirs and 54 power stations with a total installed capacity of 1025 MW. Control of all these hydro-electric power stations is undertaken by two production group control centres at Dingwall and Clunie. The Dingwall Control Centre controls the northern area incorporating the Shin, Conon, Affric-Beauly, Garry-Moriston and Foyers schemes while the Clunie Control Centre controls the southern schemes of Tummel, Breadalbane and Sloy-Awe.

To operate the hydro system with hydrological efficiency and yet retain the commercial advantage of the energy source, the control engineers within the groups have the dual role of electricity generator and water manager. Optimisation of generation revenue is paramount, but on occasion avoiding spilling or draining a reservoir may be more important than the inopportune generation of electricity. It is thus necessary to manage electricity production and water storage on a daily, weekly, monthly and annual basis

2. ENERGY MANAGEMENT

Either in response to predictions of consumer demand or as a result of successful energy trading, engineers in SHE Central Control Room at Port-na-Craig, Pitlochry schedule generation from all hydro and other forms of plant. In association with the hydro groups a Dispatch Schedule is formed taking account of any system limitations or hydro power station restrictions. The groups allocate generating limits to their individual power stations in the form of a generation profile. For each power station, the required output, in MW, is listed for every half-hourly increment during the period of a week, (i.e. each station has 336 slots of scheduled generation allocation).

Unfortunately, once the Dispatch Schedule has been produced, it may be have to be changed with little notice. An overall power balance must be maintained, matching generated output to system demand. Consumer demand changes hourly, daily and yearly due to various environmental and social factors, while available generation capacity may alter in accordance with the planned loading schedule or suddenly change due to transmission system or plant failure.

Due to the variations in load, there are peak periods during the day that require considerably more connected generating capacity than others. At these "peaks" or priority times the price for electricity is high reflecting the RECs need to purchase energy. During "troughs" in demand the price is correspondingly lower. The day is sectioned into eight time periods covering these peaks, troughs and periods of intermediate demand. The start time and length of these periods can vary as the shape of the demand curve changes for different seasons and days of the week. Having met base load demand it is obviously commercially preferable to dispatch peak-load and high intermediate-load plant at peak periods. Thus in a trading week there are periods where hydro plant must be accorded a higher priority in the dispatch schedule than at other times.

Large nuclear and thermal power stations are usually dispatched as base- and low-intermediate load stations. Traditionally hydro plant has been used as high-intermediate load capacity, and its fast access times commend its application to meeting short term demands with economic efficiency. Consequently at any time during the day the hydro generation programme may be altered as the stations are dispatched or shut down to meet anticipated increases or reductions in demand. As a result the whole process of rescheduling becomes a continuous task where it is often the case that the allocation of hydro generation is in response to the commercial opportunities arising in the energy marketplace. Optimum scheduling of plant relies heavily on the experience and estimating capabilities of key personnel to quickly determine the effect on the water system should the status of any hydro power station be changed.

3. WATER MANAGEMENT

Electrical energy is consumed the moment it is created and cannot be stored on a commercially viable basis. However, since stored water has the potential to release kinetic and pressure energy on demand, an important function of the Hydro Groups is the management of stored energy in the SHE reservoirs. The optimisation of revenue from hydro generation requires SHE to ensure that energy stored as water does not become wasted by spillage or fail to attract its highest market value by generating unnecessarily when electricity demand and prices are low. Furthermore, since the reservoir water levels and river flows form part of the natural environment, SHE must ensure that any generation by a hydro station does not upset the balance. Consequently it is vitally important that SHE schedule their water resources in conjunction with required generation (and vice versa), to produce an environmentally and economically sound Dispatch Schedule.

The management of an individual reservoir and power station is relatively simple, where the water discharged through the power station, together with historical hydrological data of the catchment are used to calculate dynamic changes in level, energy storage and volume of the reservoir. Maintaining this balance becomes more complicated in a cascade system, where the water throughput of one power station feeds into the reservoir of another, thus to control the water flows, the control engineers must have an expert understanding of the hydraulic dynamics of individual and interconnected reservoirs.

The scheduling of hydro plant relies heavily on the accumulated operating experience of the engineers who have recourse to large amounts of data describing the current status of the system together with records describing the history of operation. There is also a higher level of knowledge that the engineers draw on which is based on their instinct and the ability to forecast from experience, what the likely outcome of a decision or schedule will be. With training and experience the operating skills are slowly transferable, but the ability to be able to forecast or practice insight is a highly personal skill which takes considerably longer to build up.

Expert systems have been applied successfully to other system control and managerial processes to support the decisions as they are made and to allow the testing of prospective system settings. In addition such systems allow the recording and transfer of experience and operating skills to other staff.

A **Water Manager (WM)** Decision Support System has been developed with SHE which contains system detail and operator-based knowledge, and has the capacity to assist the control engineers to utilise hydro resources to advantage by:

1) determining the most advantageous operating regime,
2) using and maintaining up-to-date operational information,
3) taking due account of all hydrological factors and variables,
4) ensuring all environmental constraints are adhered to,
5) calculating and testing the best course of action to take for any possible change in the operating regime.

The remaining sections of this paper describe some of the features of the system and the processes employed in the expert system shell.

4. RESERVOIR DYNAMICS

Consider a simple hydro system consisting of a reservoir of rectangular area and straight vertical sides, one power station constantly feeding water into, and a second power station constantly being supplied from, the reservoir. To assess the effective operation of this system, it is essential to calculate the water level, or change thereof. In this case the level calculation is simply:

$$\text{Res. Level} = \frac{(\text{inital volume} + \text{inflow volume} - \text{outflow volume})}{\text{reservoir area}}$$

Naturally occurring reservoirs are not standard geometric shapes, generation and associated water flow does not remain steady and there are environmental and physical factors which can affect the change in water level. The hydrological characteristics of the reservoir must be examined to establish the effect on the reservoir level, of various known and predicted hydrological factors and full, partial or zero generation at any associated power station. A reservoir is subjected to a number of inflows and outflows, each constantly changing and independently of each other as shown in Figure 1.

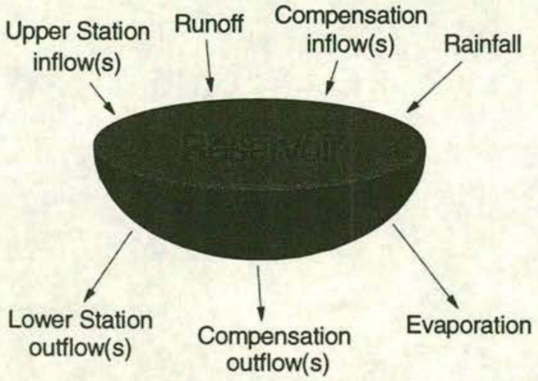

Figure 1 - Reservoir Dynamics

In the case of SHE reservoirs, these operational variables are:
(i) Inflow from upper power stations (Controlled by SHE),
(ii) Outflow from lower power stations (Controlled by SHE),
(iii) Runoff from the surrounding catchment (weather dependent),
(iv) Rainfall and Evaporation (weather dependent),
(v) Compensation inflow/outflow (Decreed by Govt or local By-laws).

There are frequently changes in (iii) and (iv) to which SHE must react and (i) and (ii) are adjusted to maintain the water levels in all reservoirs and rivers, subject to the prescriptions in (v). The levels in reservoirs and rivers are the measurable variables which effective water management seeks to maintain. This requires a knowledge of the effects of, and the ability to control, the water flow through the infeed and outflow power stations taking due account of the other environmental factors and the effect on interlinked reservoirs.

5. RESERVOIR VARIABLES

For any single reservoir within the SHE system, the following data is used in the water management of the system, in some cases using historical data.

Storage and Volume

The reservoir volume in millions of cubic metres (MCM) can be calculated from the topography of the area. Since the change in volume with level tends to be non-linear, "look-up" tables are held by SHE which correlate reservoir level with corresponding stored volume. The head (m) on the turbine and the flow (m^3/sec) from the reservoir determine the power developed (kW). Over an elapsed time the energy converted (kWh) may be related empirically to the volume of water (m^3) discharged in the period. Each reservoir has a characteristic m^3/kWh and the reservoir storage capacity in kWh may be estimated.

Run-off

A fixed value of run-off, nominally in m^3, known as the Long Term Annual Average Run-off (LTAA), is known for each reservoir. This is more usefully calculated in kWh by measuring the generated energy, compensation and intentional spillage over a year to maintain the reservoir level at the level at the beginning of the year.

A monthly average is calculated from the LTAA run-off figure, which is multiplied by a monthly factor to give a value which is classed as the 100% run-off for any particular month. However, depending on the weather and environmental conditions at any particular time, a further percentage is incorporated to produce a total run-off figure.

For example, in a catchment where the LTAA run-off was 1200 kWh the average monthly runoff would be 100 kWh. On the basis of operating experience January might be recognised to contribute more than the average value and be multiplied by a factor of 1.5. Thus 100% run-off for January would become 150 kWh. If the rainfall in a particular year was very heavy and ground absorption was low, then the runoff at the time may be quoted as 200%. Therefore, the total run-off for January of that year in these conditions would be 300kWh.

Due to the extensive data records available to SHE, a more accurate figure, the 10-year average runoff in millions of cubic metres (MCM), can be used. This consists of a monthly volume per reservoir, averaged over a rolling 10 year period. However, this figure may also be subject to the latter multiplication factor described above.

Weather

The local rainfall/evaporation effects on any reservoir are generally unpredictable, but these must be taken into account in any computation of reservoir dynamics. Several methods have been devised to model the evaporation from large volumes of water, however, each tends to be site specific depending largely on the geographical relief and ambient conditions[3]. Since this would entail a major study of all reservoirs in the SHE area, and because there are sufficient historical run-off data, the effect of the meteorological conditions is implemented simply by adding or subtracting an appropriate percentage of the total run-off to account for the weather. Although this approximation is very general, it is used to make the reservoir dynamics model weather dependent.

Generation Inflow and Outflow

The generation flows are simply calculated by multiplying the relevant turbine throughput (m^3/kWh of storage) by the output power of the turbine in kW (from the generation profile of each station) and by the time of operation at that power.

Compensation and Freshet

Each reservoir may have a fixed value of compensation inflow or outflow to maintain the appropriate river flow. This tends to be constant over a week, but may change with season.

Levels

Using the above data, and knowing their effect, the variation in reservoir level can easily be calculated for a given time period. The new level can then be compared with a number of fixed or variable levels which define the course(s) of possible action that should be taken by the control engineers to ensure correct water management. These benchmark levels are[4]:

Maximum or Spill Level at which the water in the reservoir would begin to spill over the edges or through a spillway, wasting valuable resources and possibly flooding the adjacent area.

Target Level is the control engineers' preferred level such that the best use of the run-off can be exploited. This level is estimated by taking account of all foreseen outages of generation plant, predicted system load and average monthly run-off.

Maximum and Minimum Normal Levels within which the controllers endeavour to keep the reservoir, (these may vary with season or for operational reasons).

Minimum Duty Level is the minimum level that the reservoir should be allowed to fall to, whilst retaining enough water for emergency generation and compensation flow.

Rate-of-change of levels

A further operational constraint on any reservoir is the rate-of-rise or rate-of-fall of water level over a fixed time period, (i.e. hour or day). This is particularly important where a reservoir is used by the public, since while a gradual change in water level goes unnoticed, a fast change can cause problems e.g. grounding of boats, inundation etc.

6. CASCADED HYDRO SYSTEMS

The reservoir dynamics model was originally developed using the Quoich-Garry cascade system in the Garry/Moriston Scheme. The scheme is one of the simplest serial cascade systems comprising Loch Quoich supplying a head of water to Quoich power station which in turn feeds into the Loch Garry/Invergarry Power Station system, as shown in Figure 2.

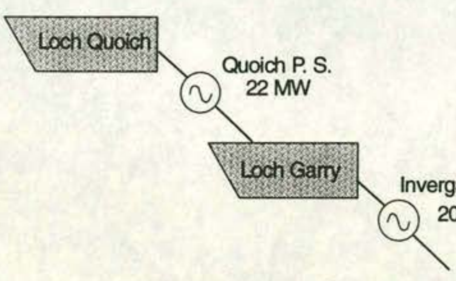

Figure 2 - Serial Cascade: Quoich/Garry Cascade

Although the dynamics of a serial reservoir and power station are relatively simple, cascaded schemes with a combination of multiple reservoirs, rivers and power stations become much more complex since the level of each reservoir, or power station output, relies heavily on the reservoir dynamics of upper and lower systems.

The nature of the cascade system is complicated further by a phenomenon known as the reservoir time constant, which is defined as the time taken for inflow entering into the reservoir to be experienced at the other end or outflow. Due to the large distances between dams/weirs, a large volume of water through one reservoir may not arrive at the downstream end of the reservoir until several hours later. Similarly there is another, longer, time constant relating the time taken for rainfall over a catchment area to run off and produce a rise in level.

Finally, since in any cascade system water flows from higher reservoirs down through the system to the lower reservoirs, the tendency is to analyse the upper reservoir dynamics then assess the effect on the next reservoir down, repeating this lower in the system. However in the complex SHE schemes, the upper reservoirs may be in isolated areas whereas the lower reservoirs are within populated recreational areas where rapid level changes and extreme levels would be intolerable. Thus the highest priority reservoir may be in the middle of the cascade whilst the lowest priority is at the highest point of the cascade. Therefore, the analysis of the dynamics needs to be done in order of priority, to ensure stable operation of the most important reservoirs first. While in most cases this difference in approach has no bearing on the flows, in moments of crisis it is has a significant influence on the outcome.

However, since most of the SHE Schemes do not form serial cascades, the Water Manager Decision Support System has been developed to represent any scheme with multiple reservoirs, power stations and in some cases weirs in series/parallel combination. Figure 3 shows one such scheme - The Tummel Valley.

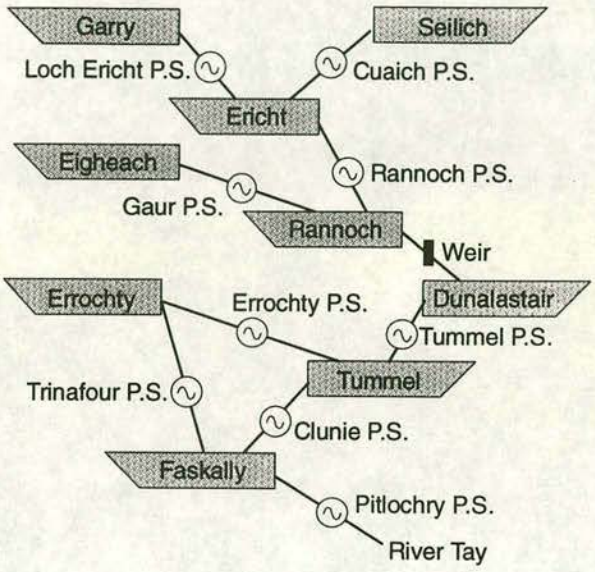

Figure 3 - Tummel Valley Scheme

The model determines the change in all reservoir water levels taking account of availability and limitations on generation, variable environmental conditions, the interrelation between hydraulically linked reservoirs and reservoir priority.

7. THE EXPERT SYSTEM SHELL

Several programming environments were investigated[5][6], but, due to the advantages stated below, the KAPPA-PC application software was ultimately chosen for the program development.

KAPPA-PC™ is a Windows-based expert system shell incorporating rule based reasoning, together with an object oriented programming (OOP) environment and procedural language, KAL, which allows user developed functions to be created. OOP is a technique in which the possible behaviours of a data structure (object) are defined as attributes of that object. An object oriented programme is therefore simply a collection of objects, each containing two basic kinds of information: that which defines the object (attributes) and that which specifies what the object can do (methods)[7]. Thus OOP is ideally suited to this type of application where major components, e.g. reservoirs, can be defined as objects with several common attributes such as volume, storage etc.

KAPPA-PC also provides an easy to use graphical interface for software development, together with a graphical communication appearance that gives the operator of the program a user friendly, easily accessible and versatile visual interface, incorporating various images such as windows, buttons, dialogue boxes, etc. Finally, the Windows environment gives KAPPA-PC an excellent application compatibility which provides easy access to database spreadsheets and text files, as shown in Figure 4.

In KAPPA-PC objects are created using a class, sub-class, instance structure, e.g. Reservoirs, Tummel Reservoirs, Rannoch Reservoir. Instances have attributes (slots) which can be common to all instances of the class, although these are made local for each instance, e.g. all reservoirs would have a minimum level, but, each particular reservoir would have a different minimum level. Further, during processing, the methods attached to objects are activated by messages passed to the object, either by procedural code or as a result of rule processing.

The structure of rule based reasoning is based upon the IF-THEN construct where statements following an IF are known as the premises and statements following a THEN are known as the conclusions. For example:

IF the reservoir is spilling;
OR the reservoir is draining;
THEN change generation;

The process used in this particular development is called Forward Chaining which proceeds from premises toward a conclusion or Goal. In this case the Goal may be *Can the reservoir problem be eliminated?* Should the problem persist once a station generated output has been changed, the rules determine the next appropriate action, and so on until the problem is solved or no practical solution can be found.

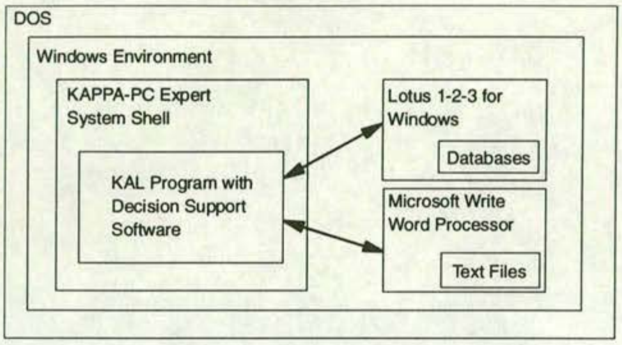

Figure 4 Program Operating System

8. The WATER MANAGER

The Water Manager has the following presentation and operational features:

❶ a user-friendly graphical interface.
❷ an on-line help system.
❸ ability to install (or delete) and model any cascaded hydro scheme utilising a flexible serial/parallel hydraulic interlinking system.
❹ dialogue boxes within which the user can view and update reservoir, station and weir data attributes.
❺ easy access to associated application software, i.e. Lotus 1-2-3 and Microsoft Write.
❻ determines the best generation profile by optimal scheduling of all hydro stations, taking account of priority time slots, target levels, station set availability and limiting conditions.
❼ runs a scenario of operation for any scheme given the following information: start-time, duration, incremental time, weather conditions, percentage runoff, and data location (internally generated or Lotus database).

Scenario Run

A scenario run determines the change in reservoir levels due to the factors discussed previously, then the WM provides:

① a profile of the behaviour of each reservoir, in graphical form, outlining any possible problem that is likely to occur. Should any reservoir level reach the maximum or minimum limits, the decision support will attempt to alleviate the situation and report the required avertive actions.
② an annunciator screen to display the state of all reservoirs, indicating if and when a reservoir level reaches any of the benchmark levels or exceeds the maximum rate-of-rise or rate-of-fall.
③ a record and on screen log display of all level indicators, support decisions and a summary of reservoir levels and station generation.
④ at the end of a scenario run, the contents of the log are automatically downloaded into a numbered/dated text file.

Decision Support

The decision support software includes a great many rules which reason towards the goal of preventing a reservoir spilling or draining. For example, if a reservoir was about to spill there are five possible actions:

Reduce generation from an upper station.
Increase generation at a lower station.
Raise an upper weir.
Drop a lower weir.
No change

These are prioritised to ensure that the most flexible item is changed first. e.g. some stations must operate at the same output throughout the day to prevent altering the natural flow of a river thereby creating an environmental disturbance. The consequences of a change to the operating regime will obviously affect the dynamics of the connecting upper or lower reservoir(s). As previously mentioned, reservoirs are prioritised to the extent that if a reservoir is about to spill to save another adjoining reservoir, then the lower priority reservoir would be left to suffer the consequences. Although this situation rarely arises, in extreme cases the option has to be considered.

Thus during a scenario the decision support system will indicate and record the appropriate action to take to prevent spillage or draining of reservoirs. It would also automatically change the generation profile if appropriate. These changes can then be reincorporated and the scenario rerun to ensure no further problems are likely to occur.

9. CONCLUSION

Using the appropriate application software, operational expertise, and decision-based logic it has been possible to write and install software which embodies the experience and thinking processes of water management and generating plant despatch. One such system, the **Water Manager** has been developed, and is currently being evaluated by Scottish Hydro-Electric control engineers to combine the dual aspects of their operation - the need to generate and the management of water

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