Theses

The Environmental Effects of Hydroelectric Power in Arctic Scandinavia.

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Declaration.

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Abstract.

There are many benefits from waterpower; demand for electricity, for example, is not constant, it fluctuates not only seasonally but daily, and even hourly. Hydropower generators are far more flexible than other sources of electricity and can respond to such variations. Furthermore, no direct environmental pollution is caused by a hydroelectric system, there is no fuel cost, and no consumption of natural resources that are irreplaceable and essential for other purposes. This said, in recent years, the significant adverse environmental effects of large hydro projects are being identified as a cause for concern. These environmental effects, both geomorphological and hydrological, are discussed using examples from six Arctic Scandinavian rivers. Statistical relationships between supply and demand of all energy, and potential developments of hydroelectric supplies are presented. Nevertheless, although there are many problems associated with hydropower developments a great deal of research is currently investigating the ways in which these effects can be mitigated. The question still remains as to whether the benefits of the increasing use of hydropower justify the inevitable disruption of the Arctic environment.

Acknowledgements.

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1. Introduction

'Dams have played an integral role in human development since antiquity. Yet the context for decision-making is clearly changing from a predominantly economic and technical focus to approaches more broadly centred on sustainable development' (Clarke, 2000; 1). Hydropower is a proven technology, harnessed worldwide for over two thousand years. The greatest attraction of hydropower in the modern world is that 'water-wheels, though one of the earliest known methods of power production, [are] still today the best of all methods as regards economy, efficiency, cleanliness, reliability, and inexhaustibility' (Halacy, 1977; 39).

Water wheels are a traditional method of grinding grain throughout much of the world, but later played a major role in the modernisation and industrial development of Europe and North America (Curtis, 1999). In the early 1800s, North American and European factories used the water wheel to power machines. These first, simple water wheels pick up flowing water in circumferencial buckets. The weight of the water then causes the wheel to turn, converting the natural kinetic energy of water into mechanical energy. The mechanical energy may then be used to grind grain, drive sawmills, pump water or several other functions. In the late 19th Century, technology developed and the force of falling water was used to generate electricity. The earliest major large-scale hydroelectric power station was built at Niagara Falls in 1879.

Prior to about 1920 water power sites were usually developed for one of two purposes. The first of these was to supply electricity to specially established industries; usually metallurgy or electrochemical, in which the cost of power represented a large proportion of the total cost of the final product. Since the commercial success of such industries depended upon electricity at the lowest possible cost, it was advantageous to operate the plant at the highest practicable annual load; therefore the industry was usually brought to the power station to avoid transmission and conversion losses. Moreover, since the manufacturing processes were generally of continuous character it was necessary to provide, as far as practible, a uniform power supply during the whole year (Brown, 1958; 36). The stations thus operated near 100% of capacity. The second purpose of water power schemes was to provide electricity to a local community for general industrial and domestic use. Public supplies of this character are normally used by the consumer to suit his own convenience, and where the cost is not a significant item in the total cost of production its use was conditioned by considerations of public convenience. The result was that demand over a large part of the 24 hours was relatively low. Moreover, in temperate climates, owing to the seasonal variations in temperature and daylight hours, there were large differences in the demand between summer and winter. Power stations providing public supplies of this character commonly operated at annual load factors of between 30 and 40 %. Water power sites are therefore developed to meet the special needs and characteristics of variable demands (Bernes, 1996).

In the following decades many more hydroelectric stations were built. By the middle of the 20th Century almost all the best sites for big dams had been used. At this time it was recognised that the standard of living enjoyed by a community is closely related to the amount of power which it consumes. Since it is 'the aspiration of every government to raise the living standards of people, not only for the sake of their individual well-being but also in order to increase their security as a nation' (Brown, 1958; 39), extensive developments of power resources occurred. In many countries this included the development of local hydropower resources which had been previously neglected. In this period fossil fuel stations, many of which could make electricity more cheaply than hydro plants, and could therefore under price the smaller hydroelectric plants, were also constructed. It was not until the great variations of price and availability of hydrocarbons during the 1970s that a renewed interest in hydropower developed.

There are many benefits from waterpower. No direct pollution of air or water are caused by a hydroelectric power plant. There is no fuel cost, and no consumption of valuable natural resources that are irreplaceable and needed for other uses. Waterpower is constantly recycled, 'driven by the huge solar power plant of evaporation, precipitation and run-off' (Halacy, 1977; 48). This said, in recent years, the adverse environmental effects of large hydro projects are being identified as a cause for concern and it is consequently becoming increasingly difficult for developers to build new dams because of opposition from environmentalists and people living on the land to be flooded.

It is due to this increased awareness of the adverse effects of hydropower, and the continuing need for more energy production, that I aim a to examine the potential damage caused by hydropower stations. In chapter 2 the role of hydropower today, both globally and in northern regions is discussed. Chapter 3 examines the varying types of hydropower plants used in differing circumstances worldwide. Chapter 4 then introduces the rivers used as case studies throughout the assessment of the effects of hydropower plants on the environment discussed in chapter 5. A quantitative assessment of some of the effects of hydropower development in Scandinavia, and the discussion of a Geographical Information System developed to assess the hydropower potential of rivers is then covered in Chapter 6. Finally, chapter 7 examines the potentials for alternative sources of energy and possible methods of mitigating current problems in modified river systems.

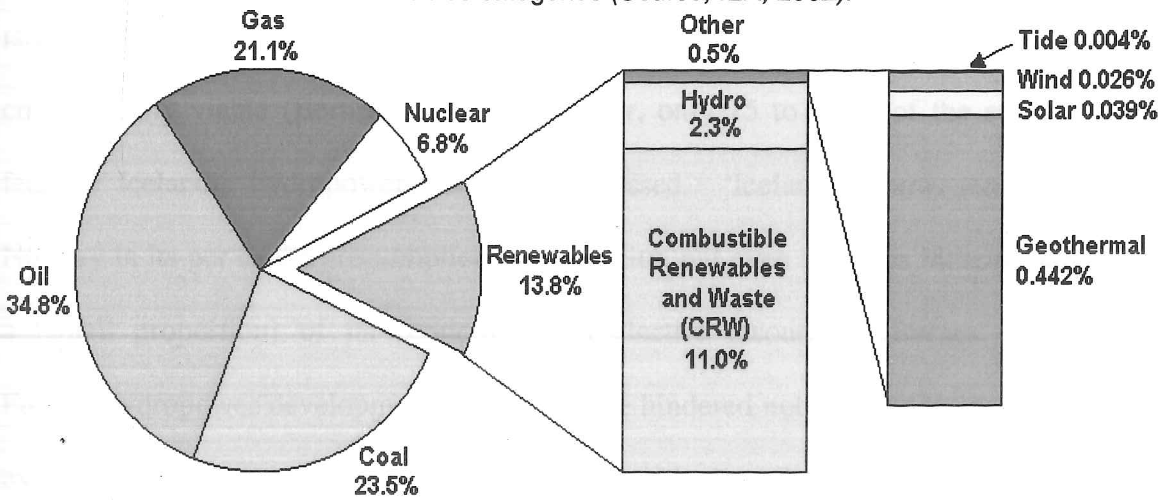
2. The Role of Hydropower

2.1. Introduction

Traditionally, hydropower has been one of the least expensive sources of electricity (Brower, 1992), but its importance is not purely a product of the quantity of energy produced. Hydropower also plays a crucial role in balancing the fluctuation of production and consumption of energy. A major component of electricity generated by hydropower is used as regulation energy, because 'it can be regulated easily, quickly and, above all, economically' (Kemijoki Oy, 2002). A versatile hydropower plant 'can change production form zero to 100 % and vice versa in a mere ten seconds' (Aula, 1996; 247). This is one attribute which other forms of production lack and is essential as consumption varies hourly, daily and seasonally. Electrical energy generated evenly throughout the year is the base load. In general most communities' electricity supply is met by base load energy, provided by nuclear power and hydrocarbon burning plants. Consumption exceeding this base load production is met by regulation power. The price of regulation energy is higher than that of base load power due to the variable requirements. It is therefore more economical to produce this regulation energy in hydropower plants (Kemijoki Oy, 2002). For these reasons hydroelectric power has always been an important part of the world's electricity supply.

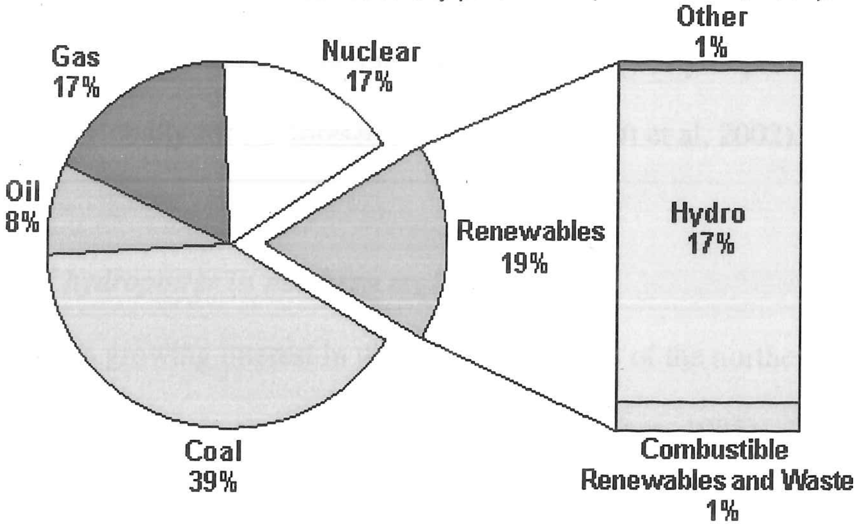
As can be seen from *Figure 1*, in 2000, renewables accounted for 13.8 % of the 115,800 TWh of World Total Primary Energy Supply (TPES) with hydropower only contributing 2.3 % of the world's TPES (IEA, 2002). Although not hugely significant in TPES, renewables (90 % of which is made produced by hydropower) are the second largest contributor to global electricity production. They accounted for 19 % of production in 2000, after coal (39 %) but ahead of nuclear, oil and gas produced power, which contributed 17 % and 8 % respectively *(Figure 2)* (IEA, 2002). Hydropower is currently the world's largest renewable source of electricity, accounting for about 17 % of demand. It provides some 30 countries with their main source of electricity (Brower, 1992). This global hydropower production amounts to about 320 TWh a year; as much as is produced by 40 to 50 nuclear stations, and there is potential to double this contribution (IEA, 2001).

Figure 1: 2000 fuel shares of World Total Primary Energy Supply: with a disaggregation of the share of the main renewables categories *(Source; IEA, 2002).*



The theoretical capacity of the worldwide hydropower is about four times greater than that currently exploited. The actual amount of electricity generated by hydropower will, however, always be much less than the theoretical potential. This is due to the environmental concerns and economic constraints. Much of the remaining hydro potential in the world exists in the developing countries of Africa and Asia. Harnessing this resource would require vast expenditure, as hydroelectric facilities generally are very expensive to construct. In Greenland, for example, it would be technically possible to

Figure 2: Renewable resources in world electricity production *(Source; IEA, 2002).*



generate almost a hundred times more electricity than is currently consumed by the island's population, but the market is so small that large-scale exploitation is not commercially viable (Bernes, 1996). Moreover, only 15 to 20 % of the economically feasible Icelandic hydropower has been harnessed. 'Iceland is now second only to Norway in its per capita consumption of electricity, but even so it has hitherto harnessed a [small proportion] of its economic hydroelectric resources' (Bernes, 1996; 142). Further hydropower developments in Iceland are hindered not by economic concerns but by environmental ones as 'the reputation of Iceland is that of an unspoilt, untouched land with grand natural vistas and clean water and air' (McCormack, 2001; 40). In Norway, Sweden and Finland, increasingly strong opposition to the exploitation of hydroelectric power for environmental reasons began to emerge as early as the 1950s and 1960s. Swedish conservationists were 'incensed at the power companies' plans to encroach on Sarek and other wilderness areas' (Bernes, 1996; 147), and at their desire to dam the major rivers that remained undisturbed. Consequently several of these projects were postponed or abandoned and gradually the pace of expansion slackened. Prediction of the energy demand and supply situation for the future is difficult, but even if scientific developments take place and domestic energy politics change, hydropower will still have an important role globally for the foreseeable future (Bjørtuft et al, 2002).

2.2. The role of hydropower in northern regions

Globally, there is a growing interest in the natural resources of the northern peripheries of Scandinavia, Canada Russia and the United States (Langager, 1985). The circumpolar zone is a 'very extensive and only partly utilised area and its importance is growing all the time while more accessible resources have become exhausted' (Massa, 1985; 476). The technological, political and economic conditions for hydropower stations in the northern rivers developed during the inter-war period and in World War II. Technological advances in long distance, high-voltage transmission of electricity caused hydropower, which formerly had been produced and used locally, to become available much more widely. These technological developments contributed to make increasingly remote hydropower generating sites economically preferable to those situated near the market (Massa, 1985). Due to such changes, nearly 80 % of the total discharge of large rivers in the northern third of the world is now controlled by river regulation (Dynesius and Nilsson, 1994), a figure which is even greater in northern Europe where, in Sweden, for example, 19 out of 20 river systems with a mean annual discharge exceeding 40 m^3s^{-1} are affected by dams and flow regulation (Dynesius and Nilsson, 1994).

In Canada, hydroelectric power is abundant, harnessing more rivers than any other country and supplying 60 % of national electrical needs (Pearce, 1991). Canada is therefore among the leading countries in the world in terms of both installed capacity and per capita production, and nearly half of this capacity is in Québec. Electricity represents about 26 % of all energy consumption in Québec, one of the highest proportions of electrical energy in the world (Massa, 1985). Hydro-Quebec is the second largest provider of electricity in Canada, with a generating capacity of over 25,000 MW. All but 5 % of which is hydroelectric, and 40 %, or 10,000 MW, comes from the Le Grande project in the James Bay region (Raphals, 1992). Furthermore, the James Bay hydroelectric project is the largest in the world. It is anticipated that by 2006 about 28,000 MW of electricity will be generated from 23 power stations built on the three drainage basins which flow into the James Bay and Hudson Bay from the east (Pearce, 1991).

In Russia, energy accounts for approximately 40 % of exports and 13 % of the country's Gross Domestic Produce, making its economy extremely sensitive to global energy price fluctuations. In general, the energy resources reserves of the Soviet Far East are enormous; 'hydropower sites are abundant and widely dispersed' (ZumBrunnen, 1990; 84). About a dozen various hydroelectric stations have been built on the large and small rivers of Siberia. In 1988 waterpower resources of the Soviet North were estimated to be 1,400 TWh, accounting for 37 % of the total USSR hydropower resources (Kudoyarov and Krivonogova, 1988). The annual per capita output of electricity in Siberia at that time stood at 6000 kWh, more than in any other area of the Soviet Union (Ivanov, 1988).

2.3. The role of hydropower in Norway

Norway occupies 323,877 km^2 on the western and northern parts of the Scandinavian Peninsula. Norway is particularly well endowed with the precipitation and the steep gradients on which hydropower depends; the elongated shape of Norway, its vast mountain ranges near the coast and heavy rainfall, when combined with numerous mountain lakes, produced by glacial erosion, provide natural opportunities for hydroelectric storage reservoirs, and therefore the generation of power (Simeons, 1980). The largest of these reservoirs is Røssvatn, having a capacity of 2.36 x 10^9 m^3. Norway was not slow to make use of these favourable conditions. In Hammerfest in the far north, for instance, lighting from hydroelectric sources was installed as early as 1890. Thirty years later, almost two-thirds of the country's population were supplied with electricity, compared with only a sixth in Sweden at that time. The greatest hydropower resources were to be found in comparatively densely populated and industrialized areas of southern Norway (Bernes, 1996). This steady expansion of the hydroelectric program made it possible to establish numerous factories requiring large amounts of power, such as a fertilizer factory at Glomfjord in Nordland, heavy water electrolysis and metalurgy became Norwegian specializations, and allowed a large amount of electricity to be exported to neighbouring countries. More recently, hydropower has become a relatively contentious issue in Norway. In the 1970s, a disagreement flared up over plans to harness the undisturbed Altaelva in the reindeer-grazing country of Finnmark. Despite the criticism, a facility was built which included a storage reservoir with water level fluctuations of up to 65 m. The opposition, primarily from the Saami community and nature conservation organizations, nevertheless emerged from the battle a good deal stronger and, partly for this reason, the expansion of hydropower in Norway, as in all of northern Scandinavia, is now proceeding far more cautiously than a couple of decades ago (Bernes, 1996; 147).

Norway is the 6th largest hydropower producer in the world with total installations of 27,359 MW and a hydropower production of 118 TWh in 1996. In 1999, hydro accounted for 39.1 % of Total Primary Energy Supply, over 5 % greater than that produced by burning hydrocarbons (*Figure 3*) (IEA, 2001). Although only producing around 40 % of TPES by hydropower, is 'without comparison the most important source of electricity in Norway' (Bjørtuft et al, 2002; 7). Norway obtains virtually all the electric power it needs from hydro schemes; about 99.7 % (*Figure 4*). This also equates to the highest global per capita amounts of electricity production and consumption (consumption amounting to 25,882 kWh per capita in 1996), corresponding to its large hydropower resources, major energy-consuming industries, and its cold climate (Bernes, 1996). The world average annual electricity consumption is approximately 2300 kWh per capita (NINR, 2000).

Predictions for Norway's total economic hydropower resources amount to about 180 TWh per year, but only approximately 118 TWh per year of this has so far been exploited (Winther and Hall, 1999). Developments to reduce this difference between production and potential are ever becoming more difficult due to river protection plans since 1973. Furthermore, resources corresponding to around 36 TWh per year; just over half of the reserves currently untapped, have been legally safeguarded against exploitation (Bjørtuft et al, 2002). In Finnmark and Troms, where the potential for further development is fairly limited, up to three-quarters of the potential is protected but in Nordland there 'are still substantial hydropower reserves with no protection at all' (Bernes, 1996). Development plans, licence applications and notifications of interest have been submitted relating to roughly another 10 TWh per year (Bjørtuft et al, 2002).

Figure 3: Norwegian Total Primary Energy Supply, 1973 to 2000 *(Source; IEA, 2001).*
(1 Mtoe = 11.63 TWh)

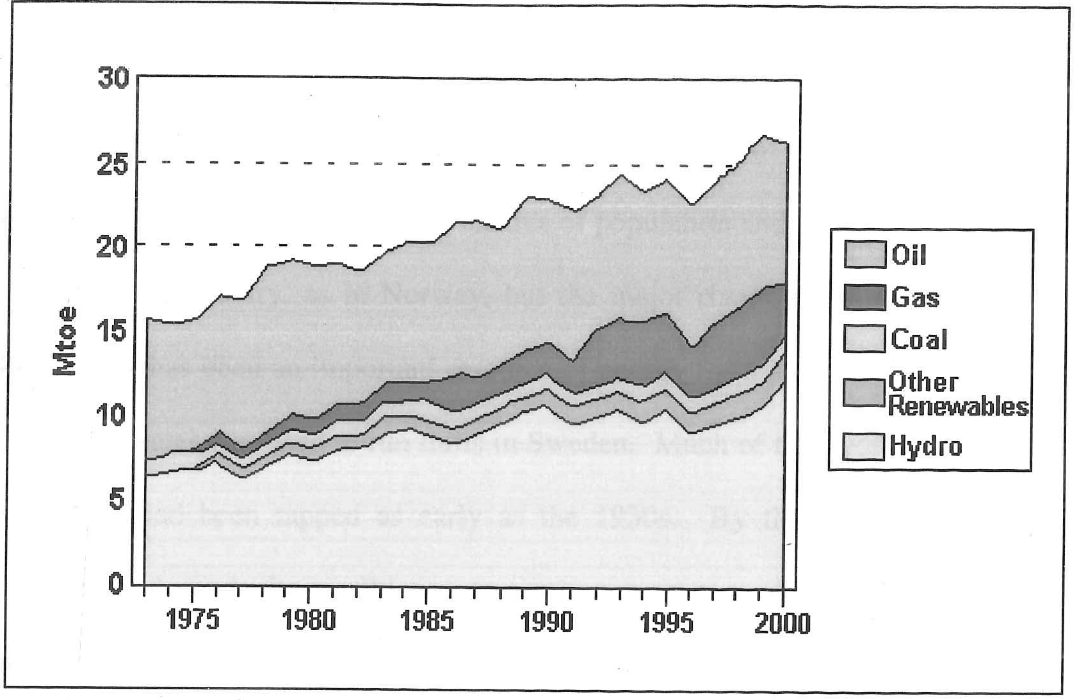
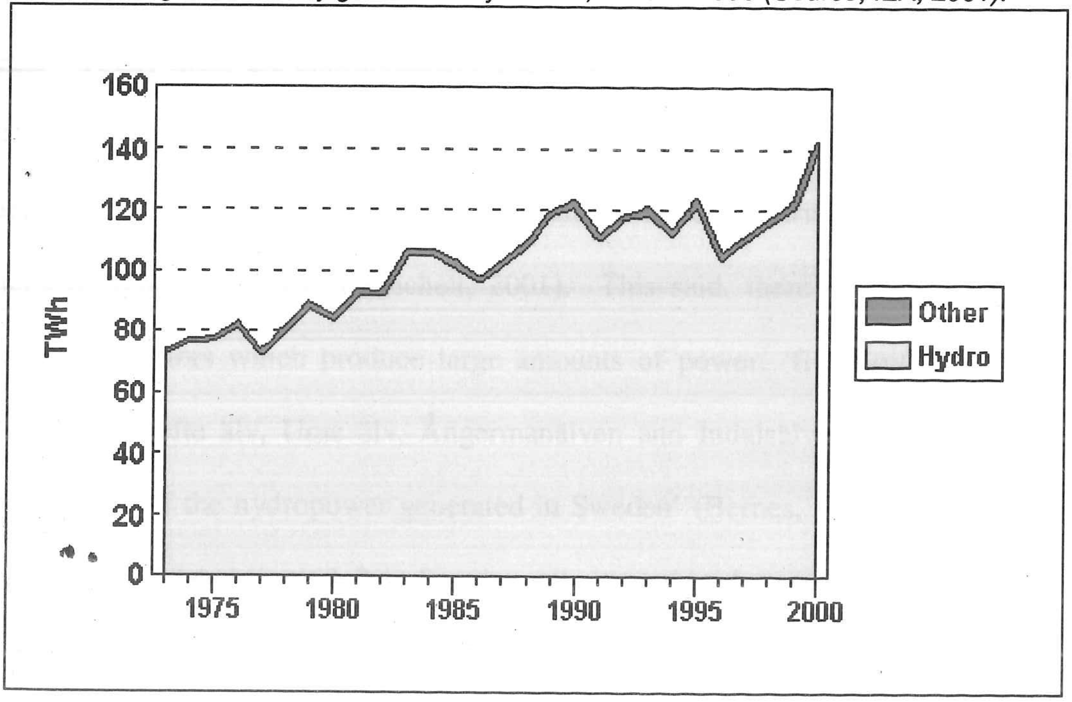


Figure 4: Norwegian electricity generation by source, 1973 to 2000 *(Source; IEA, 2001).*



2.4. The role of hydropower in Sweden

Sweden is the fourth largest country in Europe, with an area 450,000 km^2, extending from the southern Baltic to north of the Arctic Circle (IEA, 2000). Sweden, too, has an abundance of hydropower resources, but here the pattern of their distribution is less favourable than in Norway. The main centres of population and electricity demand are in the south of the country, as in Norway, but the major rivers are in the north (Bernes, 1996). Water has been an important resource of energy for a long time. As early as the 13th Century water was used to run mills in Sweden. Much of the hydroelectric potential of the south had been tapped as early as the 1930s. By then, though, advances in technology had made it possible to transmit power over distances of hundreds of kilometres and thus to utilize the country's waterpower potential much more efficiently. In the ensuing decades, one northern Swedish river after another was exploited, and north and south were linked by a growing number of high-tension transmission cables (Bernes, 1996). 'Today there are approximately 1200 hydropower plants in Sweden' (Weichelt, 2001; 9). The largest stations are situated by the great rivers in the northern part of the country. However, most of the hydropower stations are small, with outputs in the region of tens to hundreds of kW (Weichelt, 2001). This said, there is a small number of northern generators which produce large amounts of power; 'five northern rivers; the Lule älv, Skellefte älv, Ume älv, Ångermanälven and Indalsälven account for almost three-quarters of the hydropower generated in Sweden' (Bernes, 1996; 141). There are only four unregulated rivers left in Sweden, all situated in the north. Only two of these, the Kalix älv and the Torne älv, are large rivers (Beier, 2002). Furthermore, the 'exploitation of waterpower during the last 40 years has involved the disappearance of about 1500 km of streams in Swedish rivers' (Henricson and Müller, 1979; 183).

Sweden produces, annually, a TPES of around 390 TWh. Combustible renewables and wastes account for about 15 %, and hydro about 12 % (*Figure 5*). About 35 % of the Swedish energy supply is imported, mostly as oil (IEA, 2000). Hydropower plays a far greater role in electricity generation than it does in TPES, forming around 50 % of electrical production (*Figure 6*). Sweden is an electricity intensive country, with consumption amounting to almost 144 TWh in 1998. Per capita use of nearly 16,000 kWh in 1997 was the fourth highest in the OECD, after Norway, Iceland and Canada, and nearly double that of other industrialised countries such as France, Germany and the United Kingdom (IEA, 2000). In a normal year, around 150 TWh of electricity is produced in Sweden, almost half of which is produced by hydropower (*Figure 7*). This normally amounts to around 64 TWh, but the annual production varies between 50 TWh and 75 TWh, depending on the precipitation (Jansson, 2002). For instance, in 1977 sources of Swedish energy supply, according to DFE Report N. 13, listed Hydropower as producing only 12 % of the national total (Simeons, 1980). In Sweden, just over 60 % of the economically feasible waterpower has already been developed. For Europe as a whole this figure is about 55 %, and for the whole world, some 15 %. Only Norway (64 %) shows a higher proportion of waterpower utilisation than Sweden (Henricson and Müller, 1979).

Figure 5: Swedish energy production, 1973 to 2010 *(Source: IEA, 2000)* (1 Mtoe = 11.63 TWh)

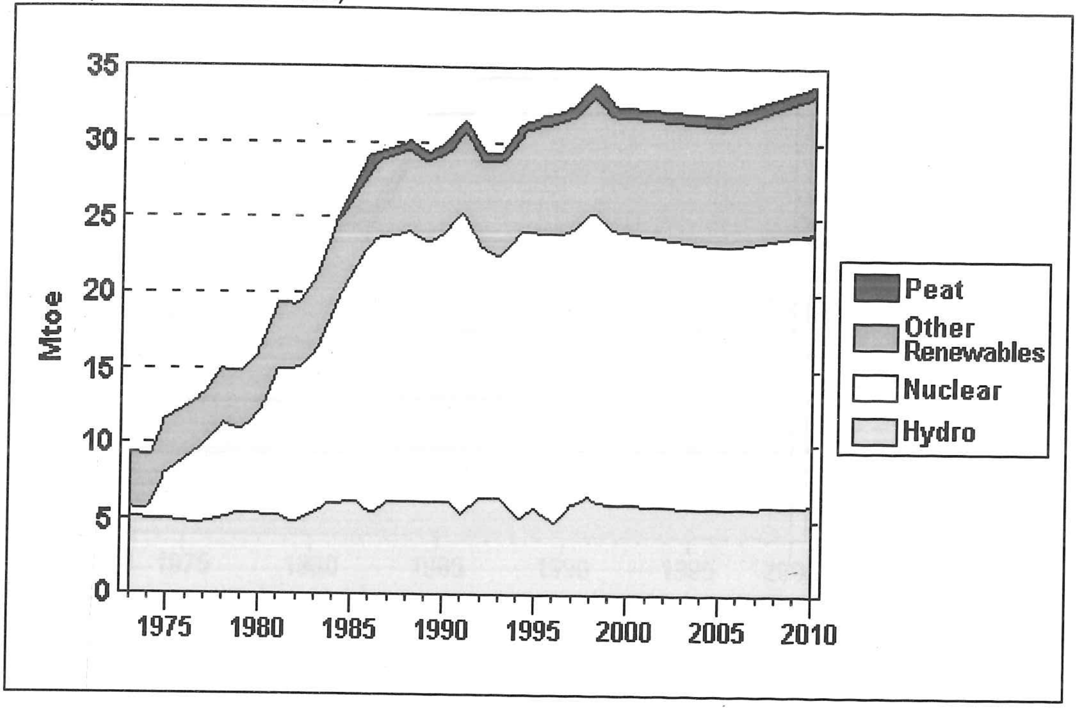


Figure 6: A breakdown of Swedish generation and consumption of electricity *(Source: IEA, 2000).*

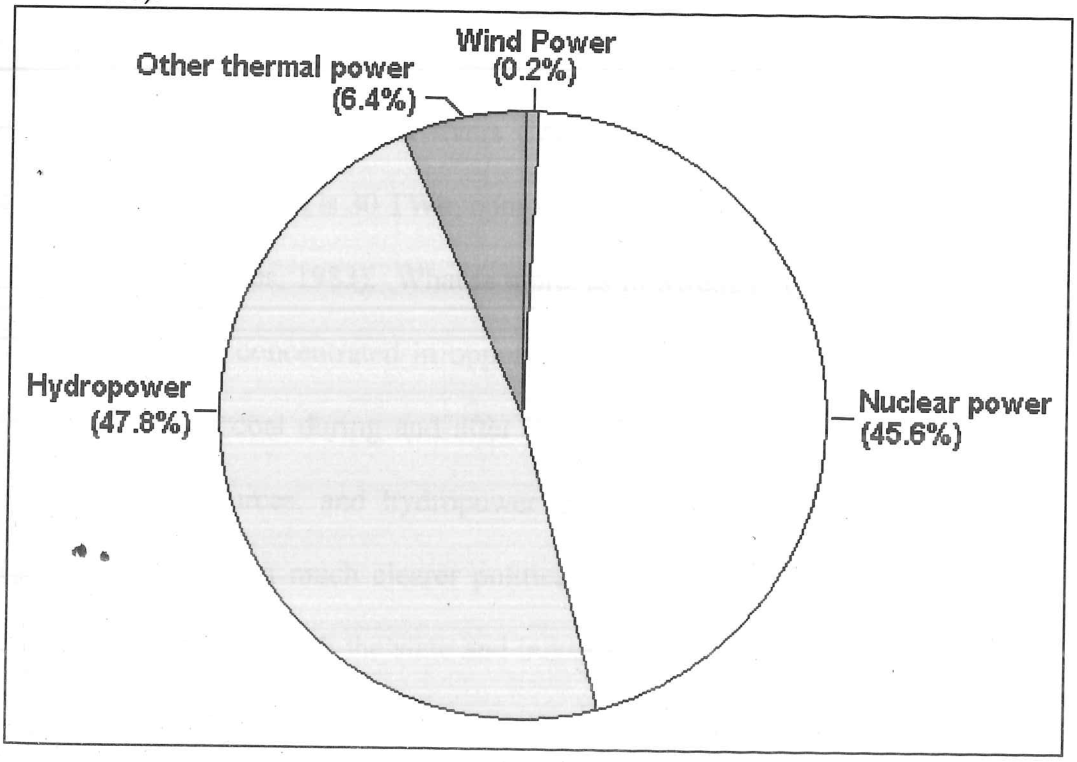
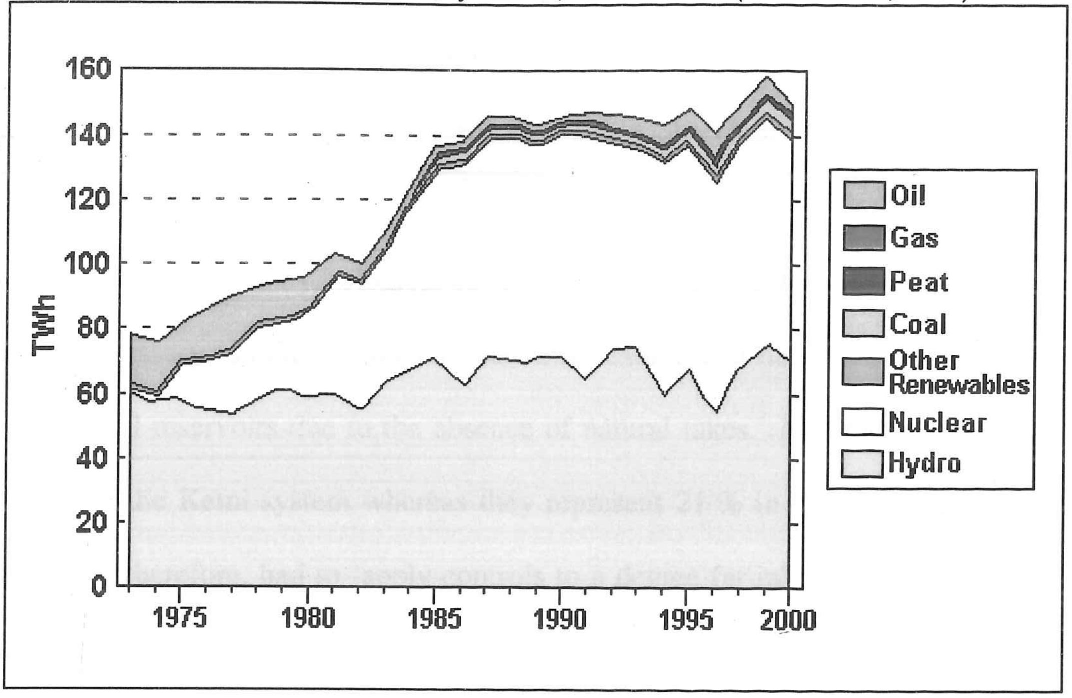


Figure 7: Swedish electricity generation by source, 1973 to 1999 *(Source: IEA, 2000).*



2.5. The role of hydropower in Finland

In spite of its comparatively large area (337,000 km^2) and its 60,000 lakes, Finland, with its gentler relief and lower precipitation, is less well placed than either Sweden or Norway to obtain energy from its rivers (Massa, 1985). Finland's theoretical total of water resources per annum is 30 TWh, compared with 80 TWh for Sweden and 150 TWh for Norway (Myllyntaus, 1983). What is more, as in Sweden, hydropower resources and energy demands are concentrated in opposite ends of the country. The high price and difficulty of buying coal during and after World War I led to a renewal of interest in Finnish energy resources, and hydropower in particular. After the proclamation of independence in 1917 a much clearer political situation emerged and, concurrent with much economic growth, both the state and industry started to build new and much larger thermal and hydropower stations (Myllyntaus, 1983). In the post-war period the extensive introduction of hydropower was an essential factor in Finnish industrialisation, which advanced exceptionally rapidly even by international standards. Furthermore, after the Second World War work began on a large scale scheme on the Kemijoki in Lapland, which today produces a third of Finland's hydroelectricity (Bernes, 1996).

Due to the unfavourable hydrological conditions in Finland control of the available water has been necessary. In the Kemi River basin, for example, it has been necessary to build large artificial reservoirs due to the absence of natural lakes. Natural lakes account for only 3 % of the Kemi system whereas they represent 21 % in the Vuokski river basin. Finland has, therefore, had to 'apply controls to a degree far in excess of those found in other countries such as France and Switzerland' (Simeons, 1980; 242). Also, to make the most of the hydropower potential that does exist in Finland, the majority of larger lakes are regulated and nearly all large watercourses have been exploited, primarily to meet the needs of hydropower production and flood protection. About half of the hydro potential is being used although due to industrial location this is concentrated in the central and southern areas. Development in these areas has also been easier, physically, than in the North, where, because of the nature of the terrain, the power potential would need to be concentrated into a small number of generating stations, with the construction of embankments and channels. Most of the unharnessed waterpower is to be found in the river networks of the Kemi, Ii and Tornio. Otherwise, the majority of areas with hydropower potential in Finland which have not yet been utilised can be found in the Arctic areas of Lapland (Aula, 1996). Although there is potential for hydropower development in Finland large-scale exploitation of hydropower is now prevented by a law which 'prohibits the development of a total of 53 individual rapids and watercourses in Finland' (Bernes, 1996; 148). Separate legislation also safeguards the whole of the

Ounasjoki, a tributary of the Kemijoki. Such laws were enacted due to the opposition of conservationists to hydroelectric power and its adverse environmental effects, aroused by the construction of the Lokka and Porttipahta reservoirs in the 1960s.

Total Primary Energy Supply in Finland is illustrated in Figure 8. The country's main energy supply in 1997 was oil, 115 TWh and 31.4 % of TPES. Solid fuel was 80.2 TWh or 20.7 % of TPES; of this, 55.8 TWh or 14.5 % was coal. Renewables accounted for 81.4 TWh or 20.9 % of TPES (IEA, 1999). Hydropower accounts for around 3.2 % of energy produced in Finland (12.8 TWh), and over 15 % of Finnish electricity production (IEA, 1999). The Finnish electricity supply industry produced some 69.2 TWh of electricity in 1997. Of this, 23.2 TWh (35 %) was produced in co-generation plants. Of the remainder, 12.25 TWh (17.7 %) came from hydropower, 20.9 TWh (30.2 %) from nuclear, and 10.9 TWh (17 %) from fossil fuels (IEA, 1999). The sources of the hydropower in Finland are concentrated around 7 systems of lakes and rivers (Simeons, 1980). Finland's electricity supply is mainly produced in the Kokamäenjoki, Vuoksi, Oulujoki, Iijoki and Kemijoki. Of these the Kemijoki produces the most. The Kemijoki and Torniojoki run through Finnish Lapland and consequently half of Finland's hydropower reserves are located within the Arctic (Aula, 1996). Hydropower, an essential part of Finnish power production, is one of only a few domestic energy supplies which can be expanded feasibly. It has also been shown that hydropower is essential, not purely for its total energy supply, which amounts to only approximately 3.2 % of energy produced, but for its flexibility of supply (Marttunen and Hellsten, 2002, 32). Production in the Kemijoki, for example, is hugely significant as it comprises one third of Finnish short-term regulation capacity (Marttunen and Hellsten, 2002).

Figure 8: Finnish Total Primary Energy Supply by fuel, 1997 *(Source; IEA, 1999).* (1 Mtoe = 11.63 TWh)

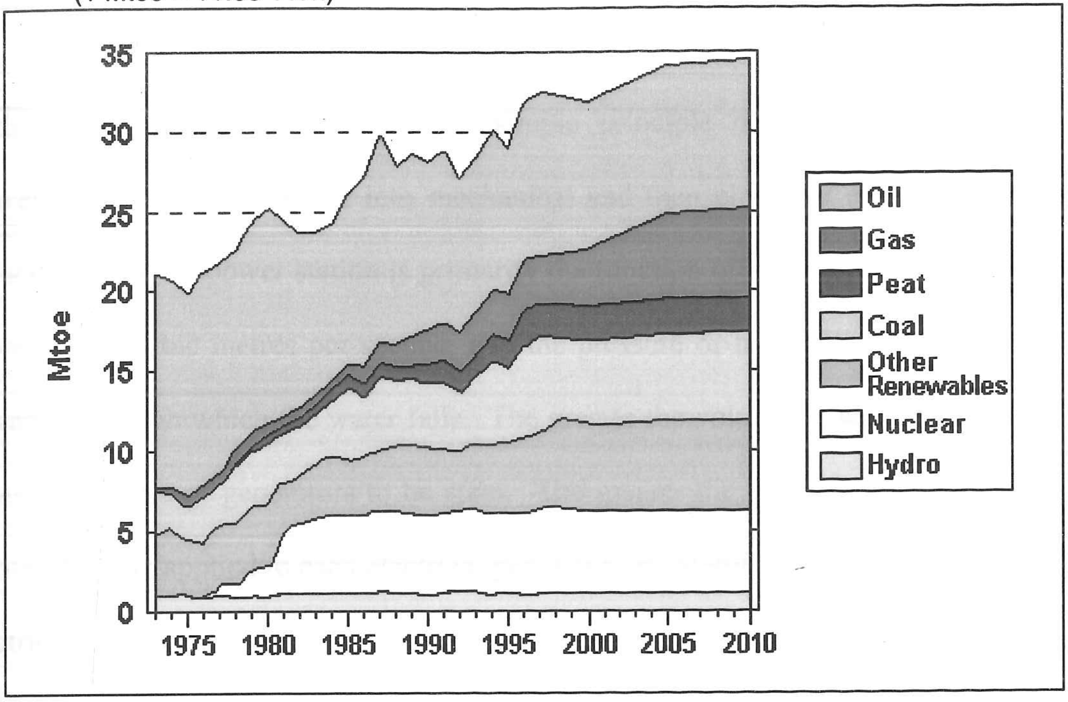
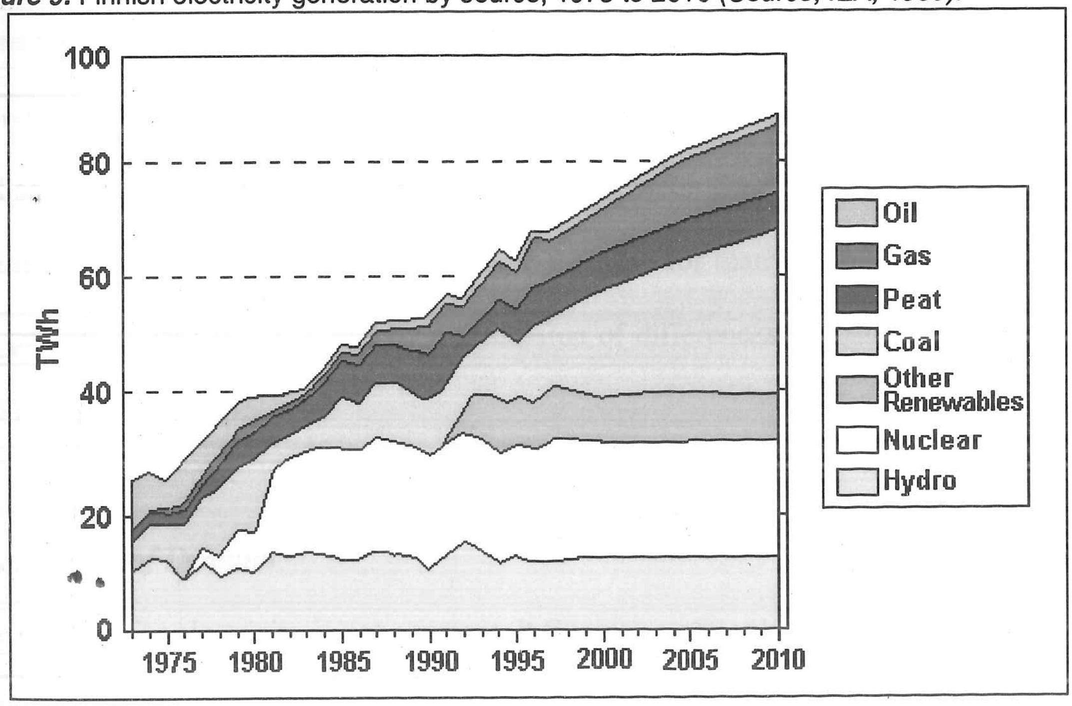


Figure 9: Finnish electricity generation by source, 1973 to 2010 *(Source; IEA, 1999).*



3. Hydroelectric Power Generation

3.1. Introduction

Hydroelectric power is based on the simple principle of a turbine and generator converting energy from water into mechanical and then electrical energy. The power capacity of a hydropower station is primarily the function of two variables; the flow rate, expressed in cubic metres per second, and the pressure or hydraulic head, which is the elevation through which the water falls. The greater the volume of water, the greater the number and size of generators to be spun. The greater the distance the water falls, the greater the spin applied to each electrical generator and therefore the greater the output of electricity (Simeons, 1980). Having water does not necessarily correspond to having hydroelectric potential. To be in usable form, that water must be in continuous supply, accessible, and concentrated in rivers with a volume, flow and descent rate sufficient to drive turbines (Bourassa, 1985). It is due to such variables that 'every hydroplant is an individual entity and no two plants are identical as regards the head, availability of power and so on' (Jog, 1989; 12). It is these variations between generators which I will discuss further in this chapter. First, I will examine the need for many of these such variations; the pattern of demand, followed by a discussion of differences in load supply, head size and finally station type.

3.2. Pattern of Demand

The demand for electricity is not constant, it fluctuates not only seasonally but daily, and even hourly. *Figure 10* illustrates the daily load curve of a typical system. 'Generally the peak demand is expected between mid-morning to noon and then in the evening, with a night-time low demand from, [approximately] midnight to early morning' (Jog, 1989; 4). This demand fluctuates further at weekends, when demand tends to be less than on week days. Furthermore, in countries, such as those of Scandinavia, the winter demand is far greater than that of summer. The minimum demand at any time may be only 50 % to 80 % of the maximum demand in a day. This proportion may be 30 % to 50 % over a year *(Figure 11)*. 'To meet the daily peak would require generating plants to be kept ready for operation for a short period every day and the heaviest yearly peaks may require some plants to operate for only a few hours or few days out of the whole year' (Brown, 1958; 70). Such station, although essential, earn very little revenue. Due to the associated problems of such demand fluctuations electricity supply authorities throughout the world try to encourage a levelling of their load to achieve more uniform and more economical operation of their generators. The most widespread method is to charge different prices for electricity, with highest prices during the daytime to try and reduce demand at peak periods, and lowest prices during the night in an attempt to increase demands.

Figure 10: A typical daily load curve *(Source: Jog, 1989).*

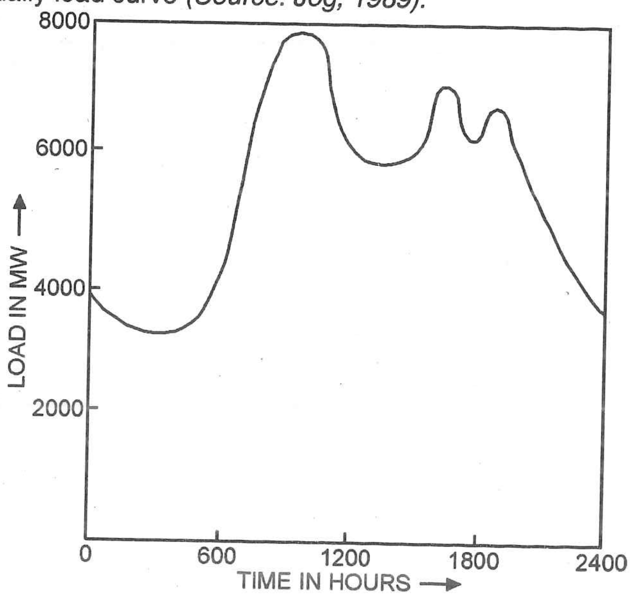
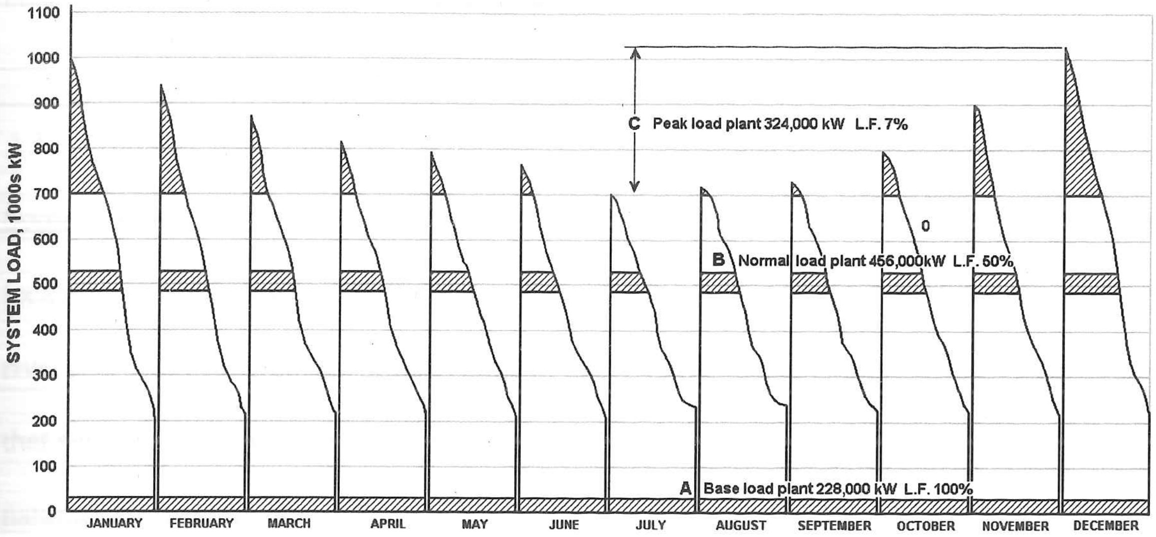


Figure 11: A series of monthly load-duration curves demonstrating how both the peak load and the energy requirements vary month by month during the year *(Source: Brown, 1958).*



3.3. Classification of power stations by method of power generation

Hydropower stations may be divided into three main groups according to nature of power generation. Many systems, such as the Kemijoki which consists of two large lakes upstream of a variety of run-of-river stations combine the modes for improved efficiency. Many pumped storage systems are also used in conjunction with other forms of energy generation. These three classifications are:

a) Conventional hydropower plants with valley storage.

b) Run-of-river plants

c) Pumped storage plants

3.3.1. Valley storage plants

In conventional hydroelectric generation stations, a reservoir has to be built on the river to store sufficient water to provide constant power generation throughout the year. By the construction of a dam storage projects extensively impound water during high-flow periods to maintain water availablility during low-flow periods, permitting a more constant flow release and consequently more constant power generation (Jog, 1989)

3.3.2. Run-of-river plants

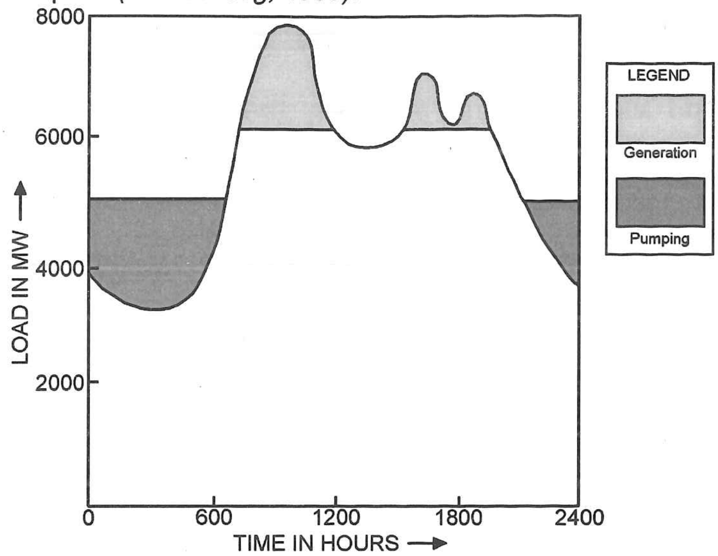
Some systems do not have dams, but channel some or all of the stream through turbines located either midstream or offstream. Run-of-river projects use the natural flow of the river and produce relatively little change in the stream channel and flow. This also means that such systems only store a day or a week's worth of water so are heavily reliant on the natural flow regime of a river. Such generators are therefore most useful on rivers with a continuous flow throughout the year and only limited periods of decreased flow; conditions which predominate mainly in colder countries but rarely in tropical regions. By avoiding the construction of a reservoir, such flow designs tend to have smaller effects on river ecosystems both upstream and downstream. The formation of a small pool does not cause the same problems of land acquisition and does not substantially alter the original topography along the banks of the river (Jog, 1989, Brower, 1992).

3.3.3. Pumped storage plants

The original concept behind the development of pumped storage plants was the conversion of relatively low cost, off-peak energy generated in thermal generators into high value, peak power. This concept has been extended to using the stations to control the flow of power and to obtain increased benefits from pumped storage. Pumped storage generators have the same characteristic features as a conventional hydroelectric generators, but the way the two operate is completely different. During off-peak periods, electricity is used to pump water from a lower to a higher reservoir when low cost pumping is available (Halacy, 1977). It is released during periods of high power demand and displaces the use of inefficient, costly alternative sources of generation. Although pumped storage sites are not net producers of electricity, and energy is wasted by the pumping process, they are a valuable addition to electricity supply systems. If the difference between the off-peak and on-peak energy cost is large the process may result in savings. Most of such installations are small and are used in conjunction with low-head run-of-river hydro stations where it is 'either impracticable to store the water during periods of low demand or it is necessary to maintain a uniform river discharge' (Brown, 1958; 136).

A combination of a thermal generator with a pumped storage generator as an auxiliary, benefits the network considerably and therefore a large number of such stations are being constructed all over the world, to play a major role in the power grids (Jog, 1989). It can be seen from *Figure 12* that in such a set-up the load fluctuations for the thermal generator have been considerably reduced. The pumped storage plant has assisted the network in two ways. First, it has improved the load factor during the low-demand period, benefiting the network. Second, it has reduced the demand on the thermal plant by generating peak power making it possible to use lower capacity units (Jog, 1989).

Figure 12: The load curve of a network with a pumped storage plant working in conjunction with a thermal plant *(Source: Jog, 1989).*



Pumped hydro storage was first used in Italy and Switzerland in the 1890s. It is now available at almost any scale with discharge times ranging from several hours to a few days. The overall efficiency obtained ranges from 65 to 85 % (Jog, 1989). Many electrical networks have a special tariff for peak-load power which is often 3 to 4 times more than the normal tariff. Therefore, in spite of the relatively low efficiency, the stations can earn additional revenue. Consequently, pumped storage is the most globally widespread energy storage system in use on power networks as no cheaper practical alternative has been invented. Furthermore, pumped storage plants have long lives, 'giving efficient service even after 25 years of operation' (Jog, 1989; 137), and outgoings are low, with low maintenance costs. There is over 90 GW of pumped storage in operation world wide, which is about 3 % of global generation capacity.

Like conventional hydropower, however, pumped storage has serious environmental obstacles. Many of the best sites available for pumped storage, involve two adjacent valleys at different altitudes, lie in pristine wilderness areas. Consequently, opposition to pumped storage projects from environmental groups and others is often strong, and several proposed projects have been cancelled. In addition to the usual concerns of inundating large areas and destroying plant and animal habitats, objections are raised about the large daily water-level fluctuations that are necessary in pumped-storage reservoirs which may interfere with recreational activities (Brower, 1992). Furthermore, deployment of pumped storage plants is generally extremely disruptive due to long construction times and high capital expenditure.

A large number of pumped storage generators are of the pure type, where there is no natural inflow in the upper lakes. Such lakes are formed high on hills by constructing self-enclosing embankments, made from the soil and rocks, either in the bed of the lake or from the excavations of the nearby areas (Jog, 1989). Whenever a dam is constructed on a river, any power generated because of the natural inflow is available as a bonus which improves the economics of the generator. A site which cannot otherwise be considered for hydropower generation therefore might become feasible for a pumped storage plant. Such stations are known as 'mixed' (Jog, 1989). The function of the lower lake is to store water for pumping up during off-peak hours and to receive the turbine discharge during the peak-power generation period. There is a constant variation of the water level due to the emptying and filling cycles. To remedy seepage and evaporation losses one of the two lakes must have some source of water as well as that for initial filling. In the pure type of stations, there is no inflow into the higher lake and the lower lake has to perform this function. In the majority of cases, the lower lake is made by constructing a dam on the river. This lower lake capacity often determines the magnitude of the project (Jog, 1989).

3.4. Classification of power generators by load supply

To meet these varying power demands, different categories of power stations have to be provided for the grid. These can be divided approximately into three categories; base-, medium- and peak load generators. Base load generators are required to work for a over 5,000 hours a year, so must be very efficient with low cost power generation. Often, such stations may require major capital investment, but this is economically justifiable due to the low cost of power. These generators have to run continuously and therefore, there is 'very little operational flexibility' (Jog, 1989; 6). Base load is generally produced by hydrocarbon burning thermal stations, nuclear generators or hydroelectric generators of the run-of-river type where storage is not possible because of other constraints and where there is continuous power generation. Rivers which have to be maintained constantly to meet the irrigation or navigation requirements are ideal for such stations (Jog, 1989).

Medium load generators tend to work between 2,000 and 5,000 hours a year, operating predominantly on week days. The cost of generation may be greater than base load generators but may have more operational flexibility. Finally, peak load generators work for less than 2,000 hours in a year. As these are used for a short duration investment in them can be comparatively less and corresponding reduction of efficiency is acceptable and economically justifiable (Jog, 1989). If the conditions prevailing in the river of the power station permit regulated releases, it can be used to generate peak power (Jog, 1989). Therefore, conventional hydroelectric stations, where discharges to the river can be controlled to generate power at the time of peak demand, are ideal.

3.5. Classification of power stations by head size

The amount of electricity that can be generated at a hydroelectric station is dependant upon two factors: the vertical distance through which the water falls, called the 'head', and the flow rate, measured as volume per unit time. The electricity produced is proportional to the product of the head and the rate of flow. Every hydro-electric generating unit consists of a turbine to convert the energy of falling water to mechanical energy (Simeons, 1980). 'The head creates the pressure which pushes the water through tunnels or pipes to the turbines where it hits the paddle wheel or turbine runner. This causes the runner to start spinning which in turn spins the generator shaft' (Simeons, 1980; 238). 'As a rule of thumb, one gallon of water [4.5 litres] per second falling one hundred feet [30 metres] can generate one kilowatt of electrical power' (Brower, 1992; 114).

Hydroelectric power stations can therefore be divided according to head size. 'High head' power stations are the most common and generally utilise a dam to store water at a high elevation. Such stations tend also to be very economical, as small quantities of water can produce a large amount of power due their high pressure operation (Jog, 1989). Furthermore, due to the large height of the dam the lake capacity needed tends to be relatively small (Jog, 1989). High head stations with storage are very valuable to electric utilities because they can be quickly adjusted to meet the electrical demand on a distribution system.

In medium head stations a larger volume of water is needed to generate the same power. Therefore a reservoir of larger capacity is needed. Consequently, the extent of the catchment areas has to be larger, normally available in the middle stretches of a river. Sometimes, if ground conditions are favourable, in medium head stations, the power station may be located on the downstream side of the dam, away from the main dam. In this case, 'the length of the penstock increases but, it is justified because of the availability of additional power' (Jog, 1989; 16).

'Low head' hydro stations generally utilise heads of only a few meters or less. Power stations of this type may have a low dam or weir to channel water, or no dam and simply use the 'run-of-river'. To produce a useful amount of power a large volume of water must pass through a low head hydro-station's turbines, volumes far greater than for similar power outputs in a high head station. As large volumes have to be handled, 'the turbines are large, as also are the powerhouse dimensions' (Jog, 1989; 16). Large capacity low head stations are generally situated in the lower reaches of a river in the deltaic regions. Here bed slopes are very small and the river bed is very wide. The length of the dam wall increases vastly and large areas are submerged because of lake formation.

3.6. Classification of dams

During the first half of the 20th Century progress in the design and construction of dams has been at least as remarkable as in other fields associated with the development of water power. It is estimated that throughout the world before 1900 there were only some 36 dams whose height exceeded 30 m. During the succeeding 50 years this number increased to over 2500 (Brown, 1958). There are now more than 40,000 dams higher than 15 metres worldwide, over 300 of them defined as 'major dams', giants which meet one of a number of criteria on height (at least 150 metres), dam volume and reservoir volume. The rate of dam building has declined in recent decades from around 1,000 a year in the 1950s to around 260 a year during the early 1990s. The dam building era in developed countries has largely come to an end as the economic and environmental costs of large dams have become more apparent and public opposition has increased.

In some situations, dams are built at the neck of a former rapid and the water is diverted to the power station by a canal and then led back to the river channel through tunnels or canals. The tunnels sometimes enter the river channel several kilometres downstream of the dam, leaving the former river bed dry except at high flows. This is the situation, for example, at the Umluspen, Stornorrfors and Båforsen power stations in the Ume älv, Sweden. Frequently, the river channel in the former rapids below the dam have been deepened, straightened and canalised, to increase their capacity to receive large flows when the flood-gates of the dams are open. In other situations the power station is located on the former rapid, which is either permanently flooded in the reservoir upstream of the dam, or the river channel below the power station is deepened and canalised. This is the case, for example, at the Tuggen and Bjurforsen Nedre power stations also on the Ume älv (Jansson, 2002).

Dams can be classified into 5 groups:

1) Embankment dams,
   a) Earthfill type,
   b) Rockfill type,
2) Gravity dams,
3) Arch dams,
4) Buttress dams,
5) Spillway dams.

3.6.1. Embankment dams

Embankment dams are made mainly from natural materials. The two main types are earthfill and rockfill dams. The materials are usually excavated or quarried from nearby sites, preferably within the reservoir basin.

Earthfill dams are constructed out of the soil available in adjoining areas, utilising fully the most economic material available. Earth is dumped in reasonably impervious mounds to retain water, although clay sealing may be needed. The upstream and downstream slopes must be stable by themselves, the inclination being at least equal to the angle of response of the soil. The dam does not need costly material like cement and is therefore cheaper than a solid gravity dam in spite of its bigger cross-section. It does not need solid rock foundations and can be founded on any soil which can provide stable support under all working conditions and prevent excessive water loss due to seepage (Jog, 1989). Embankment dams employing a more or less cohesive soil have, like dams of rubble or roughly squared masonry, have been used from the most ancient times.

Structurally, the chief disadvantage of the embankment dam lies in its vulnerability to over-topping by a flood. Inspections of the remains of ancient dams show that this has been a very common cause of their failure (Brown, 1958).

Rockfill dams consist of an embankment of loose rock. Imperviousness is achieved either by providing a membrane of concrete or asphalt laid on the upstream face or by providing a core of earth in the body of the dam (Jog, 1989). They are usually chosen for sites with wide valleys and tend to be constructed when an adequate supply of good quality rock is available in the vicinity but there is a shortage of suitable earth (Jog, 1989). Rock is blasted to break it into small enough pieces to use in embankment dams. The size of the pieces of rock varies from very small (about 2 mm) up to about 600 mm. Sometimes, the blasted rock also needs to be crushed to get the right range of sizes. The foundation requirements for rock dams are more stringent than for earth dams, but less than for gravity dams. The cross section of the dam is similar to the cross section of an earth dam where rubble is used instead of earth. The upstream and downstream slopes are determined by the natural angle of response to the rock.

3.6.2. Gravity dams

Gravity dams may be of many kinds 'depending both upon the materials such as masonry, concrete, rock, or earthfill used for their construction, and on the methods employed to economize in their use' (Brown, 1958; 208). A gravity dam is so called because it is dependent upon its own weight for resistance against the hydrostatic forces on the upstream face. 'They are generally constructed of concrete, but in countries where cheap labour is available, stone is commonly used' (Jog, 1989; 87). Gravity dams are suited to most valleys but they do need to be built on sound rock because the weight of the dam and water has ultimately to be borne by it. The dam has a centre of gravity low enough that it will not topple if unsupported at the abutments. A favourable site is usually one in a constriction in a valley where the sound bedrock is reasonably close to the surface both in the floor and abutments of the dam.

3.6.3. Arch dams

Arch dams are, again, mainly made from concrete. They are curved in the shape of a horizontal arch, with the apex of the arch directed back into the reservoir. The water thrust is resisted by the arch action of a concrete membrane with its edges resting on a strong base and abutments of good quality rock which can withstand the tremendous lateral thrust of the dam, caused by the pressure of the water. As the dam is not required to have a big mass, the cross-section provided is 'just adequate to withstand the hydrostatic forces and so can be made very thin' (Jog, 1989; 88). Arch dams are usually constructed in narrow, steep sided valleys. They need good rock for their foundations and sides of the valleys, to resist the forces on the dam. This type of dam was developed with the advent of reinforced cement concrete and therefore 'spectacular developments have taken place in the field of arch-dam construction since the Second World War' (Brown, 1958; 213).

3.6.4. Buttress dams

Buttress dams spread the hydrostatic forces from the reservoir thrust to piers or buttresses placed a short distance from each other (Brown, 1958). In turn, they transmit these forces to the foundations. As the membranes are rather thin, the weight of the dam is less than the gravity dam. The foundation requirements are less stringent than for the arch dam or the gravity dam (Jog, 1989).

3.6.5. Spillways

Spillways are dam sections provided for discharging flood waters when the reservoir is filled to capacity. Unless these waters are released, they would raise water level and water may overtop the dam. Earthfill and rockfill dams particularly, cannot be allowed to be overtopped as they may erode and fail and large quantities of stored water may rush downstream causing damage to life and property.

4. Rivers of Study

4.1. Introduction

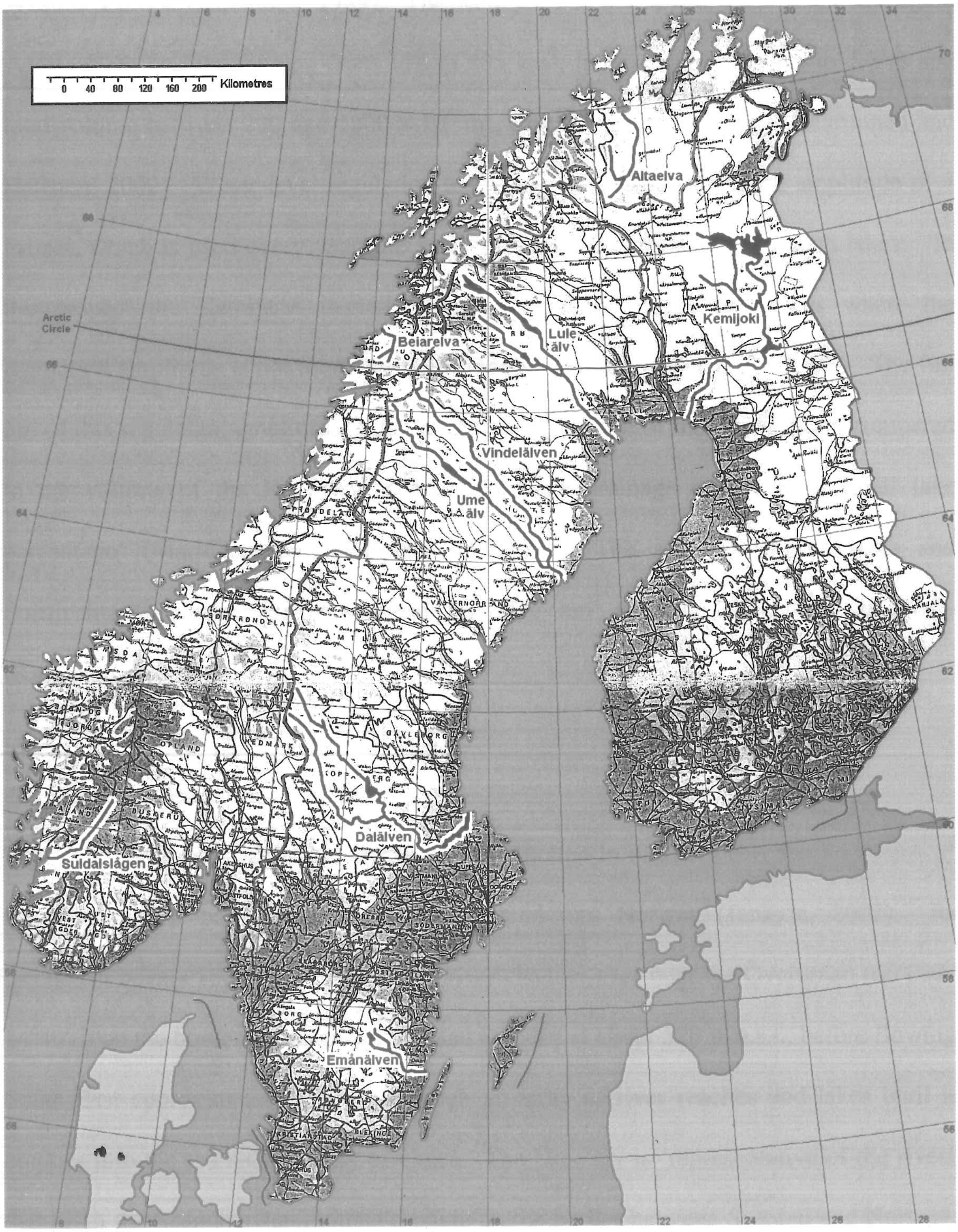
In order to examine the environmental effects of hydropower in Arctic Scandinavia a number of case study rivers have been chosen, as shown by *Figure 13*. These were selected partly due to the availability of large amounts of material published in English. The rivers Alta, Beiar and Kemi, as can be seen are all north of the Arctic Circle. The other rivers are being used as they have conditions extremely similar to rivers situated further north in which fewer studies have been conducted. These rivers, although not in the northern region of Scandinavia, may be treated as approximately analogous to those in the north.

4.2. The Kemijoki

The Kemijoki is the longest river in Finland, running about 560 km from its source near Sokasti Peak, in North-east Finland, to its mouth. It flows generally south-west to the Kemijärvi, then west into the northern part of the Gulf of Bothnia of the Baltic Sea at Kemi. With its many tributaries the catchment of the Kemijoki drains an area of 51,127 km^2, which covers the majority of Northern Finland. This catchment is located predominantly below an elevation of 300 m a.s.l. Hydropower is its primary activity, with the whole uppermost catchment area, except the Ylä-Kemijoki, fully developed for hydropower production.

The Kemijoki catchment area has a lake area of only 4.7 %, but, significantly, contains Kemijärvi (66°30'N 27°20E); the most strongly regulated lake in Finland, and Lakes

Figure 13: The regulated case-study rivers.



Lokka (67°50'N 27°30'E) and Porttipahta (68°00'N 26°30'E); the two biggest reservoirs in Western Europe (Kinnunen, 1989). The Kemijärvi is the largest lake of the Kemijoki system, with an area ranging from 128 to 285 km^2, mean depth from 1.7 to 4.5 m and total volume between 200 and 1300 x 10^6 m^3, depending on water level (Marttunen and Hellsten, 2002). Water level regulation began in 1965, with a maximal amplitude of 7 metres, which is used every year; the largest regulation amplitude in Finnish lakes. 'In this respect the Kemijärvi deviates from other Finnish regulated lakes where the regulation amplitude is not totally utilised' (Marttunen and Hellsten, 2002; 21). The full use of this regulation amplitude is due to the 'large volume of the spring flood compared to the volume of the Kemijärvi due to the large drainage area with a small lake percentage' (Marttunen and Hellsten, 2002; 21). The areas of lakes Lokka and Porttipahta vary enormously; between 216 - 417 km^2 and 34 - 214 km^2 respectively (Kinnunen, 1989).

4.3. The Ume älv

The Ume älv is situated in the county of Västerbotten in northern Sweden and some of the westernmost parts of the catchment extend into Norway (Jansson, 2002). Its catchment covers 16,800 km^2. The main river channel rises near the Överuman (66°00'N 14°40'E) on the border between Norway and Sweden at about 520 m a.s.l., before flowing South-East approximately 470 km through an array of river reaches and lakes until it empties into the sea near the city of Umeå. The Ume älv is 'representative of the rivers that drain the Scandinavian mountain range on the border between Sweden and Norway, and empty into the Gulf of Bothnia' (Jansson, 2002; 9). The formation of the large lakes in the system are due to circumstances of the geomorphically young landscape; the largest of these being the Storuman. The dam of the Båforsen Power Station, for example, stands where the Ume crosses the highest coast attained following the last ice age (Fredén, 1998). Isostatic rebound has since caused the land to rise about 240 m, and the coast to recede about 170 m (Fredén, 1998).

During the 1950s and 1960s the Ume älv was developed for hydropower, with the first power station still in use began operating in 1954 (Jansson, 2002). The river is now controlled by twenty major dams and therefore profoundly affected by hydropower although comparatively unaffected by other human activities. The alterations and the disturbances caused by hydropower production are by far the most important influences on the Ume älv. About 12 % of the total annual hydropower in Sweden is produced from the Ume älv, corresponding to 7.7 TWh during a normal year. The reservoirs in the Ume system have the capacity to store 27 % of the annual flow of the entire catchment (Jansson, 2002). Moreover, there are no undammed sections along the Ume; it consists of a continuous chain of run-of-river impoundments which use the entire fall height of the river (Jansson, 2002). Before regulation of the Ume älv, water discharge ranged between 40 and 1559 m^3s^{-1} at the confluence with the Vindelälven, near to its mouth. Water discharge is now between 0 and 918 $m^3 s^{-1}$ at the same point.

4.4. The Dalälven

The Dalälven basin is predominantly situated within the central Swedish county of Dalarna. The rivers consists of two main branches, both rising in the mountains along the Norwegian border. The western Västerdalälven and the eastern Österdalälven flow South-east, meeting at Djurås (60°34'N 15°08'E) before flowing onward to Avesta, then

North-east into the southern part of Gulf of Bothnia at Skutska. From source to mouth the Dalälven flows approximately 555 km, being the 'second longest river and fourth largest river in Sweden, with a catchment area of approximately 29,000 km^2' (Beier, 2002; 11). The largest lake in the system is Lake Siljan, with a surface area of 289 km^2, situated in the middle of the drainage area, just upstream of the major confluence at Djurås. The river catchment is greatly affected by alterations due to dams, with 39 hydropower stations and more than 500 dams, with a yearly production of 4.7 TWh; approximately 8 % of the hydropower produced in Sweden. These numerous dams are predominantly situated in the eastern river, Österdalälven, and the main river, Dalälven. The largest of the power stations is that at Trängslet, with the 125 m Trängslet dam being the highest in the country (Beier, 2002). The western river, Västerdalälven, is less affected by such physical transformation. The large size and complexity, including the large number of dams in the Dalälven, made an overview of the effects of hydropower and other physical modifications difficult (Beier, 2002).

4.5. The Emånälven

The Emånälven reaches from its sources at Nässjö and Badafors in South-eastern Sweden to its mouth at the Baltic sea by Em, south of Oskarshamn. The main river is approximately 240 km long with a catchment area of about 4472 km^2. The Emånälven is in the area of least rainfall in Sweden, but nevertheless the lower part and the mouth of the river is one of the largest continuous wetland areas in the county (Weichelt, 2001). Along the river are about 40 hydropower stations, with the supplying dams making up one third of the water course. This said, all such assemblages tend to be relatively small compared with the much larger hydropower stations in northern parts of the country, and therefore tend to have smaller effects on the system (Weichelt, 2001). The first stations built on this course were the Klinte and Brunnshult in 1909 and 1910, respectively. Unfortunately, due to fluctuations in water supply in the region, reglation of lake Solgen began in 1928; between 1926 and 1975 the mean discharge near the mouth was 30 m^3s^{-1}, however this amount varied between 2 and 270 m^3s^{-1} (Weichelt, 2001).

4.6. The Beiarelva

The Beiarelva watercourse is in Nordland County, Northern Norway. The topography of the region of the Beiarelva is characterised by steep slopes, causing the river to be relatively short at only 50 km from its source to its mouth at the North Sea, near Beiar. Consequently, most the tributaries are also comparatively small; the two major tributaries, Tollåga from the east, and Gråiåga from the west, have lengths of only 30 km and 20km respectively (Bjørtuft et al, 2002). The Beiarelva river system has a natural catchment area of 859 km^2, 7 % of which is covered with glaciers (Bjørtuft et al, 2002). The flow distribution of the river is therefore greatly influenced by glacial melt-rates and therefore climatic conditions. Maximum precipitation normally occurs in October, with the minimum in May. However the lowest discharges occur during the winter months, with maximum discharges occurring during the summer melt from May to August (Bjørtuft et al, 2002).

The Beiarelva catchment has only been influenced by hydropower development since 1993, and the associated developments are common with modern hydroelectric regulation. Water is diverted from the river system through 11 intakes, one of which is situated in the main river itself. This permanently diverts and transfers water from the

Beiarelva catchment to the neighbouring catchment and Storglomvatn reservoir, west of Beiarn; the largest of all Norwegian reservoirs. Its water is then used in the Svartisen Hydropower Station 40 km west of Beiarn. Such diversions can bring about serious implications and the Beiarelva is representative for this type of regulation (Bjørtuft et al, 2002).

4.7. The Suldalslågen

The Suldalslågen is in Rogaland County, south-west Norway. The river has a natural catchment area of 1463 km^2, of which about 75 % is above the timberline which can be considered as high mountain areas. Today the catchment area is increased to 2139 km^2 due to the establishment of diversions from other rivers to the Suldalslågen watercourse for use in the Ulla-Førre Hydropower Plant (Johansen et al, 2002). This consists of 7 reservoirs, located both inside and outside the Suldalslågen watercourse. The largest reservoir, Blåsjø, is the second largest in Norway, with a volume of 3105 x 10^6 m^3. Furthermore there are 4 power stations within the system, all of which began operation between 1980 and 1986. Again, due to the high altitude of much of the catchment, the flow distribution is strongly influenced by the snow regime. The lowest discharges occur in the winter months and maximum discharges during the spring melt from May to July, even though maximum precipitation of, on average, 2700 mm occurs from September to December (Johansen et al, 2002).

5. Environmental effects of hydroelectric power

5.1. Introduction

'In considering the [justification] of proposals for river basin development the indirect benefits to be derived from the construction of regulating works should not be overlooked' (Brown, 1958; 155). Among these benefits are improvements to fisheries and recreational facilities; the opening of hitherto inaccessible districts by the construction of roads; the encouragement of tourist traffic and the general benefits resulting from increased commercial activity in the region. For example, hydropower has served as a gateway for tourism and other activities in areas which used to be virtually undisturbed (Bernes, 1996). Moreover, the balancing of the river discharge results in a reduction of the flood flows, with consequential benefits to the communities which dwell on the flat lands bordering the river. Indeed there are many instances of river basin development where flood control was the primary object: for 'the incidence of large floods may have serious effects on the health and prosperity of a community, and their control may often play an important part in a conservation scheme' (Brown, 1958; 155). The annual benefit, for example, of hydropower production in the Kemijoki basin is about 10 million € (Marttunen and Hellsten, 2002).

It may be asked that if hydropower is so great, why don't we make more use of it? This is predominantly due to the environmental problems caused by such developments. Next to costs, the environmental effects of the alternative modification have to be taken into account. The advantages of hydropower stations as a renewable energy source refer to electrical generation without carbon-dioxide emissions. On the other hand, adverse environmental effects on the ecosystem and morphological conditions of the watercourse, have been caused by hydropower stations (Bednarek, 2001). In northern regions many research projects concerning the consequences of lake regulation have been conducted since the 1980s. 'As a result, current knowledge of the relationship between water level fluctuation and littoral flora and fauna is relatively good' (Hellsten, 1997; 357). One of the fundamental biophysical features that make large dam effects unique from other large-scale projects is the fact that each river system is a continuum. This distinct feature predisposes river habitats and surrounding communities to far reaching consequences of upstream dams, at the reservoir site, and downstream. Many of these social and environmental effects have been well documented in numerous reports worldwide, yet despite our improved knowledge, many unanticipated ecological perterbations continue to occur. 'These unanticipated impacts often increase the risk for certain marginalised communities whose livelihoods are dependent on the wide range of services provided along rivers' (Clarke, 2000; 42)

Hydropower is therefore somewhat controversial, because its exploitation can have serious adverse effects on landscape, fauna and flora. The most extensive physical encroachments on the Arctic environment have occurred in conjunction with the exploitation of hydropower, a source of energy available in greater abundance in Fennoscandia than in most other parts of Europe. Along the Scandinavian mountain range, for instance, Bernes suggests that 'it has changed the natural environment more radically than any other human activity' (Bernes, 1996; 143). Moreover, Dynesius and Nilsson (1994) state that 'The damming of rivers has been identified as one of the most dramatic and widespread deliberate impacts of humans on the natural environment'

(Dynesius and Nilsson, 1994; 753). Quite often the environmental and social problems of hydropower projects have been known for many years but have been hidden behind political advertising campaigns and only gradually become appreciated. Recent controversies in such regions have caused people to examine the balance between conserving the environment and raising the standard of living more closely (Massa, 1985).

It is these controversial environmental effects of hydropower which I will examine in this chapter. All the consequences of hydropower development are interrelated, but for purposes of easy analysis and discussion I have divided them into a series of sub headings. The first, and maybe primary cause of environmental problems, to be discussed is that of *lake and river regulation.* Closely linked with this I then analyse the problems of *land submergence*, with the associated problem of the *formation of floating peat islands*, and the *formation of dry river beds.* The discussion then moves onto the alteration of hydrological conditions in the affected river systems; the *alteration of temperature regimes*, the *interruption of sediment movement*, *shore erosion*, and *changes in water chemistry*. Finally, I assess the *effects on riparian flora and fauna.*

When considering all of these effects it must be taken into consideration that regulation of water level does not actually introduce new environmental factors. All the factors present in regulated lakes also exist, to some degree, in unregulated lakes, but it is the amplitude and timing which is usually different compared to lakes in natural states (Hellsten, 1997). Moreover, 'the environmental effects of hydropower are by no means confined to the rivers and lakes directly involved, but extend over large areas of the

(Dynesius and Nilsson, 1994; 753). Quite often the environmental and social problems of hydropower projects have been known for many years but have been hidden behind political advertising campaigns and only gradually become appreciated. Recent controversies in such regions have caused people to examine the balance between conserving the environment and raising the standard of living more closely (Massa, 1985).

It is these controversial environmental effects of hydropower which I will examine in this chapter. All the consequences of hydropower development are interrelated, but for purposes of easy analysis and discussion I have divided them into a series of sub headings. The first, and maybe primary cause of environmental problems, to be discussed is that of *lake and river regulation*. Closely linked with this I then analyse the problems of *land submergence*, with the associated problem of the *formation of floating peat islands*, and the *formation of dry river beds*. The discussion then moves onto the alteration of hydrological conditions in the affected river systems; the *alteration of temperature regimes*, the *interruption of sediment movement*, *shore erosion*, and *changes in water chemistry*. Finally, I assess the *effects on riparian flora and fauna*.

When considering all of these effects it must be taken into consideration that regulation of water level does not actually introduce new environmental factors. All the factors present in regulated lakes also exist, to some degree, in unregulated lakes, but it is the amplitude and timing which is usually different compared to lakes in natural states (Hellsten, 1997). Moreover, 'the environmental effects of hydropower are by no means confined to the rivers and lakes directly involved, but extend over large areas of the surrounding countryside as well' (Bernes, 1996; 147). In the open landscape of the Scandinavian mountains and Iceland, power stations, dams, access roads, transformer stations and overhead power lines may be seen for great distances. 'To most people, such installations are an alien and unwelcome intrusion on an otherwise natural environment' (Bernes, 1996; 147).

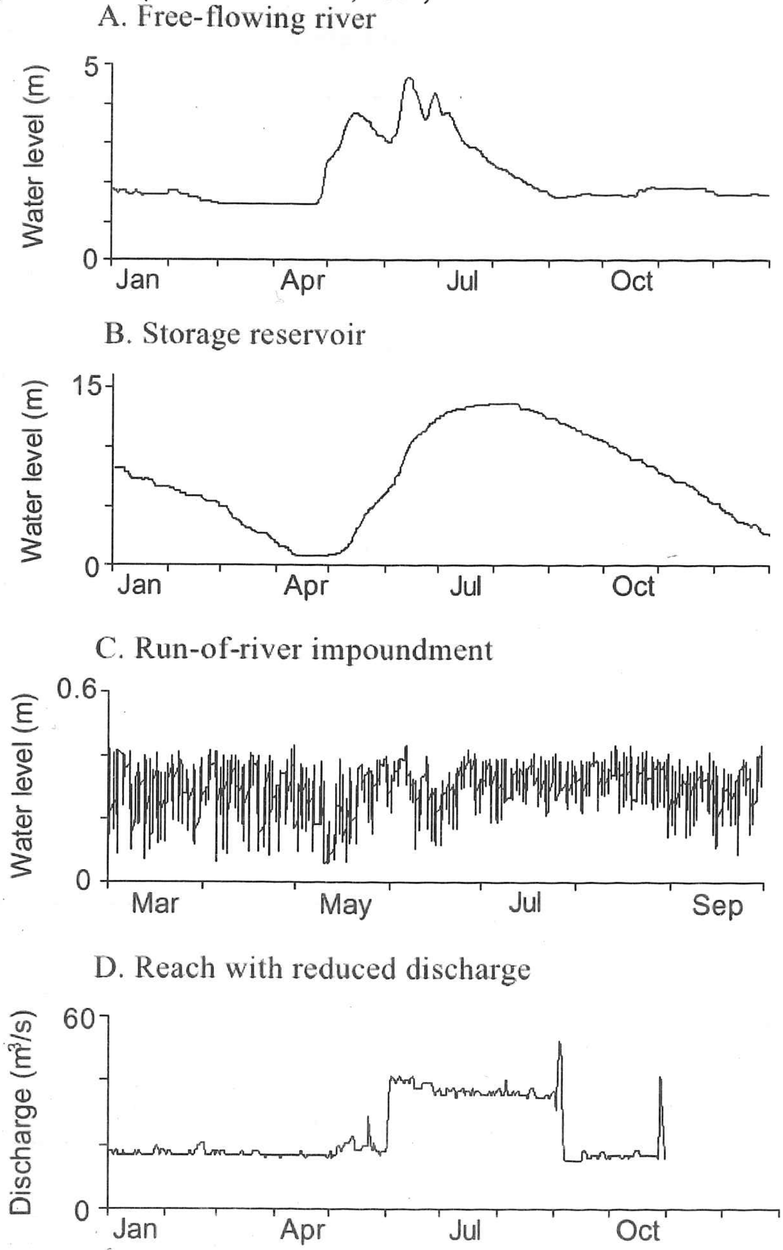
5.2. System regulation

Rivers of northern Scandinavia are generally characterised by large variations in water flow throughout the year. In free-flowing rivers, such as the Vindelälven, seasonal water-level fluctuations tend to be large, ranging up to 6m between the highest and lowest levels, with 'the annual maximum spring flood typically two orders of magnitude larger than the annual minimum discharge in late winter' (Jansson, 2002; 23). The annual water-level maximum occurs during spring or early summer (*Figure 14A*) due to snowmelt in the mountains, delaying the development of river-margin vegetation until water levels recede (Lillehammer and Saltveit, 1979). The mean water levels then gradually recede until the next spring flood, broken only by a small rain-induced increase in the autumn months (Jansson, 2002).

Water flow and water level variation has been fundamentally changed to obtain maximum hydroelectric power production during periods of maximum demand (Beier, 2002). 'Storage during times of plenty for subsequent use in times of scarcity is fundamental to the efficient use of water resources; the management of reservoirs and the lands which supply them is therefore a matter of great importance' (Brown, 1958; 331). The greatest demand for electricity arises in winter, but this is also the time of year when natural rates of flow in the major rivers of the north are at their least (Bernes, 1996). In storage reservoirs and some large lakes the water level is normally at it's lowest in spring and is then raised to reach its maximum in late summer. The water level is subsequently lowered during autumn and winter (Beier, 2002). In this way the spring flood is delayed or greatly diminished. The autumn flood is also diminished or altered, during an important period when fishes migrating to spawn. Due to artificial fluctuations of the water level the exchange of minerals and organisms between the riparian zone and the river channel is also altered (Beier, 2002). In a regulated river, water flow can thus be fast when it would normally have been at its slowest, and vice versa (Bernes, 1996).

The run-of-river impoundments of the middle and lower reaches also provide water for power stations. The most apparent effects of such impoundments on discharge are a more balanced yearly regime and large daily variations, as seen in *Figure 14* (Henricson and Müller, 1979). Furthermore, in reaches with reduced discharge due to underground passages through tunnels and unimpounded reaches downstream of dams, water-level fluctuations often have low amplitude but retain a largely natural seasonal rhythm *(Figure 14)* (Jansson, 2002).

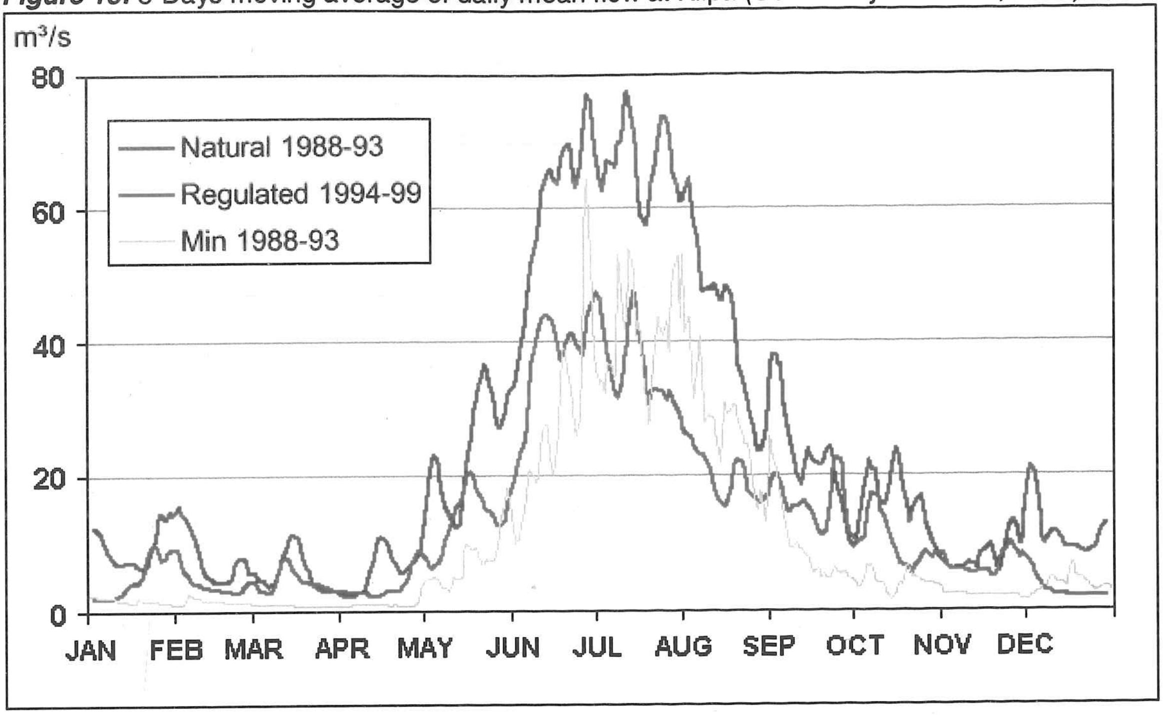
Figure 14: Hydrographs for (A) a free-flowing river and (B) - (D) the three major types of regulated flow *(Source: Jansson, 2002).*



The extent of the effects of regulation may be demonstrated in the case study rivers. For example, the main effects on the Kemijärvi are related to water level regulation, 'aiming at increasing hydropower production and decreasing flood damage both in Lake Kemijärvi and in the River Kemijoki downstream' (Marttunen and Hellsten, 2002; 18). The Kemijärvi is characterised by a strong spring flood, which was higher than 2m in its natural state with a discharge peak of more than 1800 m^3s^{-1}. Water level regulation has eliminated the spring flood by lowering the water level during winter, leading to larger winter discharges for hydropower production. Such hydrological alterations have lead to a regulation with a maximal amplitude of 7 metres, which is fully utilised every year, creating a surface area ranging from 128 to 285 km^2 dependent on the water level (Marttunen and Hellsten, 2002).

The hydrological conditions of the Ume have also been greatly altered by hydropower development. The river now includes 20 major dams, forming a stair-stepped series of storage reservoirs and run-of-river impoundments. The regulated discharge varies between 0 and 918 m^3s^{-1} compared with a previous natural discharge of between 40 and 1559 m^3s^{-1}. Water levels therefore fluctuate between 0.1 and 1 m in height either daily or weekly throughout the year in the run-of-river impoundments. In some storage reservoirs further upstream, however, 'seasonal water level fluctuations are larger, with a maximum range of 20 m' (Andersson et al, 2000; 84). Also, the discharge in the upper part of the Beiarelva is reduced, on annual basis, by an average of 3.5 m^3s^{-1} (Bjørtuft et al, 2002). The most significant changes after regulation are the discharges in the summer months from May to September. *Figure 15* shows that mean flows after 1994 in July and August are even less than the minimum experienced flows prior to hydropower development (Bjørtuft et al, 2002).

Figure 15: 5-Days moving average of daily mean flow at Klipa *(Source: Bjørtuft et al, 2002).*



Finally, the extent of anthropogenic environmental manipulation can be highlighted in the Stora Lule älv, Sweden. Cumulatively, the reservoirs in the Lule älv system can accommodate almost three-quarters of the average annual run-off. This river is regulated to a higher degree than any other major watercourse in Europe or Siberia, and in its lower reachês 'natural seasonal variations in flow have been more or less completely eliminated' (Bernes, 1996; 143). In some smaller river systems, the water regime is even more fully controlled. Up to 85 % of the annual run-off carried by the Røssåga, for example, can be stored in Røssvatnet, Norway's third largest lake (Bernes, 1996).

5.3. Land Submergence

The most obvious effect of hydroelectric dams and sometimes also of run-of-river impoundments, is the flooding of vast areas of land. 'This effect is especially severe when the reservoirs are situated close to mountains, in dry areas, or far north where the river valleys are usually the most productive landscape elements' (Nilsson and Dynesius, 1994; 46). With the problem of land submergence it is often of greater significance socially than environmentally. Impoundments result in the flooding of vegetation communities along the river banks and fertile lake shores which before construction have been used for agriculture or forestry. Land losses are often not extensive but the lost land is generally of high quality due to its riparian nature (Massa, 1985). More than 400,000 km^2, representing 0.3 % of the world's land area, have been inundated by reservoirs worldwide. However, the significance of the loss is greater than this figure suggests as river valley land provides much of the world's most fertile farmland and most diverse forests and wetland ecosystems. If submerged land is barren not much compensation is necessary, but if it contains buildings or areas of fertile land its acquisition may be costly. Furthermore, in densely populated districts the construction of reservoirs may result in the displacement of large populations. Examples of such displacement, although not in the Arctic region, can be seen in China and India, where between 30 and 60 million people have been displaced by large dams. In the bulk of cases studied, the majority of people evicted, who are usually poor indigenous farmers, are further impoverished economically and suffer cultural decline, greater rates of sickness and death and great psychological stress. In some cases people receive no or negligible compensation for their losses. Where compensation is given, cash payments are very rarely enough to compensate for the loss of land, homes, jobs and businesses. Where compensation is in the form of land, population pressure in many countries means that the available land is usually of poorer quality and smaller than the original holdings. These high costs of moving displaced populations, in many cases, seriously 'restricts the choice of reservoir sites and limit the scope of the project and the benefits to be derived'

(Brown, 1958; 173). Also, in northern regions, as previously mentioned, it is generally the lands of indigenous peoples that are flooded, changing a way of life, and threatening many rare ecosystems: consequences which we cannot morally place a monetary value upon.

In the northern regions of Scandinavia most hydropower reservoirs have been made by damming existing lakes or systems of lakes, but in many cases maximum water levels have increased so much that extensive areas are inundated from time to time. In the Swedish mountain region alone, just over 730 km^2 of land have been flooded. In the flatter terrain of Finland, fluctuations in reservoir levels are generally moderate, but the areas submerged can be very extensive. Two of the Nordic region's largest reservoirs, Porttipahta and Lokka, in the Kemijoki drainage basin, are not allowed to vary by more than 11 m and 5 m, respectively, and recently have rarely fluctuated by more than 2-3 m. Nevertheless, at their fullest, they together cover an area of 630 km^2. Before these reservoirs came into existence there were no lakes of any appreciable size here and their creation involved the flooding of 440 km^2 of what had been described as the largest coherent mire area in western Europe (Bernes, 1996; 144). Much of the land lost in this way consisted of valuable reindeer pastures and several old reindeer herders' migration routes have been cut off (Ivanov, 1988).

5.4. Formation of floating peat islands

When peat bogs are flooded by a new reservoir various problems may arise. Peat contains a high proportion of water, but en masse much of it is still lighter than water, especially with bacteriological action, and as a result it is inclined to break away from the subsoil and float on the surface of the reservoir. The resulting 'floating islands' as they are called, vary greatly in size and may be 100 m in diameter and up 5 or 6 m thick. Floating islands are a grave potential danger to intake screens and may clog spillways and flood control gates. This trouble usually occurs only on the occasion of first flooding, but has been known in some areas to persist for many years. If floating islands appear shortly after first flooding they are usually dealt with by the construction contractor, but if they persist for some time, the maintenance gang must be alert to the danger and prepared to deal with it (Brown, 1958).

The islands are usually brought in-shore where they are cut up and removed to a safe place above flood water level. During the process of cutting up, which may conveniently be done by steel wire ropes, there will be a fair amount of detritus produced in the reservoir which cannot well be brought ashore. Intake screens are carefully watched at such times. The detritus does not necessarily float on the surface of the reservoir, but may come to the screens at depth and not be immediately apparent (Brown, 1958).

5.5. Formation of dry river-beds

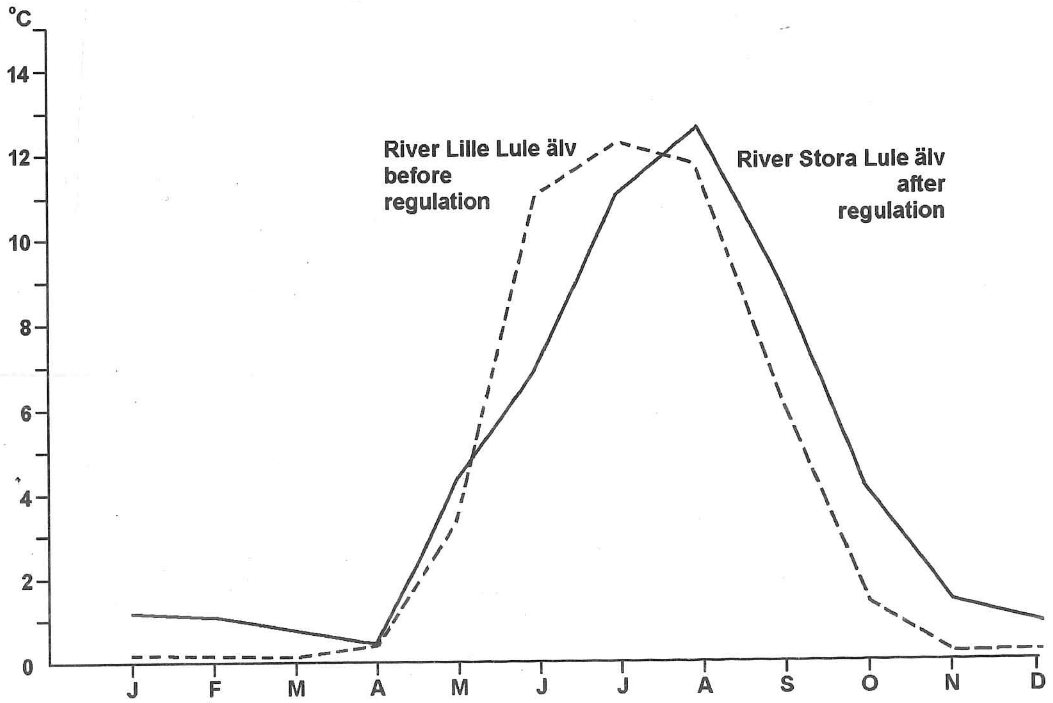
A river that is fully exploited to generate electricity is transformed from a freely flowing watercourse into a 'staircase' of one or more sets of reservoirs, dams and power stations. In some sections of rivers, sometimes several kilometres long, the river channel is dry or has very little flow because the water is often diverted through tunnels, leaving long stretches of the original river channel almost completely dry (Jansson, 2002). As a result, several types of important features and habitats, such as waterfalls, rapids, and floodplain wetlands, may disappear from entire regions. The loss of waterfalls and rapids indicates the loss of numerous species of plants and animals specific to running waters (Dynesius, and Nilsson, 1994). There are also reaches that are not impounded, but where flow is affected by dams. Such reaches maintain their annual discharge but water flow is controlled by the discharge at the upstream dam (Jansson, 2002). These problems are then heightened by the fact that as much as 6 % of the world's river runoff is evaporated through human manipulations, mainly irrigation but also by evaporation from reservoirs (Dynesius, and Nilsson, 1994).

The problems of dry river beds is seen in the Emån, at the Klinte and Brunnshult hydropower stations, where the water is lead through tunnels. The only water reaching the old river channels is leakage water from the hydropower stations, having major consequences for the flora and fauna of the river and on the deciduous forest on the banks (Weichelt, 2001). Also, on the Suldalslågen almost 50 % of the annual flow through the Hylen power station at Suldalvatn is diverted. This causes a disruption of the river continuum and a change of downstream flow, in turn causing major physical alterations to the system (Johansen et al, 2002). The Hylen hydropower station is therefore instructed to release a minimum discharge to the Suldalslågen in an attempt to minimise effects of the diversion. This discharge varies from at least 12 m^3s^{-1} in the winter to at least 150 m^3s^{-1} during the snow melt period. In the summer the release is 60 m^3s^{-1}, gradually decreasing to 12 m^3s^{-1} in late autumn (Johansen et al, 2002).

5.6. Alteration of temperature regimes

Hydropower installations also give rise to changes in the natural thermal regime of rivers. In rivers with no lakes or reservoirs the water temperature will reach the freezing point in the beginning of the winter with subsequent ice formation *(Figure KK)*. Due to withdrawal of warm water stored in deep reservoirs, downstream winter temperatures tend to be higher, causing ice cover to be reduced and delayed, or even non-existent, some distance downstream of the reservoir (Billfalk, 1992). The downstream temperature in summer is also often considerably colder than is natural *(Figure 16)*. The magnitude of this change depends on how many tributaries with more natural temperature regimes join with the watercourse downstream of a reservoir.

Figure 16: Monthly mean water temperature in the Lilla Lule älv before regulation and in the Stora Lule älv after regulation *(Source: Henricson and Müller, 1979)*.



The changing temperature regime of a hydro-affected river system effects river dynamics, flora and fauna in the system as well as the hydropower production itself and communities in the area. One of the most harmful of these effects is the increased winter draw-down; as a consequence of 'the descending water level in winter, ice presses against the bottom sediment' (Hellsten, 1997: 351). This ice, pressing against the bottom sediment, causes both freezing of the sediment and erosive scouring to take place. These effects are most obvious in regulated lakes where an effective reduction of the water level allows wide areas to be affected by lowering ice, as, the higher the water level, the smaller the area of frozen bottom zone. In the Kemijärvi, studied by Hellsten (1997), the 'frozen zone reached a depth of 1.3-2 m', in the natural lake 'only the uppermost part of the littoral was frozen' (Hellsten, 1997; 251). This is obviously an extremely important factor in regulated lakes such as Kemijärvi, which are characterised by changing seasonal water levels. These problems of ice formation also extend to affect hydro power stations and their efficiency, consequently, 'when designing and operating hydropower stations in cold climates due consideration for the various effects of ice and ice formation processes is of prime importance for the economy of such projects' (Billfalk, 1992; 1206). The major problems of ice for the operation of hydro power stations in such systems are the clogging of intakes due to frazil and drifting ice, as well as head losses and reduced discharges due to ice jams (Billfalk, 1992). There is clearly a basic desire from power companies that such northern climates should not restrict the operation of power stations, such as the full use of the peak power capacity. However, it is suggested that, in rivers fully developed for hydropower, spring break-up is usually not particularly troublesome. The ice often loses its strength before it comes into motion. Temporary blockage of intakes may occur but it is still usually not very harmful and easily remedied (Billfalk, 1992).

Temperature regime is also one of the most important physical factors for fish; affecting respiration, activity and growth. It can be expected that the lower water temperature in downstream reservoirs will affect fish growth adversely, especially as the transport of nutrients and food downstream is also reduced (Beier, 2002). In the Suldalslågen, for example, winter temperatures are similar to those found in the unregulated river, but during the summer months there has been a decline in water temperature corresponding to approximately 100 day-degrees. A decline in fish growth was expected, however, due to other alleviating factors, such as lower fish density and reduced competition, fish growth has increased (Johansen et al, 2002). Finally, in some places, regulation of the flow of water has modified the local climate along the rivers. One effect generally unwelcome to people living nearby is the prolonged fog that can often arise in river valleys where, because of the artificially high rate of flow in winter, the water surface never freezes (Billfalk, 1992, Bernes, 1996).

5.7. Interruption of sediment movement

'Filling of reservoirs with silt is a problem in long-term power production. It is detrimental to irrigation, flood control, and navigation' (Halacy, 1977; 48). Major changes occur in hydrological systems due to changing silt loads carried by modified rivers. This silt load consists of the topsoil denuded from previously fertile riverine lands which is deposited in newly built reservoirs. The construction of a dam across a river will always set up new equilibrium conditions. Silt, normally carried downstream to the lower reaches of a river, is trapped by a dam and deposited on the bed of the reservoir. This silt can slowly fill a reservoir, decreasing the amount of water which can be stored and used for electrical generation. Furthermore, river levels upstream will also be raised until equilibrium conditions are again restored. In the main body of the reservoir, silting will occur wherever the velocity of the incoming river water drops below that necessary to maintain the silt in suspension. Therefore, those reservoirs which are narrow and deep will tend to silt less than those which are broad and shallow (Brown, 1958). The river downstream of the dam is also deprived of silt which fertilises the river's flood-plain during flood periods.

Many lands, which once had thriving populations, are today littered with the remains of the reservoirs and irrigation works which formerly sustained them. When these reservoirs and canals became filled with silt, generally through neglect, the regions became gradually depopulated. Examples of such abandoned works are to be found throughout the East in Iraq, Persia, India and Ceylon, and even in Spain. 'It was not until towards the end of the nineteenth century when Sir William Willcocks began his studies of the ancient irrigation systems, in what was then known as Mesopotamia, that the serious attention of engineers was directed to the problem of preventing the eventual loss of usefulness of reservoirs by the deposition of silt' (Brown, 1958; 346). However, these problems of silting are not only relevant to ancient systems; they are of major concern in modern ones. In recent years the United States have become seriously concerned over the continued deterioration in the capacity of many of its reservoirs as the result of siltation. It has been stated that 64 % are estimated to have an effective life of less than 100 years, and it is probable that not more than 15 % can be regarded as being effective for 200 years or more. For example, Lake Meade, the reservoir behind the Hoover Dam, lost 4.5 % of its capacity in only 13 years and the Guernsey reservoir lost 33 % in 20 years (Halacy, 1977). At this rate, Lake Meade is predicted to have a useful life of less than 100 years.

The effects of such siltation can be clearly seen in two of the Scandinavian case study rivers; the Suldalslågen and the Beiarelva. The transport of sediments, both suspended and bed load, has been investigated in the Suldalslågen during the last decade. Between 60 and 80 % of the contribution of sediments to the river come from agricultural areas, and between 20 and 40 % from gullies in the valley, both natural and man-made. The total annual yield is estimated to be between 100 and 500 tons (Johansen et al, 2002). Naturally the sediment flow out of the Suldalsvatn was very small and the establishment of the dam has probably not reduced the sediment inflow into the river. However, bed load calculations indicate that the diversion of almost 50 % of the annual flow has reduced the transport capacity of the river. This has lead to an accumulation of sediments and an increase in the level of the riverbed. Moreover, the extensive accumulation of sand on the riverbed has clogged the interstices between cobbles and boulders, and thus affected many fish habitats (Johansen et al, 2002). Since 1989, in the Beiarelva watercourse measurements have been taken at the Klipa gauging station, some half way down the river course. In this river system the effects of hydropower are slightly different to those in the Suldalslågen, as it contains no major reservoir, consisting predominantly of and a diversion of water into the Storglomvatn reservoir, situated in an adjoining river system. After the diversion of water in 1993 the transport of suspended materials has gone through various changes. The yearly load has, on average, been reduced to less than 50 %. However, the daily maximum concentrations seem to have increased after 1994. These maximum concentrations occurred during situations with more or less natural flow in the river and no, or very little, water diverted. In such situations an extra amount of sediments has been brought into the main river either 'as sediments from the tunnel system' or 'as sediments from extra erosion in the tributaries just downstream of the intakes' (Bjørtuft et al, 2002; 18). Due to reduced flow and especially reduced flood peaks, the river's transport capacity has been reduced causing an accumulation of sediments, mainly in the upper parts of the system. It is expected that this reduced sediment transport will cause future changes in the river delta where Beiarelva runs into the sea (Bjørtuft et al, 2002).

5.8. Shore erosion

In many regulated lakes, water levels are raised during autumn to increase regulation capacity for hydropower production. Generally, erosion is at its greatest during autumn, when the water level is usually high, strong winds occur, and the shore is partly without sheltering vegetation (Marttunen and Hellsten, 2002). The seriousness of this problem is caused by the regular fluctuation of water level which causes severe erosion on the entire shore zone of a storage reservoir between the high- and low- water marks. The raised water level at the beginning of the regulation increases shore erosion; if the regulated water level is above the former mean highest water level, for example, rapid erosion of the shore takes place. Riverbanks along lake-like impoundments are usually exposed to increased wave action because of channel widening, and frequent water-level fluctuations resulting from flow regulation in the power stations. These actions change the structure of the riverbank by eroding the fine-grained substrates, and in the winter an expanding ice sheet compresses the riverbanks making them even more sensitive to erosion. These disturbances make plant establishment difficult (Andersson et al, 2000). Consequently, as soon as the water drops below its highest level, 'conspicuous, almost sterile fringes emerge along [reservoir] shorelines' (Bernes, 1996; 146). When the water is at its lowest, these zones may sometimes be several hundred meters wide. What is more, in reservoirs with widely varying levels, benthic vegetation below the low-water mark is often disturbed or eliminated. This is because, when such reservoirs are full, the water is so deep in the areas concerned that adequate light is no longer able to reach the bottom (Bernes, 1996).

The most important effects of a reservoir are likely to occur downstream from the dam as the clear water discharged from a reservoir may induce increased erosion (Brown, 1958). Under a given set of flow conditions the amount of material picked up from the bed of a river and carried in suspension will tend to increase until an upper equilibrium limit is attained. It therefore follows that, if the course of a river flowing over an erodible bed in conditions of temporary stability is interrupted by the construction of a reservoir, the relatively clear water released by the dam will have increased powers of erosion. The rejuvenated river will commence once more to cut into its bed and the process of erosion will go on until the charge picked up again corresponds to conditions of stability (Brown, 1958). In the Ume älv, for example, downstream from both storage reservoirs and run-of-river impoundments, erosion of the riparian zones is increased because upstream dams interrupt sediment transport and therefore the water has a large potential to regain suspended sediments (Galay 1983, Williams and Wolman 1984).

5.9. Changes in water chemistry

The flooding of land in conjunction with hydroelectric projects can result in temporary eutrophication of associated water systems, caused by a decompostion of organic matter, with a release of phosphorus and other elements from flooded ground (Hellsten et al. 1993). 'Immediately after damming there is a rapid increase in aquatic production because of nutrient leakage from the inundated soil and vegetation' (Nilsson and Dynesius, 1994; 46). In the Porttipahta and Lokka reservoirs in Finnish Lapland, average phosphorous concentrations of 28 and 48 μgl^{-1}, respectively, were observed in the 1980s, and 'here the extra nutrients formed the basis for quite a profitable fishery' (Bernes, 1996; 171). In recent years, though, phosphorous amounts in these reservoirs have decreased, and in the long run a hydroelectric scheme can leave a body of water poorer in nutrients than it was originally. After some years the aquatic production decreases, often to below the former ones, as constantly flowing stretches of rivers are replaced with pondage or storage reservoirs, water often remains stagnant for long periods, allowing a larger proportion of particle-bound nutrients to sink to the bottom (Bernes, 1996).

This situation is far more serious in areas where organic matter is submerged, particularly in reservoirs where large areas of mires and bogs have been flooded. During the inundation of peat-covered areas bacteria are released from submerged vegetation transforming any natural mercury or other heavy metal elements present in underlying rocks into soluble, toxic methyl-mercury or similar compounds, which may enter the food chain (McCully, 1996). This is extremely dangerous as ethyl-mercury is a neurotoxin, ten times as toxic as elemental mercury (Nilsson and Dynesius, 1994). This compound accumulates in muscle and nerve tissue and, as a result, is transmitted up the food chain and particularly enriched in fish, reaching concentrations of up to 100 x 10^6 times as great as that in the surrounding water (Raphals, 1992). High concentrations of methyl mercury have been discovered and documented in many fish throughout Scandinavia and Canada. Some of this has been associated with industrial pollution. Scientists have suggested that high concentrations of mercury may persist in waters for 30 to 100 years after dam closure (Pearce, 1991). Because mercury and other metal accumulations in the bodies of fish pose a major health hazard to those who depend on these fish for food, it has been suggested that mercury contamination has become the 'most serious human health issue connected to dams' (Raphals, 1992; 51). The water quality of many reservoirs also presents a health hazard due to new forms of bacteria which grow in many of the hydro rivers. In this respect, run-of-river type hydro stations generally have lesser effects on the environment.

The Kemijoki catchment has a relatively high percentage of peatlands (40 %) and is therefore greatly affected by the aforementioned problems of mercury loading (Marttunen and Hellsten, 2002). The construction of the large Lokka and Porttipahta reservoirs has also increased the loading of nutrients and mercury into the Kemijärvi (Virtanen et al. 1993). In the Kemijärvi there was a significant increase in the mercury content of sediment during the first years of regulation but, unlike most hydropower systems, due to short retention times and high discharges of water, the Kemijärvi is quite resistant to nutrient loading and water quality problems, with only 6 % of loading sedimented into the lake (Kinnunen, 1989; Virtanen et al, 1993).

Also, a few recent studies of large reservoirs formed behind hydropower dams have suggested that decaying vegetation, submerged by flooding, may give off quantities of greenhouse gases equivalent to those from other sources of electricity. If this turns out to be true, large hydroelectric facilities that flood large areas of land might be significant contributors to global warming. Run-of-river hydro generators without dams and reservoirs would not be a source of such greenhouse gases.

5.10. Effects on riparian fauna

River margins are important elements in the conservation of ecological integrity. 'In small and intermediate-sized northern rivers, margins are the major producers of food for aquatic animals' (Nilsson, 1996; 418). When floodplains are drained as a result of river regulation, food availability, especially for aquatic animals, may be substantially reduced, due to a decrease in primary productivity and the prevention of plant biomass from entering the water (Nilsson, 1996). The effects of the controlled water regime of a reservoir may have detrimental consequences for fish and other animal populations. Damming a river can impede fish from migrating upstream to spawn. These effects on migration are highly significant as more than one-quarter of the dams in the World Commission on Dams survey ranked impedance of migratory fish as 'the most significant impact caused by hydropower schemes' (Clarke, 2000; viii). Furthermore, one of the most harmful consequences of water level regulation is the diminishing 'suitable spawning and nursery areas and [the] deterioration of the quality of the remaining habitats' (Laine et al., 2002; 65). Generally, in stretches of rivers that have been dammed, the current is reduced so much that they now resemble lakes rather than running waters. In Nordic reservoirs of this type the fish fauna therefore becomes dominated by lacustrine species, while species more highly prized by anglers, such as grayling and brown trout, are only to be found in rivers which are still fast flowing (Bernes, 1996; 146).

Before the development of hydropower, Scandinavian rivers had a rich stock of anadromous atlantic salmon *(Salmo salar)* and brown trout *(Salmo trutta)*. 'The reproduction of salmon and sea trout is now based on hatcheries in [these three] countries' (Henricson and Müller, 1979; 193). This has occurred as the economically valuable migratory fish stocks of large and mid sized rivers are severely depleted by hydroelectric developments, blocking migration routes to their spawning grounds (Laine et al., 2002). Marttunen and Hellsten (2002) even go as far as stating that the migration routes have been 'permanently closed' by power stations. Salmonids are therefore affected not only in watercourses fully developed for hydroelectric power, but also in those whose exploitation is only a single power station near the river mouth. The Pite älv and Vindelälven belong to this latter category, despite the fact that in Sweden they are often described as undisturbed. These barriers to migration have consequently resulted in many 'genetically unique salmon and trout populations being lost forever' (Bernes, 1996; 146). In northern Norway, for instance, hydroelectric schemes have eliminated the original salmon stocks of the Pasvikelva and four other rivers. Similarly, the Kemijoki and Lule älv have lost their original populations of both salmon and trout (Bernes, 1996; 146).

The Kemijoki was one of the best salmon rivers in Europe until 1949, when the first dam and hydropower station were completed close to the river mouth (Laine et al., 1998). The construction of the Isohaara dam caused a serious reduction of the fish populations used by local inhabitants, putting an end to 'the salmon fishing industry which for centuries has marked the economic and cultural life of Lapland' (Massa, 1985; 469). The fish fauna of the Kemijärvi now comprises 18 fish species, which is approximately the average number in large Finnish lakes. The number of species before water level regulation is not well known, but Sormunen (1964) estimated that it was between 15 and 22. Numbers of different species in the lake seem not to have altered, however, because of the permanent closure of migration routes, populations of atlantic salmon, brown trout and anadromous whitefish have declined in the Kemijärvi and about 50 % of adult burbots have become sterile (Marttunen and Hellsten, 2002, Korhonen, 2000). Presently, fish biologists classify the Kemi River, excluding the Ounas tributary, as belonging to 'the worst quality class among the fishing waters in Finland, because the original species of fish nearly disappeared and fish-breeding activities are no longer sensible' (Massa, 1985; 469).

In the Emån hydropower stations and dams are definite obstacles to migration (Weichelt, 2001). This is proven by the small numbers of fishes present between the Brunnshult and Klinte hydropower stations. The dams of Klinte and Brunnshult also have a deleterious effect on the fish population, since the hydropower stations probably dam large areas with suitable biotopes for *Salmo trutta*, but it is suggested that by means of a minimum release of water suitable biotopes for brown trout could be recreated in the old river channels (Halldén et al, 2000). Such an operation strategy, trying to recreate natural flow regimes, has been introduced in the Suldalslågen. Generally, the seasonal flow pattern resembles the natural flow as the Hylen power generator is not operated during June and July to maintain summer flows up and to avoid luring returning salmon into the wrong fjord branch (Johansen et al, 2002).

In many rivers attempts to correct the adverse effects of hydropower stations on fish stocks have been made by restocking. One may argue that the release of reared fish is not a direct effect of physical modification, however, these activities are at present by law inseperable from hydropower industry, and 'of fundamental importance for the fish communities and their genetic diversity' (Beier, 2002; 9). Furthermore, in many regulated waters, attempts have been made to maintain fish stocks by introducing new fish and crustacean species for their food, but such introductions have not always proven successful and have often had undesirable side effects (Bernes, 1996). In many cases, 'stocking of hatchery-reared fish to compensate for the reduction or loss of natural salmonid production has sometimes aggravated rather than prevented genetic erosion' (Bernes, 1996; 146). Presently approximately 2.5 million trout and salmon are released yearly in Sweden, 250,000 of which are released in the Dalälven to compensate the loss of natural fish. Such releasing of reared fish into rivers has been developing since the 1950s when it was enforced by legislation requiring the hydropower companies to compensate production loss of salmonid fish (Beier, 2002).

It is not only aquatic vertebrates that are affected by the continuously fluctuating water levels in run-of-river impoundments. The two most disastrous effects of river regulation on mammals and birds are the permanent inundation of vast areas of land, and the disruption of the seasonal flood regime along the river (Nilsson and Dynesius, 1994). For example, systems modified for hydropower have proved to be fatal for the Eurasian beaver *(Casto fiber)* which require a stable water level during the winter. In the Fax River in Sweden, for instance, beaver were forced out of their burrows in severe cold, and their winter stores of forage were flushed away because of rapid variations in water flow (Nilsson and Dynesius, 1994). Despite these many problems created by hydropower developments, in Sweden it has been shown that the Eurasian beaver populations increased simultaneously with the period of intense hydroelectric development during the

1950s to 1970s, as decreased hunting has made it possible for beaver to return to former habitats in unregulated rivers and brooks (Nilsson and Dynesius, 1994).

Furthermore, the temperature regime, and the location and duration of ice-cover in run-of-river impoundments has also affected many species in such rivers. In northern Scandinavia there are few rapids left to offer unfrozen water areas in winter. Such habitat reductions affect fishing animals such as European otter (*Lutra lutra*) and American mink (*Mustela vison*). The decline of the latter of these two species is not markedly problematic as it is an introduced predator with associated adverse effects of its own. Rapids, which remain unfrozen in winter can also be important wintering areas for white-throated dipper (*Cinclus cinclus*). On the other hand, new unfrozen stretches are added in run-of-river impoundments, but their importance for species such as European otter and white-throated dipper is yet undetermined. In Sweden, the population of European otter has recently been much reduced, but the role of hydroelectric development in this is unclear. Skoog (1975) claimed that European otter disappeared after hydroelectric development, but Olsson et al. (1988) compared the frequency of tracks of European otter in regulated and unregulated rivers in northern Sweden without finding any obvious differences that would depend on regulation. Also they could not explain the occurrences of otter in regulated rivers by adjacent unregulated tributaries (Nilsson and Dynesius, 1994). Changes in the location of open water areas during the ice period can also affect the bird fauna, as holes in the ice in spring are important resting and feeding sites for migrant birds. Both Skoog (1975) and Svendsen (1990) provide Scandinavian examples of the establishment, under regulated conditions, of new resting sites during spring migration for, among others, whooper swan (*Cygnus cygnus*), common goldeneye

(*Bucephala clangula*), mallard (*Anas platyrhynchos*) and tufted duck (*Aythya fuligula*). Also, downstream of the power stations in cold climatic zones, increased ice fog and hoar frost on remaining forage plants deter, among others, black grouse (*Tetrao tetrix*), willow grouse (*Lagopus lagopus*) and moose (Skoog, 1975).

5.11. Effects on riparian flora

'River systems and their riparian zones play key roles in the regulation and maintenance of biodiversity in the landscapes. They have a fundamental role in the movement of organisms and dead matter' (Dynesius, and Nilsson, 1994; 753). River margins are one of the most species rich ecosystems of the world with some rivers' vascular plant flora including as much as 20 % of the species in large regions. 'This high species richness is partly explained by the complex and dynamic nature of river margins' (Nilsson, 1996). The river corridor is especially important in high latitude catchments. The average net production of plants on unregulated shorelines along northern rivers is more than twice as high (about 20,000 $kgha^{-1}yr^{-1}$) as the net production of plants in boreal forests (Nilsson and Dynesius, 1994).

The annual dynamics of water level fluctuation is an important factor affecting shore biota. Within the boreal zone, 'the typical water level curve of a non-regulated lake includes a sharp and rapidly declining spring flood peak after a late winter minimum' (Hellsten, 1997; 359). Typically, in many Scandinavian regulated lakes the water level rises during the summer, whereas in non-regulated lakes it decreases after the spring flood (Marttunen and Hellsten, 2002). In a regulated lake, this transition of the flood peak from the end of May to the beginning of June is ecologically important; it reduces the growth of shore vegetation, because many species cannot tolerate prolonged submersion (Hellsten, 1997). The riparian zones along run-of-river impoundments are very narrow. As for the storage reservoirs, the riparian zones are inundated for longer periods compared to the free flowing rivers, causing stress to flood-sensitive species, and limiting the time for plant growth (Bernes, 1996). The broad bank zones of unregulated rivers, in which vegetation gradually thins towards the water's edge, are therefore replaced in these reservoirs by an abrupt dividing line at the high-water mark between undisturbed land vegetation and a virtually bare shore. In other parts of a regulated river system, for example below a large reservoir, natural variations in the water level may be reduced or eliminated. This, too, affects the vegetation, since many river-margin plants are adapted to, and dependent on, flooding every spring. 'Suppression of the spring flood or high water at the wrong time of year may be all that is needed to eliminate sensitive species' (Bernes, 1996; 146). Along the Ume älv, the density of riparian plant species is now, on average, a third lower and their cover 85 % less than along its unregulated tributary, the Vindelälven (Jansson, 2002).

Riparian vegetation and the composition of the riparian flora have been fundamentally altered in the Ume älv following exploitation for hydropower production (Nilsson et al. 1991). Along the Ume älv most of the river margins become inundated during the growing season for longer periods than in free-flowing rivers. The vegetation is consequently restricted to a narrow strip close to the high water level, with sparse occurrences of amphibious species or rapidly reproducing annuals. The percentage cover of trees and shrubs on margins along the Ume is on average 0.5 % and the mean cover of herbs and dwarf shrubs in the same areas is 1.6 %. Such amounts along the free-flowing

Vindelälven are 44 % and 48 % respectively (Jansson, 2002). However, 'few, if any, riparian plant species have gone extinct from the river' (Nilsson et al, 1991; 969). In a comparison of the Ume and Vindel rivers, twenty-five 200 m stretches of river margin were investigated: 260 species were found along the Ume älv, compared to 258 along the Vindelälven (Nilsson et al. 1991).

In the Suldalslågen increased winter lower flows, and especially the absence of large floods, has led to increase in moss growth which has, in turn, impaired the fish habitats (Johansen et al, 2002). Moss may have both a direct and an indirect effect on fish, affecting both habitat and food quality and food availability. Areas with dense mats of mosses held lower densities of salmon parr than areas where the it had been removed (Johansen et al, 2002).

Dams are not only barriers to the movement of fish but also to the downstream movement of plant propagules (Andersson et al. 2000). The dams and the altered flow regimes also affect the dispersal of riparian plants. Natural rivers and their adjoining riparian zones are also effective paths for plant dispersal: the rivers carry large numbers of plant propagules over long distances (Nilsson et al. 1991, Johansson and Nilsson 1993), and riparian zones are rich in water-dispersed plants (Johansson et al. 1996). In free-flowing rivers floating propagules are rapidly transported far downstream during floods (Nilsson et al. 1993). In impounded rivers, current velocity is low and floating propagules either sink or become swept ashore by winds. A few propagules may pass dams through turbines or spillways. Species with long-floating propagules are more likely to pass, because passages are hard to hit, and long floating-times increase the probability of success. Species with short-floating propagules may be absent from impoundments because they fail to recolonise after local extinction. Riverbanks will thus be colonised by species from other sections of the same impoundment and from surrounding uplands rather than by species from upstream areas. This situation has affected the composition of riparian plant species in regulated rivers in northern Sweden, including the Ume älv which been converted to stairs of lake-like water bodies interrupted by dams and underground passages, therefore significantly affecting distribution of waterborne vascular plant propagules (Nilsson et al. 1993, Andersson et al. 2000, Jansson et al. 2000). Furthermore, in free-flowing rivers, litter that is produced in riparian zones or brought there from terrestrial areas, is removed during floods, transported by the river and deposited on the river bottom or in the riparian zone. Following regulation, seasonal floods that remove litter from the riparian zone may be reduced and downstream transport is decreased owing to the slow current velocity in the reservoirs and by the dams (Jansson, 2002).

6. Quantitative analysis of Scandinavian hydropower.

6.1. Land submergence – electricity potential analysis.

A trial analysis was conducted to determine the relationship between annual electricity production in a river basin and the associated lake area, thus giving an approximate estimate of the area of land submerged if hydro developments were to increase (*Table 1*). Due to time constraints and availability of data it was practicable to assemble a comprehensive data set for such analysis for the Finnish systems only. The lack of analysis of the Norwegian and Swedish systems is problematic as the results obtained from the Finish systems cannot be regarded as accurately representing the situation of the other countries due to their different geomorphological conditions. The more uniform precipitation in Finland, compared with large local variations in the other countries also affects the application. Nevertheless the analysis serves to demonstrate a practical determinent.

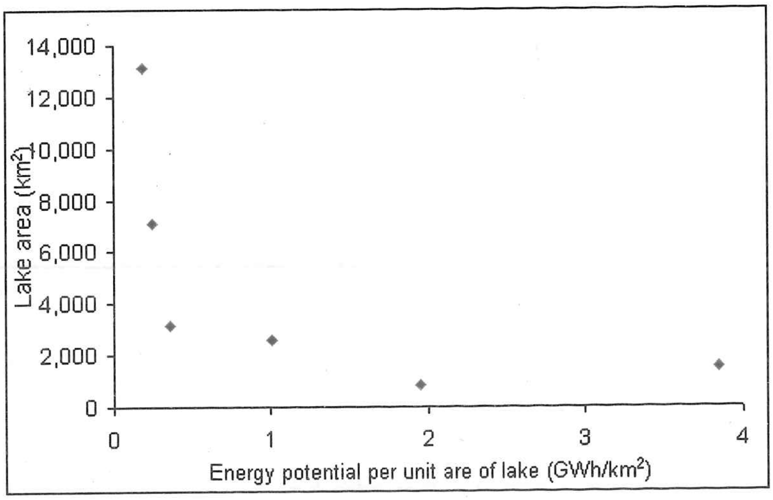
Table 1: Water courses in Finland and their energy potential.

River Basin	Lake area in catchment (km^2)	Catchment area (km^2)	Lake area as a % of total catchment	Annual energy capacity (TWh)	Energy capacity per area of lake (GWh km^2)	Energy capacity per area of catchment (GWh km^2)
Vuoksi	13,100	61,500	21.3	2.35	0.18	0.038
Kymi	7,067	37,000	19.1	1.75	0.25	0.047
Kolemaen	3,160	27,000	11.7	1.15	0.36	0.043
Oulu	2,565	22,500	11.4	2.58	1.01	0.115
Li	820	14,400	5.7	1.60	1.95	0.111
Kemi	1,493	51,500	2.9	5.75	3.85	0.112
	28,205	213,900		15.18	**Avg: 0.54**	**Avg: 0.071**

As can be seen in *Table 1* the annual energy capacity per unit area of lake for each lake system has been calculated. From these simple calculations it can be seen, as shown in *Figure 17A*, that lake area and energy potential per unit area tend to be negatively correlated. This said, lakes covering smaller areas do not necessarily contain smaller volumes of water as they may be deep within a steep sided valley. The lake area as a percentage of the catchment area gives an estimation of this proportion; precipitation is relatively uniform throughout Finland, therefore a small lake in one catchment will still receive the same inflow as a larger lake in a similar sized catchment and so must be deeper to retain it. Such greater reservoir depth requires the dam to be higher and therefore the head at the generator is greater, so producing more power. This is demonstrated in *Figure 17B* in which energy production per unit area and lake area as a proportion of the catchment are clearly negatively correlated.

Figure 17: Energy production in Finnish lakes.

(A)



(B)

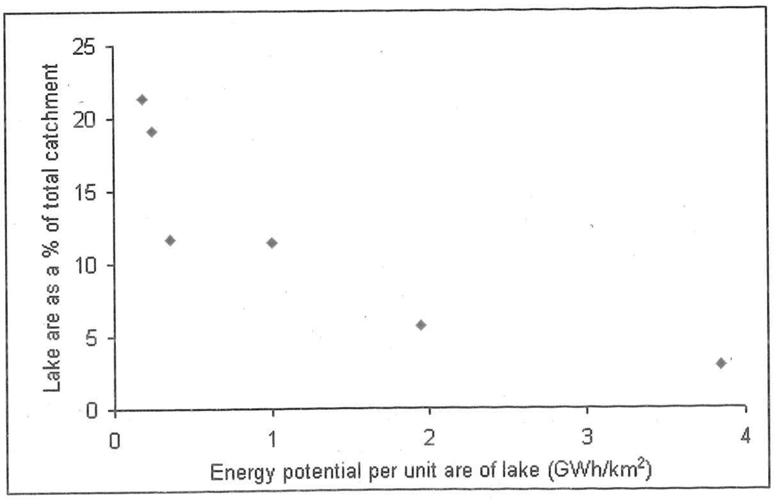


Table 3: Summary of electricity produced by hydropower in Scandinavian countries.

	Area (km^2)	Total Electricity generation (TWh)	Electricity generated by hydropower (TWh)	% of total generation produced by hydropower
Norway	324,000	112.01	111.34	99.40
Sweden	450,000	144.93	68.28	47.11
Finland	337,000	66.99	11.86	17.70

An average energy production per unit area of lake was calculated; 0.54 GWh km^2 *(Table 1)*. Using this estimate an approximate total lake area was calculated if Finland were to attempt to produce all its present electricity demand by hydropower. Finland produces around 67 TWh of electricity annually, which using the above approximation would require 123,900 km^2 of reservoir; almost 37% of the total area of Finland, a situation which is obviously impossible.

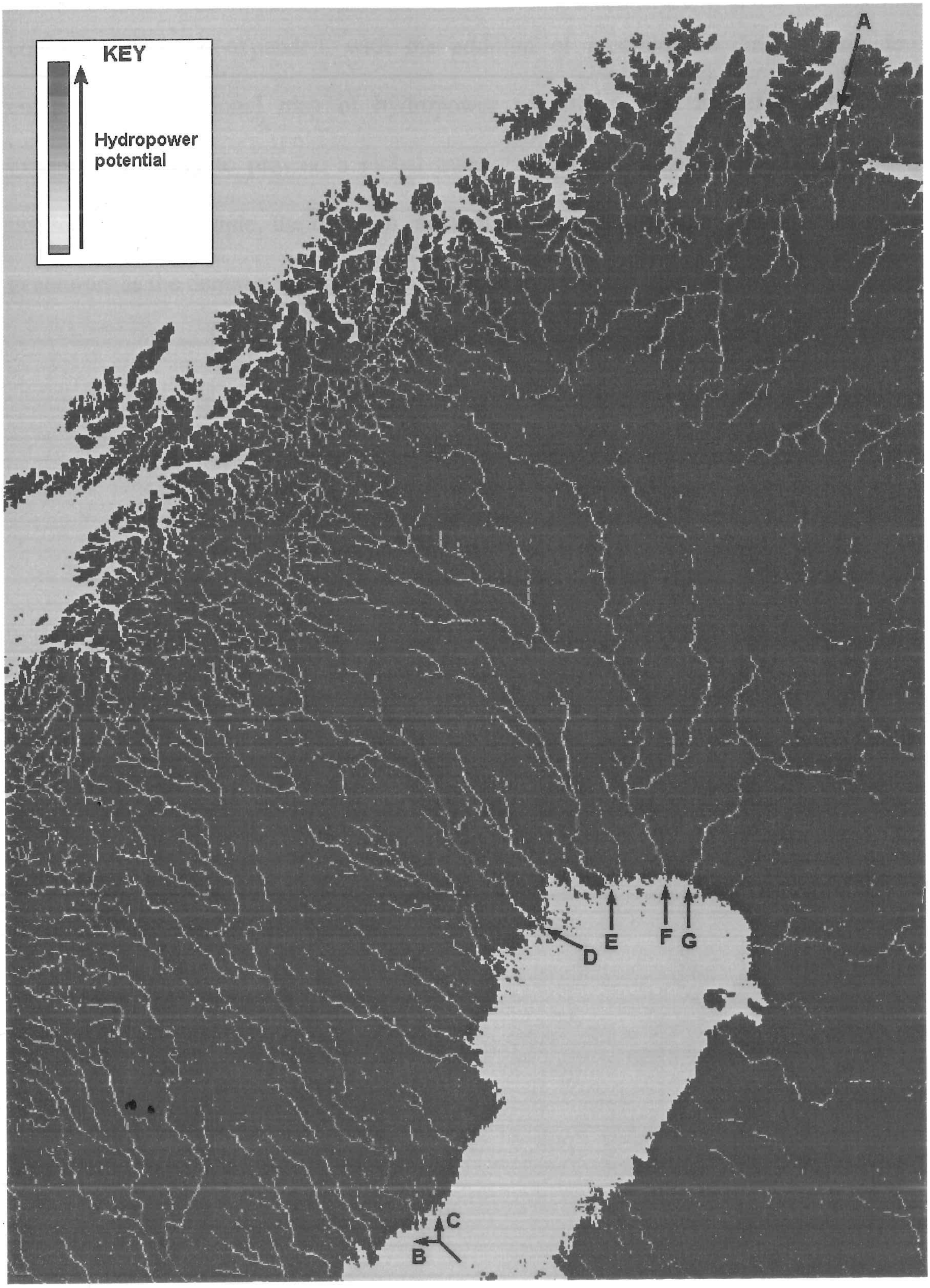
6.2. Geographical Information System of hydropower potential.

A Geographical Information System (GIS) was developed to examine the hydrological potential of rivers. This potential is measured by the area of lake needed at any given point to generate a unit of power. This gives an idea of whether present stations are located in the most efficient places and may indicate the most suitable areas, in terms of energy production, for future generators (*Figure 18*).

In the creation of the GIS several simplifications were necessary, such as that the cross-section of the rivers are assumed to be parabolic and that the side slopes of valleys are identical to each other. Using a digital elevation model with a resolution of 1 km, obtained from the USGS 'Land Processes Digital Active Archive Centre', a model of hydropotential according to valley conditions was established. This showed those areas in which river slope and valley slope angles are steepest and therefore have the potential to store a quantity of water in the smallest area of lake. A model of flow accumulation, again obtained from the USGS 'Land Processes Digital Active Archive Centre', was then applied to accomodate the varying size of river catchment areas. This is an important component as the hydropower potential of an area is not only determined by local slope characteristics but also by annual water supply. Precipitation statistics are therefore also important, but in this model, for ease of application they were not incorporated. This was justified as, other than the west and the south-western tip of Norway, amounts of precipitation are relatively uniform throughout Scandinavia. A section of the completed GIS, showing the northern region of Scandinavia, can be seen in *Figure 18*.

From *Figure 18* it can be seen that the rivers with the greatest theoretical potential for hydropower production tend to be those which are, in fact, already the most harnessed by power stations. The Ume älv, Lule älv and Kemijoki; three of the most rigidly regulated rivers in northern Scandinavia, are shown to have many stretches with vast hydropower potential. There are also rivers which have such propensities for hydropower production which have not been harnessed due to environmental and political considerations. The Vindelälven, Kalix älv, Torne älv and Tenojoki all appear to have extremely vast potential, but are not dammed. The first three of these rivers are protected by the Swedish Natural Resources Act and power production from the Tenojoki is problematic because it forms the northern boundary between Norway and Finland and therefore ownership is contestable.

Figure 18: Illustration of the GIS for the northern area of study. (A) Tenojoki, (B) Ume älv, (C) Vindelälven, (D) Lule älv, (E) Kalix älv, (F) Torne älv, (G) Kemijoki.



This GIS has demonstrated that, for northern Scandinavia, it is relatively accurate and could therefore be expanded, with the addition of precipitation data to provide a comprehensive regional map of hydropower potential. The model could also be expanded spatially to provide a global map of hydropower potential. This could be utilised in, for example, the decision making processes surrounding future locations of generators as the demand for energy continues to increase.

7. Mitigation of effects and alternatives to hydroelectric power.

7.1. Introduction

Since the environmental effects of hydropower developments have been publicly realised conservationists have put forward arguments against such schemes. In Sweden, four major rivers; the Torne älv, Kalix älv, Pite älv and Vindelälven are protected, under the Natural Resources Act, from further exploitation for hydropower (Bernes, 1996). Furthermore, in northern Finland the Ounasjoki, the most important tributary of the Kemijoki, is protected and plans to construct the new Vuotos reservoir on the main course of the Kemijoki have been stopped. 'There are, however, powerful pressure groups, also inside the province of Lapland, who want to continue the hydropower development to relieve unemployment in the North' (Massa, 1985; 471). 'Legislation forbidding dams on remaining free-flowing tributaries and main-channel reaches is a minor tool' (Dynesius and Nilsson, 1994; 760). More important the growing environmental consciousness has fostered a will to find ways to minimise the adverse effects of existing dams and diversions or alternatives which allow expansion without the associated environmental degradation. Remedial measures in fragmented rivers can re-naturalize the system to various extents, but any important changes will be difficult to make without reducing electricity production, a situation which may not be economically feasible (Nilsson, 1996). It is suggested that some of these solutions 'would [never] give us the former pristine rivers back, but rivers that, at least in the long term, would attain a near-natural appearance' (Nilsson, 1996; 416). Although the appearance of regulated rivers as largely artificial compared with free flowing ones will remain even after remediation we must not think that remediation which provides only minor results is unnecessary. Even small improvements are important, but remedial measures should not be seen as 'the solution that will save us from future environmental deterioration associated with the disruption of hydrological systems' (Nilsson, 1996; 428). Mitigation, for example, was the most widely practised response to adverse ecosystem changes for the large dams in the World Commission on Dams Survey in 2000. This showed that for 47 projects reporting the effectiveness of mitigation measures, only 20 % worked very well, 40 % did not mitigate anything, and 40 % were moderately effective (Clarke, 2000; viii). In general though, the goal of remedial measures should be sustaining ecosystem integrity. A living system exhibits integrity if, when subjected to disturbance, it sustains a capability to recover towards an e stable state that is 'normal and good' for that system (Regier, 1993). This does not mean that nature has to be brought back to pre-human states, which is a very difficult scenario for river managers to achieve (Milner, 1994). Stable states, other than the pristine or naturally whole, may also be taken to be 'good' (Regier, 1993).

Some of these mitigation strategies, which I will discuss here, include the re-establishment of more natural flow regimes, construction of fish ladders, and fish restocking. Alternatively, it is suggested that only small-scale, less environmentally harmful power stations are developed, that dams could be removed or even forms of electricity generation, other than hydropower, could be utilised.

7.2. Flow alteration

Most factors affecting the riparian ecosystems are clearly related to water level fluctuation. The possibilities 'to alleviate the harmful effects of the water level regulation are therefore limited if the fluctuation is not reduced' (Hellsten et al. 1996). The benefits of taking simple measures, such as minor adjustments to water level regimes, can be great even if the local change is relatively small. One example is the suggestion to let the water level in run-of-river impoundments vary over the year in a way that corresponds more to a natural water level regime (Nilsson, 1996). Also, in order to mitigate some of the adverse effects on plant and animal life, power stations can be required to maintain a certain minimum flow of water from reservoirs, so that flow rate is not permitted to be reduced to zero at any time (Bernes, 1996, Weichelt, 2001). Furthermore, the reintroduction of occasional peak flows and large scouring floods can move the system closer to its natural state. Unfortunately, such flows would temporarily have significant adverse consequences on hydropower generation (Weichelt, 2001). To minimise such adverse effects of increased releases, peak flows should be created during periods with high surface run-off, which would diminish the release from reservoirs (Weichelt, 2001). In the Suldalslågen it is suggested that the most effective use of such peak flows would occur with a frequency of about 5 years, flooding approximately 500 m^3s^{-1} through the system. Each of these flood events should also last several days to 'ensure that scoured material is washed out of the river' (Johansen et al, 2002; 39). Finally, another efficient method for improving the ecological continuity of hydrological systems is the restoration of tributaries; many tributaries in Fennoscandinavia are dredged for timber floating and spawning grounds of salmonids have been affected by siltation. Such restorations may have significant benefits for fish stocks locally (Marttunen and Hellsten, 2002).

7.3. Fish ladders and restocking

Other measures to increase ecological potential include the installation of fish ladders and fish stocking. Built to enable migrating fish to bypass hydroelectric dams, fish ladders have not always made things any better, often because spawning grounds further upstream have already been disturbed or destroyed (Bernes, 1996). Furthermore, 'fish ladders improve ecological continuity, but have a clear negative effect on hydropower production' (Marttunen and Hellsten, 2002; 52). Consequently, in many systems, even if fish ladders do partially improve ecological continuity, they are often not economically viable as hydropower production is normally the main objective of regulation (Marttunen and Hellsten, 2002). Further problems with fish ladders can be illustrated with the Isohaara fishway, close to the mouth of the Kemijoki. Unfortunately, this was suspected to only favour the ascent of sea trout and be size selective for salmon; 'Sea trout seemed to have no particular difficulty in ascending the fishway, but in spite of the increased fishway efficiency, the number of salmon was still small' (Laine et al., 2002; 76). Fish stocking is an alternative method of overcoming the problems of fish migration in northern Fennoscandinavia. In heavily regulated and constructed watercourses fish stocking is often the only economically feasible way to sustain fish stocks (Marttunen and Hellsten, 2002). In the Kemijärvi, for example, the annual value of such stockings, which are made to compensate the adverse effects of regulation, is 75,000 €.

7.4. Small-scale waterpower schemes

Curtis, (1999) suggests that most of environmental problems associated with hydropower schemes only apply to poorly planned, very large-scale schemes. The majority of the globally produced hydropower is produced by huge multi-megawatt, sometimes even gigawatt-sized schemes. Carefully planned hydropower installations, especially those on small scale, should have minimal adverse environmental effects (Curtis, 1999; 124). It is further suggested that any problems due to the small-scale of such schemes are likely to be outweighed by the associated environmental benefits. On average, a typical 10 kW hydroelectric installation will prevent the annual consumption of the equivalent to 21 tonnes of oil and 36.5 tonnes of oxygen. It will also avoid the release of 70 tonnes of carbon dioxide and one tonne of sulphur dioxide into the atmosphere (Curtis, 1999). On the other hand research by the German Environment Agency has concluded that small-scale hydropower generators have a disproportionately higher adverse effect on the environment than large generators. They concluded that smaller stations, typically those with less than 1 MW capacity, have a far greater deleterious environmental consequence than larger projects, suggesting that the smaller the station and closer to nature the river, the more unfavourable the environmental and economic cost-benefit ratio. Based on this new research, the agency is recommending that no new generators of less than 1 MW capacity should be constructed, and any decommissioned units of this size should not be reopened. The focus is now on existing large hydropower units, particularly those which have dams with further development potential. Despite these difficulties involved in valuing beneficial or adverse effects, the production costs of stations which cannot reach break-even point indicate that power generation with small hydropower station is a rather expensive way to avoid emitting pollutants into the atmosphere. Bednarek concludes that 'the negative impacts (measured in the value of the restored watercourse) compensate the positive effects (measured in avoidance costs) and therefore the costs are not disproportionate' (Schleiter et al, 2002; 47).

7.5. Dam Removal

Dam removal has received increasing attention over the last several years as a viable alternative to rehabilitation of unsafe dams (Shuman, 1995). With increasing attention on dam removal for ecological restoration it is important to understand the ecological effects of removals, since these may influence what can be subsequently expected of a river. Proposed dam removals are usually quite controversial, making a unified decision difficult. Furthermore, dam removal is sometimes portrayed as a very simple process, whereby all that needs to be done is to open the dam and let nature heal itself. 'A comprehensive environmental assessment of dam removal and reservoir, retention alternatives is necessary to overcome both the often simplistic view of dam removal and to establish a more complete understanding of both restoration and retention alternatives' (Shuman, 1995; 259). It must also be noted that the success of efforts to restore river continuity depends significantly on the extent of the regulation throughout the river. 'If only one dam is removed on a river that has several, the continued presence of upstream or downstream obstructions limits the extent of the restoration process' (Bednarek, 2001; 809).

The ecological consequences of dam removal vary depending on the period at which we are examining the riverine ecosystem. Before the advantages of dam removal over longer periods are discussed the generally deleterious effects of dam removal over shorter times should be considered. 'Some of the most significant impacts include sediment mobilisation, contaminated material, and an increase in the threat of supersaturation' (Bednarek, 2001; 809). The removal of a dam results in sediment movement downstream. The reservoir of the dam will have been accumulating sediment for years and the rivers' recovery time depends on factors such as the length of time sediment has been accumulating, the velocity of the river, the gradient of the riverbed, and the techniques of removal (Brower, 1992). This sediment is usually fine silt and sand as coarser rock is likely to have settled in the inflow of the reservoir. 'Such increased sediment loads can damage spawning grounds for various organisms such as fish and mussels [and] the roots and stems of macrophytes are damaged through abrasion' (Bednarek, 2001; 809). However, the increased turbidity from dam removal, should mostly be a temporary effect. Several completed dam removals have demonstrated that sediment eventually flushes out of a turbid river channel. Furthermore, because small sized sediments sorb relatively more contaminants than coarse sediments due to their large ratio of surface area to volume, a release of fine sediment impounded behind a dam may 'constitute a major hazard to the river' (Bednarek, 2001; 810). If precautions are not taken, dam removal can result in a re-suspension of the contaminated sediments behind a reservoir.

Although sediment transport invariably occurs following dam removal, its severity is hugely variable form system to system. There are few studied dam removals in northern Scandinavia, but two examples from Northern America indicate this variable sediment-flushing time. The Fort Edward Dam on the Hudson River was removed in 1973. This removal provides some lessons regarding dam removal and the need for comprehensive environmental assessment studies in advance. It was estimated that 336,300 m^3 of sediment had moved downstream in one year after removal of the dam, and that 765,000 m^3 remained in the floodplain above it after the first year (Shuman, 1995). Additionally, immediately after the removal of the Newaygo Dam on the Muskegon

River, Michigan, it is estimated that about 40 % of the original volume of impounded sediment was washed downstream. The remaining sediment is moving downstream as a sediment wave at approximately 1.6 km per year. Over time, 'the sediment wave has elongated and diminished in amplitude and will ultimately flush through the system in 50 to 80 years' (Shuman, 1995).

Biological considerations are equally important in assessing whether a dam should be removed and are sometimes the underlying justification for support of removal. In the last few years there have been recommendations by environmentalists for dam removal based solely on the environmental effects of a dam on the river ecosystem. 'Most proposed removals have focussed on dams having significant effects on anadromous fish migrations' (Shuman, 1995; 249). Additionally, the loss of floodplain wetlands, and therefore associated fauna, is frequently a significant result from impounding a river. If a dam is removed, the riparian areas will be flooded more often, restoring their vegetation and some wetlands. Many wide-ranging terrestrial species that require abundant riparian vegetation will benefit (Bednarek, 2001). Dams prevent the tidal surge from moving upstream very far and reduce the floods that help carry fish downstream. For coastal rivers, the interactions of cyclical freshwater flooding and marine tides will be affected by dam removal. Anadromous adult fish and shrimp often use spring floods to carry them to coastal breeding regions. Small, weak-swimming fish also utilise the tidal surge to move them upstream from estuaries and coastal regions towards spawning habitat. 'Dam removal should eliminate this obstacle to migration and movement' (Bednarek, 2001; 806). Dam removal may eliminate several problems associated with fish passage for migration or movement within the river channel; eliminating mortality due to the inability of fish to pass the dam, allowing organisms to inhabit previously impounded areas. For example, the removal of small dams in Denmark has 'resulted in salmonids and other fish being able to reach optimum spawning grounds, enhancing their chances of survival' (Iverson et al, 1993; 87). The possibility for dam removal to restore these biological attributes should be assessed when considering the fate of a dam (Shuman, 1995).

7.6. Alternatives to hydropower

'In many cases there is no need for detailed studies in order to find an answer to [whether or not there are any feasible alternatives to hydropower]. For instance, there are no real alternatives for hydropower in Finland at the moment' (Marttunen and Hellsten, 2002; 41). Furthermore, there is 'no single source of electricity that could replace hydropower with an environmentally better option, without considerably increasing the cost of electricity' (Jansson, 2002; 38). Hydroelectric power has several distinct advantages over many other energy sources. For instance, atmospheric pollution is confined to the construction phase. 'The Nordic countries' relatively moderate sulphur dioxide emissions are due, at least in part, to the fact that they have been able to rely largely on hydroelectricity, rather than on the burning of fossil fuels' (Bernes, 1996; 143). Furthermore, relatively speaking, hydropower generation is non-wasting self-replenishing and non-polluting, and as shown previously hydropower is essential not purely for its total energy supply, but for its flexibility of supply (Marttunen and Hellsten, 2002, Jog, 1989). More significantly, hydropower is an essential part of Nordic power production, and 'one of only a few domestic energy supplies which can feasibly be expanded' (Marttunen and Hellsten, 2002; 32).

Hydroelectric power stations cause many environmental changes, some of which are just beginning to be understood. These must be weighed against the environmental effects of alternative sources of electricity. Until recently there was an almost universal belief that hydropower was a clean and environmentally safe method of producing electricity. Hydroelectric power generators do not directly emit any of the standard atmospheric pollutants, such as carbon dioxide or sulphur dioxide, given off by fossil fuel fired power stations. In this respect, hydro power is better than burning coal, oil or natural gas to produce electricity, as it does not contribute to global warming or acid rain; by using hydroelectric power CO_2 emissions are eliminated but for the emissions from decomposing flora submerged by reservoirs (Eds Iceland Review, 1998). Similarly, hydroelectric power stations do not result in the risks of radioactive contamination and waste disposal associated with nuclear power generators. For instance, nuclear power production has not been used in Norway and it is not on the political agenda. 'As other European countries are phasing out their nuclear power production introduction is unlikely in Norway for the [next few] decades' (Bjørtuft et al, 2002; 31). Also, nuclear power cannot replace hydropower due to its poor sustainability for short-term peak-load power generation. It is suggested that gas turbine generators could replace hydropower, however, economic limitations may not allow this as their efficiency is lower and the proportion costs of electricity are higher compared to existing hydropower stations (Marttunen and Hellsten, 2002). While actively searching for new and more environmentally neutral energy sources, it is necessary that communities should develop and use better methods of limiting electrical and heat production (Beier, 2002).

8. Conclusions

It has been established that hydroelectric power generation is essential in northern areas of Scandinavia. Hydropower clearly benefits the global environment, in terms of the reduction in greenhouse emissions and acid rain pollution. However, as described in Chapter 5 the associated lake development produces significant adverse environmental effects.

The parameters for making decisions concerning dams have been changing over time. While there is a clear evidence of increased attention to social and environmental aspects in this process, 'technical, financial and economic activities still remain the most frequent overriding decision factors' (Clarke, 2000; vi). The basic question, which still remains unanswered, is whether continued development of northern hydroelectric resources to maintain and expand the industrialisation of northern countries justifies the inevitable disruption of the northern environment. More detailed research into large-scale regulation of rivers is needed to enable making informed decisions on this future role of hydropower, as, at present, it still remains that hydroelectric power is the form of energy which has 'the fewest imperfections of all' (Bourassa, 1985).

Appendix A. Bibliography

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