Environmental impacts of renewable energy

Thesis

How to cite:

Clarke, Alexander David (2012). Environmental impacts of renewable energy. PhD thesis The Open University.

Thesis for a Doctor of Philosophy Degree

Environmental Impacts of Renewable Energy

Alexander David Clarke BPhil

February 2012

Energy & Environment Research Unit

Faculty of Mathematics, Computing and Technology

The Open University

Date of Submission: 1 September 2009
Date of Award: 10 February 2012

Thesis for a Doctor of Philosophy Degree
Alexander David Clarke BPhil
Energy & Environment Research Unit
Faculty of Mathematics, Computing and Technology, The Open University
February 2012

Environmental Impacts of Renewable Energy

Contents

Abstract

This PhD study addresses the question of whether the environmental impact of renewable energy sources is related to the power flux density. The object was to examine whether there are some general rules concerning the environmental impact from renewable energy sources, and whether a common factor could be the power flux density, of unit kW/m^2 as an underlying principle. The background and nature of the study are described with definitions of key concepts. The role of energy in the environment, powering the natural world and having a set of functions, are explained. The need for a general theory and the rationale is considered for eight primary renewable energy sources. The literature on environmental impact from these sources is reviewed. The theory and the hypothesis are explained with questions raised. A test devised to explore the relevant interactions (sediment transport and land use) is outlined, using data from a selection of well known hydro electric power developments. The 'Stream Power' concept and a variety of parameters were used for identifying losses of energy and power to a river's natural processes, resulting from impoundment dams. The test was carried out on the reservoir reach and the river downstream. It is concluded from applying the hypothesis to hydro electric power, that the environmental impact may indeed be related to the power flux density, for the two main impact parameters investigated, land use and sediment transport, though this is not conclusively statistically confirmed due to the small sample size. The hypothesis is extended in the Appendix to the other water based renewable energy sources, tidal barrage, marine current, and wave power, and to the lower energy flux density sources such as wind, solar and biomass. It is concluded tentatively that there is a qualitative argument that the environmental impact of all renewable energy sources may be related to power flux density, in terms of both land use and some functions in nature of the energy flow.

List of tables, boxes and figures.

Tables

Boxes

Figures

Chapter 1

Environmental Impacts of Renewable Energy

1.1 Introduction

The undoubted importance of the use of renewable energy for environmental reasons as an answer to problems of finite fuel resources and potentially irreversible effects of atmospheric pollution makes it doubly necessary to understand how renewable energy is itself constrained by environmental impact. It is crucial for the successful implementation of renewable energy to understand the underlying structure and patterns of its environmental effects.

However, the new renewable, mainly electrical energy generating technologies and their effects, are relatively novel and unknown. There are at least eight different renewable energy sources and many different technologies are employed for harnessing them. Usually, several different sources can be exploited in any one area. It is generally agreed that the ultimate limitations to the deployment of renewable energy will be the size of the resource and environmental constraints. Currently it is the author's view that environmental impacts are considered in a somewhat ad hoc manner and are not well characterised. There appears to be only patchy understanding of the fundamental principles determining environmental impact. As renewable energy exploitation rapidly expands it will be important to understand which factors are the prime limiting and shaping ones. Identification of the key factors involved would provide policy makers, engineers and technologists with suitable tools for decision making and design choices.

Once the fossil fuels are depleted, apart from nuclear sources of energy, only the renewable sources will be available to humanity. Long before that time, fossil fuels will rise in price as demand exceeds supply. Potentially, the size of the resources of renewable energy is large, though in practice many constraints will apply. The advantages of renewable energy are that it is unending, though finite in extent, and that it can avoid much of the long term effects related to atmospheric carbon emissions. Nevertheless, exploitation of renewable energy will involve tapping into natural energy flows, altering them, and, effectively, competing with their other functions, both in nature and those related to human activities. For example, extracting energy from rivers can reduce sediment transport, and desert solar power stations can effectively sterilise the land below them. The use of biomass energy can directly compete with food production, as the recent debates over food versus fuel can testify. On a scale of the hierarchy of need, food production for a still growing world population, could out weigh energy production, all things being equal. Wildlife in natural rivers modified for energy extraction, or rainforests converted to palm oil plantations, can then suffer the effects. Therefore it is important to discover how to best use renewable energy resources, for example how much energy can safely be extracted from a flow, and exactly how should we be extracting it so as to avoid undue impacts.

A great benefit of modern technology design is that there are alternative technical options available, and schemes can be designed and tailored to fit appropriate objectives. A wealth of environmental science and data now exists, so that lack of knowledge can no longer be an excuse for inappropriate developments (Petts 1984). This process of adjustment will involve much effort, in reconciling the different disciplines and bringing their considerations and information to bear on energy developments that will be badly needed (Holdren 1980). In our rush to develop new energy resources we will have to be sure that we are not losing environmental objectives to energy objectives.

In seeking to find solutions to the apparently contradictory demands on these resources (maximum energy output, minimum environmental impact), new concepts are required so that human ingenuity can be brought to bear. That is what is being attempted in this thesis in a small way, via an analysis of the impacts of renewable energy.

In this thesis the emphasis is on energy flux density and changes to it, as a key factor. The terms 'energy flux density' and more precisely 'power flux density', discussed below, are used in this thesis. As a measure of how intense or diffuse the energy flow is, power flux density is defined as kilowatts per square metre in this thesis. It is proposed that this may be a key factor in the environmental impact of renewable energy sources, and the main aim of the thesis is to examine this assertion.

1. 1.1 Nature of this Study

This study considers mainly the physical direct effects on the environment of renewable energy, from capturing, abstracting and converting some of the energy from the natural energy flows such as sun light, wind and flowing water. The study does not in most instances address the "upstream" impacts, such as the carbon emissions, from producing the materials and manufacturing involved in renewable energy conversion devices and structures. It is considered that much work has already been carried out on that issue. Such impacts can in some cases be significant, especially where the particular renewable energy technology is "materials intensive", (Mortimer 1991), i.e. where the converter devices and structures involve a large mass of materials per kW captured, or where noxious materials are used. An example of the latter might be the use of gallium arsenide in some solar photovoltaic cells. However, the approach of this study is that a 'materials intensive' renewable energy conversion technology may also represent an immature technology, as yet lacking optimally engineered materials use. In terms of this study, the power (kW) captured per unit of materials mass can be related to the energy flux density; and the 'upstream' effects can then be deduced using existing data. In contrast to studies of the external costs of using energy, e.g. the ExternE study (ExternE 1995), this study does not have the economic costs as its prime focus.

The study as stated takes a different approach from that of previous studies in that it looks explicitly at energy *flows,* rather than assuming that energy equates to fuels or is *store* based, an example of which is the 'Fuel Cycle' approach of the ExternE study. The rationale for this is that previous studies have been dominated by fossil fuel and nuclear technology concerns, such as the fuel cycle, particulates emissions or nuclear wastes. Such concepts are not appropriate to most of the renewable energy sources, with the exception of Biomass.

Use of a 'Fuel Cycle' approach is understandable given the current predominance of fossil and nuclear sources in world energy use. However, this study looks ahead to a time when greater renewable energy capacity will be demanded by policy makers, and the status of renewable energy will be elevated. This study considers eight different renewable energy sources, but focuses largely on hydro electric power for its investigation on the basis that this is the oldest of the modern renewable energy sources, and therefore there is considerable data available.

1.1.2 Outline of Thesis

Having outlined the basic rationale for this study, and the structure of the thesis, the remainder of chapter one introduces some key definitions and develops some initial analysis concerning factors that influence environmental impacts. Chapter two then reviews the literature on environmental impacts from the use of renewable energy sources. In chapter three some basic theory is presented and the hypothesis is explained, while chapter four describes the questions it raises and the approach adopted to setting up a test. In chapter five, the setting up of the test is described, with the cases and data sources involved. Chapter six concerns the results from the test, analysis and synthesis. First conclusions from applying the hypothesis to hydro electric power are contained in chapter seven. Chapter eight discusses the overall conclusions. An extension of the hypothesis, on a qualitative basis, to other water based renewable energy sources and the low energy flux density sources such as wind and solar, is contained in two sections of the Appendix.

1.2. Definitions

1.2.1 Definition of the Environment

The term 'environment' is defined in systems theory as that which is outside the boundary of the system, itself consisting of interconnected parts (von Bertalanffy 1968, Boulding 1956). Bertalanffy distinguishes between closed systems and open systems where energy and materials are exchanged across the system boundary. In more general usage environment can mean surroundings, or conditions, the spatial context, and the outside links, biologically and physically, to the wider world (Blowers & Smith 2003). It includes processes, systems, for example life support systems. The concept involves boundaries; where these are drawn, as well as issues of scale both in time and space.

However, the environment is not a single entity -it can be divided into at least three basic components for the purposes of impact assessment.

-i) The Natural Living Environment
-ii) The Natural Inanimate Environment
-iii) The Human or Cultural Environment (Clarke 1993)

i) The Natural Living Environment

This is comprised of Flora and Fauna as it exists independent of human activity. It requires energy to fuel its growth and maintenance, in addition to the maintenance of climatic, soil and water conditions within a certain range. The activities of flora and fauna help to create and influence these conditions.

ii) The Natural Inanimate Environment

This consists of the earth's surface, the oceans and the atmosphere, which are acted upon by energetic processes. The action of energy on the earth's surface is known as geomorphology, and on oceans and the atmosphere oceanography and meteorology respectively. These processes are an important factor in the morphology of landscapes, e.g. the hills and valleys, and also the maintenance of soil and aquatic conditions. Energy flows contribute to the shape of shorelines, beaches and marine conditions. They can be important to the continuation of existing shore lines and other features.

iii) The Human or Cultural Environment

This category includes firstly human activities on the environment to cultivate wild areas changing them into for example, agricultural land, forestry plantations or urban environments. Managed landscapes are achieved through such means as drainage works, earth moving or changing the vegetation.

Secondly, the human need for certain minimum environmental standards of air and water quality, noise and light requirements is included here. Thirdly, under this category come human aesthetic notions about the environment such as the value of landscapes or certain features in the landscape.

The human or cultural environment concerns man's interaction with the other two parts of the environment, and the degree to which humans interfere with those categories, ranging from high interference e.g. intensively farmed areas or cities to low e.g. fisheries on largely unregulated wild rivers.

Clearly the animate and inanimate categories of the natural environment are of great importance to the Human Environment. While humans are merely another form of life, human demands on the environment have changed it enormously. The inanimate environment has a determining effect on the patterns of human and other living organisms activity through climate and it might be considered to be a more fundamental category than the other two. But both humans and other living organisms have, in their turn, the capability to influence events in the inanimate environment. Though the scale of geomorphic or meteorological events is very large, so too can be the impact of humans in desertification, or on large areas of tropical forest. In both cases the local climate can be altered by changes in water retention and evapo-transpiration.

These three categories, the natural living environment, the natural inanimate environment, and the human or cultural environment are not always tidy ones but are grouped this way since each can be considered to have its own requirements or functions, or even 'purposes'.

1.2.2 Environmental Impact / Effect

The term environmental impact has been defined and used in a variety different ways. Catlow (1976) draws a distinction between environmental *effects* and environmental *impacts* in a UK Department of the Environment report on Environmental Impact analysis. He states that while effects are the physical and natural changes resulting directly or indirectly from development, the impacts are the consequences or end products of those effects, represented by aspects of the environment on which we can place an objective or subjective value. The way in which the term is employed in this thesis is not quite the same, for although distinguishing between effects and impacts appears to convey precision; in practice it is hard to decide where to draw the boundary line.

Another term that may be usefully related to environmental impact is 'Environmental Stress'. This has been described as 'any force that pushes the functioning of a system or subsystem beyond its ability to restore its former structure and function' (Meir 1972 cit in Petts 1984). This is useful as it can describe a mathematical process.

In this thesis the term Environmental Impact is used in the sense of changes to prevailing environmental conditions and is close in meaning to environmental effects. Both of these terms should be amenable to some form of measurement. In describing environmental impacts as changes, these could comprise those that have a greater significance and permanence than mere effects. However the distinction is hard to make. Impacts, as used here, are not in themselves necessarily either detrimental or beneficial. However, the uncertainty about the effect of these changes leads to a presumption in favour of the status quo, and impacts are usually viewed with suspicion.

Both the degree, and the rate and frequency of change are important variables when measuring environmental impact. The significance of the changed conditions can be assessed by considering their role in particular environments and ecological systems and will need to be discovered. Any conditions that are critical to the functioning of ecosystems or whole environments will need to be identified.

1.2.3 The Role of Energy in the Environment

Natural energy flows are of fundamental importance to the environment since they provide the energy for the growth and maintenance of living organisms. In addition the geomorphologic processes that occur in the inanimate environment are the result of the action of energy on the earth, seas and atmosphere. Many of these processes are understood well and have been thoroughly documented, though within particular disciplines.

For any natural energy flow a set of roles or functions in the environment can be ascribed. For a general description of these functions, see below and table 1.1 below.

Table 1.1 Some Functions of Energy Flows in the Environment

Solar	Primary energy flow to earth, heating of seas, heating of air mass, heating of land mass, evaporation of water -hydrological cycle, photosynthesis.
Wind	Heat transport by air movement, mixing & by water vapour transport and direct movement of water, dust transport, erosion, flora and fauna transport, seed and pollen transport, insect transport.
Biomass	Photosynthesis: primary energy (1st trophic level) for all living matter, support and growth of biosphere, breakdown of rock and soil formation, micro climatic effects.
Hydro	Erosion, sediment transport, deposition of sediment, oxygenation, nutrient and organism transport, flushing.
Tidal	Sediment transport, erosion, nutrient and organism transport, oxygenation, water mixing.
Wave	Erosion of rocks and shoreline, long shore currents transport of sediments and transport, deposition of sediment, oxygenation, water mixing.
Ocean thermal and currents	Major energy reservoir / buffer, major heat transport, surface atmospheric effects, ocean nutrient and organism transport.
Geothermal	Mineral conveyance / replenishment, chemical reactions, crust mechanics functions, warm marine upwelling effects on currents and nutrient transport.

(Clarke 1993)

Energy flows may, in some instances be critical for functions on which many important processes of the existing environment depend. For instance river sediments are important for the replenishment of flood meadows or deltas, while the transport downstream of biomass by a river constitutes nutrient and food sources for the flora and fauna. Abstraction of energy from natural energy flows by renewable energy technology may significantly influence such functions with resulting significant environmental impacts. An example of this is sedimentation in the High Aswan dam, on the Nile in Egypt (El-Moattassem 1994).

Renewable Energy Definitions

"Renewable Energy sources are those derived from continuous energy flows found naturally in the environment". (Twidell & Weir 1986). There are at least eight different primary renewable energy sources:- Solar, Biomass, Hydro, Wind, Wave, Tidal, Marine Currents, Geothermal (Boyle 1996).

Natural Energy Flows

Interactions occur between energy and the environment -in both directions. The natural energy flows that renewable energy harnesses are very diverse, making comparison between them difficult. The basic types are: Solar radiation, Solar radiation converted into chemical biomass form, Moving Air, Moving Water, Ocean Thermal temperature differences, Heat from geothermal sources.

1.2.4 Environmental Effects and Impacts of Renewable Energy

Impacts from using renewable energy can be divided into common effects and source specific effects, as has been noted by the author (Clarke 1995). See Box 1.1 and 1.2 below.

Box 1.1 Common Effects of renewable energy

Common Effects:-

Land use / use of space
Planning / Compatibilities
Noise
Visual
Safety
Wildlife

Source specific effects :-

Geomorphic effects (Hydro, Tidal, Wave)
Gaseous emissions (Biomass, Geothermal)
Liquid emissions (Biomass, Geothermal)
Soil effects (Biomass)
Drainage effects (Hydro, Tidal)
Eutrophication (Hydro)
Subsidence, minor seismic effects (Geothermal)

Box 1.2. Source specific effects of renewable energy.

The environmental effects from using renewable energy that are common to all sources are shown in Box1.1, and include themes such as land use, planning compatibilities and issues concerning minimum standards of e.g. human habitation. Effects which are specific to one or a few particular sources, shown in Box 1.2, can be distinguished such as for example soil effects from biomass harvesting or effects on drainage from HEP schemes or tidal energy.

Clearly it is possible to identify some common processes and themes despite the very wide variation in the sources themselves and their conversion technologies.

However, there are difficulties in addressing the subject of environmental impacts from such diverse sources as renewable energy flows. While energy is central to the maintenance of natural environments, it cannot necessarily be said that all environmental impacts are energy related. This would be to use the term 'energy' in a very wide sense, for example chemical pollutants are chemically reactive, and in the strictest sense this could be narrowed down to the ionic charge of the molecules, which could be termed an energy imbalance. An example could be nitric oxide acid atmospheric pollutants. However, the amount of energy per molecule is tiny, and overall the actual energy flow from combustion that goes into creating nitric oxides would also be small. It could still be argued that the reactive power per molecule is relatively high, that is the density. Notions of energy can thus apply, in a certain manner, to pollutants which are unwanted by-products.

Central to the natural environment, as a life support system, are the systems and processes involved in cycling the major physical resources such as the well known hydrological cycle, the carbon cycle, nitrogen cycles and so on. It is energy that drives these systems, the energy of the natural energy flows listed above. Clearly intervening in these cycles to any great extent could have consequences.

Environmental impacts also concern the maintenance of stable conditions such as the pH of water, atmospheric pressure and composition as well as temperatures within the bounds of ~-50 to + 50 °C. Such environmental conditions are not all primarily related to energy flows directly. Other impacts such as the reduction of biodiversity from biomass plantations are not essentially energy related, being biological and ecological in nature.

1.3 Need for a general theory

Although there has been considerable and growing work studying the environmental effects of using renewable energy sources, the impacts have not been well defined even though they have been listed comprehensively. Few general principles have been suggested or established. Renewable energy sources offer the prospect of reduced environmental impacts compared with conventional sources, in particular fossil and nuclear sources. However, renewable sources do have impacts, and while these may be relatively insignificant at low levels of deployment, they may well have a cumulative effect. In terms of environmental impact, 'threshold' levels of application may apply beyond which certain sources should not be used, for example at greater densities, if excessive impact is to be avoided. It will be important to establish general principles as the deployment of renewable energy sources increases. In particular there will be a need to predict and plan for large scale development, as capacity increases to a point at which the majority of the resource is exploited. It will be important then to establish limits to total exploitation based on the effects and impacts as well as the wider issues of economics and technical feasibility.

As capacity increases, and more of the potential is exploited, sensitivities may emerge that were hitherto imperceptible. An example may be the issue of windfarm siting and landscape protection, which has been commented on by Hedger and others. For example Hedger states "... how the lack of a coherent policy and assessment framework can lead to difficulties for a new industry, as well as planning departments" (McKenzie -Hedger 1995).

Comparisons *between* different renewable sources are required since most locations have the possibility for more than one energy source. Some renewable energy sources are very site specific, for example hydro electric power, while others are not, e.g. solar photovoltaic. The renewable energy sources themselves are highly diverse and their technologies yet more so, hence comparison on a 'like for like' basis can be problematic. For policy makers, renewable energy sources may be considered together as a group, offering the means of delivering environmental objectives, though in reality the character of the technologies and the industries supporting them may be very different. Many commentators have long pointed to the difficulties posed in trying to compare such diverse sources and technologies, e.g. Holdren et al talk about an "apples and pears" problem (Holdren et al 1980).

Many commentators have drawn attention to the *diffuseness* of renewable energy flows, particularly in relation to concentrated fossil fuel stores. But just how diffuse are the renewable energy sources? Other commentators such as Walker have pointed to the importance of land use for renewable energy in 'Land Use and Renewables', (Walker 1995, McKay 2008*a*). Both the use of land per kilowatt of output and the issue of compatibility of different land uses are important here.

The first topic, land use per kilowatt of output, suggests that consideration of how intense or diffuse a renewable energy flow -or indeed a source is will be significant. This leads to the notion of power flux density, mentioned above. This parameter might then be adopted as an initial common denominator in the attempt to characterise and compare the different renewable energy sources. Although the issue of amount of land used per unit of energy could be thought of as a fundamental parameter (McKay 2008*a*), this is not to suggest that all the environmental impacts can be explained in terms of 'power flux density'. Nevertheless, it may transpire that this parameter, power flux density, has a more pervasive effect on the nature of the source and the technology used to harness it, and therefore on its impacts. This subject is pursued in chapter three where the development of the theory is explained.

1.3.1 Hypothesis

The starting point for the hypothesis, i.e. consideration of the diffuse nature of renewable energy sources, has been outlined above. The hypothesis can be phrased as a research question:

Is the environmental impact from renewable energy sources related to the power flux density?

The author recognises that this is a very broad question and it is beyond the limited ability in a single thesis to answer this question. Of necessity therefore what follows is a preliminary analysis. The hypothesis is that the power flux density is related to impacts arising from renewable energy, and changes in it, and this is the subject of this study. However, if there is a relationship it is unlikely, except perhaps in some respects, to be entirely straightforward. What follows below is an attempt at analysing the effects and impacts from using renewable energy, which is a very broad area. Of necessity this is a multidisciplinary subject straddling the fields of energy, technology, and engineering, as well as the biological, geographic and earth sciences and environmental studies.

In short, the development of the theory as explained below leads to a further three parameters being proposed for a more complete understanding of the processes involved in environmental impact.;

i) -proportion of the flow abstracted,

ii) -the efficiency of energy conversion

iii) -number of energy conversions.

(Clarke 1993)

While this may appear to complicate the assessment model, it should enable further explanation and hopefully prediction of impacts, even for novel renewable energy sources and processes.

1.3.2 Site specificity versus General Principles

There is an argument found in the literature that discovering general principles for the environmental impact of renewable energy sources is not feasible due to the site specific nature of each development, as well as the variety of sources and technologies employed. Indeed there can be wide variation in the impacts of the same type of renewable energy developments, for example for hydro electric power plants. In reality though, these impacts will be explicable, given the effort and will. Every individual site will have a unique mix of environmental characteristics but these are unlikely not to have been encountered before. Rather more likely, it is often the paucity of developments for a particular source, for example full scale tidal barrage plants, that has prevented proper experience being gained. Even so the range in variation between different projects needs to be investigated. The more unique a site is, the higher its perceived value environmentally is likely to be. Sensitivity levels to conditions may then be more critical. On occasion this might be due to higher power flux densities, that is, more intense flows of energy, and such sites may then be those most attractive to renewable energy developers. If renewable energy developments are to be considered more than one-off projects, that is they are to be deployed in quantity, it will be necessary to devise common parameters for assessing impact based on sound scientific principles and processes. This will mean recognising site specific variations in the context of general practice, rather than variations being thought of as a barrier to characterisation.

There may even be in the author's experience, some resistance to the notion of general principles and common measures for assessing impacts from renewables, from those who are currently practitioners in the field of environmental assessment who may feel threatened by new techniques. It may be argued that assessment of impact is subjective, or in some way a 'black art'. Other groups who might tend to scepticism about the viability of general environmental impact principles may be some engineering and developer groups who have traditionally regarded environmental issues as barriers and environmentalists as 'the opposition'. Such attitudes have been on the decline in recent years with the growth of a body of well founded knowledge, though in the past, there has been a tendency among some to deny scientific or academic credibility to the environmental sciences.

As stated, some arguments against the identification of general principles centre on the idea that environmental assessment is a subjective issue, and not only is every site unique but so is every person in their predilections. Such arguments are usually based on an interpretation of the 'environment' mainly in social or aesthetic terms and thus beyond the more objective measures.

The search for common patterns is vital to a learning process which has as its aim, a partial reconciliation of the apparently contradictory objectives of a) energy abstraction from natural energy flows and b) nature conservation.

1.3.3 Conclusion to chapter 1

It can be concluded that as renewable energy source development and resource exploitation proceeds, the ultimate constraints on renewable energy sources will tend to be resource size and environmental ones. The environment can be defined as comprising the natural living environment, the natural inanimate environment, and the human or cultural environment. Environmental impacts and effects can be defined as changes. Natural energy flows maintain the natural environment, and a set of functions in nature can be identified for each natural energy source. Since natural energy flows power the natural environment, there will be a need to determine the prime environmental limiting factors. This study will concentrate on physical rather than social environmental effects of renewable energy. Some common effects and some unique to certain sources can be identified. There is a very wide variety and diversity of the different renewable energy sources making understanding of principles environmental impacts complex and difficult. Nevertheless, as dependency on renewable energy sources increases it becomes increasingly important to understand the fundamental principles of environmental impact. It is considered by this author that currently impacts are not well characterised and understood. Since different renewable energy sources may be available in one area, and may be in competition with each other for certain resources, it is important to have a reliable means of comparison. There is thus a need for a general theory of the principles of impact from renewable energy sources. As yet some have argued against the validity of general principles on the basis that site specificity and sensitivities are too varied to make this practical. However common parameters will need to be devised if renewable energy developments are to be made in quantity.

Chapter 2

Literature Review

2.1 Introduction

There is a considerable quantity of literature on the subject of environmental impacts from renewable energy, dating from the 1970s to the present time.

The author has reviewed a selection of the literature of environmental impacts from renewable energy sources in Clarke (1995), as well as works on individual sources such as wind (Clarke 1988) and biomass (Clarke 2000). It is not proposed here to review again all the individual impacts of each renewable energy source, but to concentrate upon key developments in the approach to assessing impacts from renewable energy.

Since the 1990s much has changed as renewable energy utilization has grown, and emerging technologies e.g. marine current or wave, have been brought into commercial operation. Environmental awareness has increased amongst the public, the energy industry and governments. Scientific knowledge of the effects of energy use has increased greatly, while evidence for anthropogenic climate change has consolidated. The privatisation of electricity and energy markets in the UK has resulted in some renewable electricity being sold competitively on the basis of its environmental credentials, as "green power".

The rise in energy prices over the last ten years, led by the rise in oil prices from ~$10 to a peak of almost $150 per barrel by July 2008, falling thereafter to ~$40 as a result of recession, and then rising once more, has renewed the urgency for government policies to plan for a post-oil and post-fossil fuel age.

Together with increasing evidence for the potential severity of climate change effects, this has led to policies for strong renewable energy supply growth; in turn this has caused further examination of the size of total resources available and their constraints.

2.1.1 Recent Developments

Since the 1990s, much experience has been gained of new renewable sources on a larger scale than previously, for example in wind energy, and in many countries biomass energy. In the UK installed wind energy capacity is over 2GW at the time of writing, while Denmark had some 3.125GW of wind energy capacity installed by the end of 2007, contributing over 21% of electricity generation (EWEA 2008) and Germany had 22.247 GW contributing over 7% of electricity supply. Wind capacity installation has been expanding worldwide at a rate of 31% per annum and surpassed 100GW in 2008 (EWEA 2008) and is now approaching 200GW. Despite the expansion of wind energy in the UK there has been effective opposition on environmental grounds, which has slowed development down.

Another significant change since 1995 is that the emphasis of environmental policies has been put more firmly on carbon dioxide reduction and green house gas (GHG) control as the prime impact example. CO_2 and GHGs then serve as a proxy for other impacts.

This emphasis in energy policy on replacing fossil fuels, in order to control atmospheric carbon emissions, has resulted from the increasing confirmation by the Intergovernmental Panel on Climate Change of the warming effects of the continuing growth of CO_2 and other greenhouse gasses in the atmosphere (IPCC 2007). Although considerable uncertainty remains about the rate of climate changes to be expected, and models are not yet considered to be capable of accurate forward forecasts, there is a growing consensus that warming due to accumulation of GHGs in the atmosphere will cause climate changes and melting of ice, leading to further changes, e.g. in sea level.

As a reaction to this growing consensus on climate change, government policies have been implemented, with regulation addressing global warming, including renewable energy policies, in addition to more general environmental regulation e.g. on air pollution. Accompanying this has been the development of assessment and accounting techniques for carbon, and its environmental cost, such as those pioneered by the ExternE project (ExternE 1995), for CO_2 and GHG pollution by energy technologies, directed towards government policy areas (WEC 2004).

The growing maturity of some of the renewable energy sources such as onshore and offshore wind, and some biomass options especially in continental Europe, has led to renewable energy sources being seen as a serious electricity and energy supply option by governments in e.g. the EU and the UK. As an example of how seriously renewable energy sources are now taken, the government's 2009 'The UK Low Carbon Transition Plan' (DECC 2009a) allocated them a major supply role. The emphasis, then, is now on achieving government targets, and raising the capacity of renewable energy generation.

At the scale of individual renewable energy schemes, there has been considerable further development of local impact assessment techniques for individual developments, for example software for individual wind farm development impact assessment and site evaluation (Resoft 1999, Garrard Hassan 2004, Windpower Monthly 1998).

While much has changed and there has been considerable progress on various fronts, some of the original uncertainties and problematic aspects of renewable energy sources still remain; practical resource size, consequences for land use, and the degree and extent of impact from what are very diverse and relatively novel technologies, many of which have not been exploited on a larger scale.

2.2 Key issues in the literature

Holdren et al (1980) were some of the first to discuss the problem of comparing the effects of different energy alternatives for renewable sources in a much quoted paper 'Environmental Aspects of Renewable Energy Sources'. They state in an introduction that begins with the subject of "externalities" that "the environment is central to the energy problem, not peripheral". The paper considers what information is required for comprehensive comparative assessment of energy alternatives, summarizing the technological characteristics of the most promising renewable energy technologies, emphasising how they cause environmental problems, comparing and offering suggestions for the implications of energy choices. The elements of a systematic environmental assessment are described as steps in tracing the complexity of causal linkages: origin of environmental effects, insults to immediate environment, pathways by which insults lead to stresses, stresses resulting in altered environmental conditions, and damages which are the response of components to stresses.

A complete analysis would need to contain, the authors state, information on: the distribution of damage in space and time, ease of control of the damage, degree of irreversibility, how the damage scales, and degree of uncertainty. The authors acknowledge that such complete information is not available even for well studied technologies. The "...most intractable problems in environmental science..." posed are the processes linking insults to pathways and stresses and their relation to damages. The key point that renewable energy flows are diffuse is made, and that this results in greater land use and materials use. In addition the very important point that renewable energy flows power the environment and biosphere and "...large enough interventions in these natural energy flows and stocks can have adverse effects on essential environmental services."

Of all the alternative sources compared -passive and active solar, solar thermal electric, photovoltaics, terrestrial and orbiting solar satellite, wind, hydro and ocean thermal energy conversion, hydro electric power is considered the worst option due to its ecosystem damage per unit of energy. The increasingly scarce resource of "free flowing rivers" is pointed out.

Some basic measures of relative severity of environmental effects are suggested: land use, water use, non-fuel materials, occupational accidents and diseases, public risks from accidents, effects of routine emissions on public health, effects on climate and ecosystem effects. Although the effects of dispersed renewables are considered to be only local, if large enough deployment of centralised renewable sources occurred, the effect of redistribution of energy flows would become appreciable, the authors state. Ecosystems while being valued as part of "reverence for nature" also provide goods and services, which contribute to human wellbeing, e.g. nutrient recycling, soil formation, water storage and flow regulation as well as maintenance of a genetic library (biodiversity).

However, although there is a large body of observational data on ecosystems, the authors consider that few general principles are known. This is explained by the "tremendous complexity and stochasticity of such systems which makes prediction of human induced stresses extremely difficult". Therefore they state, "comprehensive comparison of different energy technologies is at a necessarily very primitive stage being qualitative rather than quantitative".

Another influential work, the OECD Compass Project Report 'Environmental Impacts of Renewable Energy' (OECD 1989) considers that "renewable energy technologies can in general be considered as more environmentally favourable than most other sources" but they have different impacts. Stating, that because "renewables tap more dilute energy flows which are generally of a more physical rather than chemical nature, the impacts of renewables tend to be more physical rather than chemical". The subject of the larger land use and materials inputs of renewables is discussed. However, important positive aspects of renewable energy use are that "renewables generally imply more localised, shorter term environmental effects". While the report considers a range of renewable energy technologies, the authors state that "at present, methodological tools to enable a truly rigorous analysis...are not available". This they believe is due to the inability to identify system boundaries, which are particularly problematic for renewables. Although it is possible to mitigate the impacts of renewables, "unfortunately past experience suggests that the full impacts are only recognised after adverse effects have reached significant levels, because insufficient attention has been given to predicting harmful effects in advance and remedies incorporated into the maturing technology as an integrated system."

An influential group of commercial and academic specialists, the Watt Committee, published a comprehensive report 'Renewable Energy Sources' (Watt Committee 1990), which as well as reporting on the status of the technology and prospects for exploitation in the UK, considered environmental impacts of energy production, both as a stimulus and as a barrier. They state that renewables are popularly thought to be an environmental improvement but can introduce impacts of their own, such as visual intrusion, noise, and radio interference from wind turbines, toxic emissions from biofuels, interference to fish and water flow from hydro, conflict of land use and other disturbance to the natural habitat. The authors significantly note that "no satisfactory method of comparative assessment in this area exists". They acknowledge that environmental considerations have become more important in energy policy due to the effect of global warming and climate change through CO_2 and other GHG emissions. As a result "renewable energy technologies "thus find themselves in a most encouraging position as far as research development and demonstration policy in IEA member countries is concerned".

Once again only qualitative comparisons are made, devoted to impact summaries between renewable and conventional sources, showing the relative magnitude of effects as small, medium or large. These emphasise the advantages of renewable sources over conventional ones, as the only impact shown which is greater for renewables than for fossil or nuclear is land use, due unsurprisingly to its lower energy density.

A somewhat more recent contribution from a conference held by the UK Solar Energy Society 'The Environmental Impacts of Energy Technology' (Hill & Twidell 1994), included presentations of papers on photovoltaics and the environment, as well as the role of energy efficiency in reducing impacts and environmental cost assessment of conventional electricity generation. Hill outlined many of the themes referred to below and cites some of the papers above.

Twidell, in a paper 'The environmental impacts of wind and water power' (Hill & Twidell 1994), proposed five categories of environmental impact: physical, chemical, biological, ecological and aesthetic. Twidell referred to energy flux density at first capture, as a factor with strong influence on physical and aesthetic impacts, though he did not develop this very much. He noted however, that hydro power has ~100 times the energy flux density of wind and solar, and that another factor is the efficiency of conversion. Twidell adopted a similar approach to that of the present author in an earlier paper (Clarke 1993).

Since the middle 1990s, efforts have been made to develop comparative assessment techniques that rest upon quantitative data rather than the qualitative descriptions prevalent until then. This process is still continuing with for example government agencies, the Carbon Trust, the Sustainable Development Commission, the Tyndall Centre and the UK Energy Research Centre as well as university researchers, industry consultants and developers, developing assessment techniques.

As these technologies begin to be deployed and enter the planning system, the focus however tends to be on the potential social and environmental impacts and implementation problems of specific energy options such as on-land wind farms and more recently offshore wind, wave and tidal energy systems. For example, the Strategic Environmental Assessment of offshore wind technology (DECC 2009b).

Some of these studies may feed into wider comparative impact assessments, but as yet there is no reliable methodology for making comparisons, although some of the techniques used in the studies may provide a starting point.

2.3 Assessment Techniques

2.3.1 Cost Benefit Analysis

The difficulty of assessing impacts of very diverse renewable energy sources has been addressed by a variety of assessment techniques. Underpinning many of these is cost benefit analysis. Cost benefit analysis attempts to measure, in money terms, all of the benefits and costs of a project or activity, and to allow the project to proceed if the sum of the benefit exceeds the sum of the costs by a sufficient margin (Methods Guide 1982). It aims to provide monetary values for social and environmental effects and damages which are not reflected in the normal market place and therefore do not have an allocated cost in monetary terms. Such costs are effectively "external" to the normal market valuation process which allocates monetary values and are termed "externalities". The technique relies on listing costs and benefits, allocating them a monetary value and then assessing the ratio. Thus more can be taken into account than in a purely economic appraisal since the value of social and environmental factors can be put into the balance. For example pollution effects such as the damage caused by acid rain can be valued and a cost allocated. The technique can be extended to e.g. renewable energy sources such as wind energy, where for instance loss of visual amenity can be costed as has been done for example for Cornwall where a 1.9 mECU/kWh cost has been cited as an upper limit (ExternE 1995 Vol. 6 p80).

Costing and valuation assessment techniques used previously have often relied on cost benefit analysis as a way of reconciling the great variations in the different renewable energy sources.

As with systems theory, a weakness of cost benefit assessments lies in the determination of where the boundaries are drawn. What is included and what excluded can alter the result significantly. Additionally, the results will only be as good as the data and models adopted. There can be great difficulties in allocating monetary values to certain impacts such as aesthetic factors or biodiversity which at present are either very uncertain or even indeterminate, or unknowable.

2.3.2 Life Cycle Analysis

Another technique that has matured and come into widespread use is Life Cycle Analysis (LCA) (also termed Life Cycle Assessment and Life Cycle Inventory), which is a method of evaluating processes, products, and activities through their life cycle *"from cradle to grave"* (European Environment Agency 1998). LCA traces the whole of the cycle of materials, energy and processes involved in products and activities, from the raw materials in nature through manufacture and use to final disposal (Royal Soc. Chemistry 2005).

The first stage involves quantifying the raw material acquisition, the natural resources and energy inputs, and the outputs, consisting of air emissions, solid waste and wastewater. The next stage analyses material manufacture, a third stage considers product manufacture, and in the fourth stage product use is analyzed. The last stage considers product disposal. For each stage inputs from the previous stage are included and energy inputs and outputs of air emissions, solid waste and wastewater. These stages are common to most LCA exercises, but can be extended or modified for particular cases (EEA 1998).

After constructing a flow chart, the inputs and outputs of each stage need to be identified and listed for the inventory. This will record the energy and materials inputs and outputs, for the particular product, process or activity. Since not all the inputs and outputs in LCA can be identified, it is necessary to select the main ones. Standard units need to be used for the mass and energy tally. A common framework is required for comparison and data kept to a minimum.

Life Cycle Analysis is an accounting tool, which uses standard data to indicate pollution and impact associated with emission and resource consumption, which may not apply in specific cases. Although LCA appears to convey an impression of precision, in fact it can only convey an indication of the likely impacts (Jensen 1997). The scope of the exercise needs to be carefully determined with any gaps and omissions needing to be taken into account.

Life Cycle Analysis and Assessment are used to compare different products, processes or activities, to identify the main inputs and outputs and their impacts, including pollution, and to determine which stages in the Life Cycle cause the main impacts. As such, LCA provides a type of environmental sensitivity analysis. A choice of options can then be made to reduce overall impact.

LCA tends to be most successful when used for products or elements of processes that can be easily delineated. For example when applied to the individual energy converter devices such as wind turbines or solar photovoltaic modules it can help highlight which stages of their life cause the most impact. Where systems are more complex or open ended, involving wider cycles, the narrow focus can be misleading, however. LCA can however provide a useful analytical tool when used properly. The International Standards Organization (ISO) has developed a standard for LCA: ISO 14042, 14040, & 14044 Life Cycle Impact Assessment standard (ISO 2006).

A recent example of a comparative LCA for energy system is the study by the World Energy Council (WEC 2004) which seeks to quantify the key impacts for all energy sources including renewables, though mainly in terms of GHG emissions.

LCA has been used extensively in assessing impacts from energy, and in "internalizing the externalities", i.e. bringing into the cost realm impacts which have formerly been unaccounted for. For example land use impacts, which lie at the root of the raw material stage, can be incorporated in a framework which addresses such issues as biodiversity and soil quality (Mila i Canals, et al 2006). The methodology of LCA is used by the ExternE project, reviewed below.

In addition to the technique of allocating a monetary value to all of the effects, as in cost benefit analysis, another approach to the problem of comparing incommensurate entities is known as multi-criteria analysis (MCA).

Bucholz et al state in a paper 'Multi Criteria Analysis for bioenergy systems assessments' (Bucholz et al 2009), that "MCA can be defined as "formal approaches which seek to take explicit account of multiple criteria in helping individuals and groups explore decisions that matter" "(Belton and Stewart, 2002 cit in Bucholz et al 2009). This approach stands in contrast to the "single goal optimisation approach", with "unifying units", (e.g. cost-benefit analysis), as the authors state.

A variety of methods have been devised and MCA can be classified as Multi Objective Decision Making (MODM) approaches where an indefinite number of scenarios or sets of principles are involved. The degree of fit of the principles with the scenarios is given a numerical value. Each principle can be weighted to reflect how it is valued by the community.

Bucholz et al assess four different MCA tools on the basis of their ability to help design and plan for sustainability in a bioenergy project in Uganda, in this paper (Bucholz et al 2009). A 10kW generator, wood gasifier plus plantation, supply chain and mini grid scenario was tested against existing individual petrol and diesel powered generators. Land area used, at 3–14 ha, depending on productivity as well as gasifier efficiency, still resulted in a competitive price against kerosene, petrol and diesel. The use of a "radar graph" showed unsurprisingly that the fossil fuel scenario resulted in decreased competition for fertile land (Bucholz et al 2009).

The advantages of using MCA according to the authors, are that it can structure the problem, it can assist in identifying the most uncertain and least robust parts and lastly it can bring stakeholders into the decision making process. However, the authors state that considerable variation in results was obtained from the four different MCA tools, though social criteria were identified by all as being decisive.

While Multi Criteria Analysis can offer one solution to the problem of comparing "apples and pears" in that social criteria can be weighed together with economic criteria, it can still rely on generalised parameters, such as in this case "reduced pollution". Average values are employed and their range can be problematical. It is perhaps best suited for political decision making, involving such social factors as the amount of employment produced (Bucholz et al 2009).

UK Government agencies have been involved in assessment of environmental and social impact studies such as the large scale pan-European ExternE study, see below, which aims to cost the impacts of various energy sources so that comparisons can be made and assessed on a cost-benefit basis.

2.4 Externalities of Energy Project: ExternE

A large international collaborative study by the European Commission and until 1995, the US Department of Energy commenced in 1991, (ExternE Vol1 1995), aiming to be the first systematic approach to the evaluation of external costs of a wide range of different fuel cycles. It aimed to provide a transparent basis on which different impacts, technologies, and locations may be compared.

The external costs of energy are those not accounted for by the market, i.e. environmental and social costs. A multi- disciplinary approach is taken, including health, ecology, materials science, energy, economics and atmospheric modelling. The two types of information sought are quantification of impacts and then the valuation of these impacts under a common measuring system.

The accounting framework comprises the Fuel Cycle stage resulting in an Activity, then the Activity resulting in a Burden, then the Burden resulting in an Impact, and finally the Impact itself, which leads to Valuation.

On the question of where system boundaries are drawn, this may be "upstream" e.g. impacts of steel making are included if they are significant, but upstream impacts are not taken to a logical infinitesimal extreme. "Ideally impacts should be assessed over full life time and full geographical range" the authors state. In this manner the ExternE is a version of a life cycle analysis.

The methodology used is the "Impact Pathway Methodology". Impact Pathway Methodology involves defining the impact pathways, identifying the models of impact, the pathway stage, and the reference environment characteristics (ExternE Vol1 1995). The ExternE summary describes this method as "bottom up" as opposed to most published studies that are "top down", i.e. using average data, not related to the location or time. Site specific data is used and applied in impact pathway methodology.

Krewitt, reviewing the ExternE Project in a paper (Krewitt 2002), concludes that the answers provided by the ExternE study do indeed match the questions, but are only partial answers, reflecting the complexity of the environment, though this is, he acknowledges a big achievement in itself. He recognises the reputation and achievements of ExternE in providing a 'benchmark' standard for studies of externalities.

His criticisms concern the uncertainties and limitations of external costing, e.g. the robustness of valuations, such as 'Value of a statistical life' (VSL), the coverage of key impacts, and external cost estimates in a policy context. VSL concepts needed to be modified for the case of shortening of life expectancy, as opposed to risk of mortality. The coverage of key impacts such as climate change from global warming, resulting in minimum values of 0.1 Euros to a maximum value of 16.4 Euros, given the uncertainties involved, are considered "at least badly misleading". The author considers that ExternE also fails to recognise the reversibility of an impact adequately. On the issue of "beyond design accidents" and nuclear waste impacts over huge time spans being positively discounted, this "... 'awards' the irreversibility of the effect, by bringing the monetary value of the long term effects practically down to zero." This is a fair point, though there may be confusion about the type of wastes involved and the wide variation in half lives. Intermediate level nuclear wastes are indeed much easier to deal with after long storage periods.

Krewitt points out that on renewable energy sources, the variability of the impacts from the material intensity of renewable energy technologies reflect excessively the energy mix of the country of manufacture, (i.e. high or low fossil fuel / carbon, e.g. Germany versus Switzerland), rather than adopting an average representative value. Nor, does he believe, site specificity is adequately acknowledged for renewables with regard to the limited availability of suitably low impact sites.

Concerning the policy influence of external cost estimates, despite ExternE failing to calculate sufficiently robust, comprehensive and precise external cost data, external cost estimates were still incorporated into European environmental policy. The magnitude of electricity price “adders” that are required to internalise external effects, for global warming, has been limited to a maximum of 5 Euro cents / kWh. Krewitt considers that this should be a lower boundary, not a best estimate, considering the limitations of estimations, the uncertainty and magnitude of the issue. However, he points out that the "relative ranking of energy technologies was much more robust, indicating lower external costs for electricity generation from hydro, wind, and in many cases, from PV compared to fossil fuels."

2.4.1 Conclusions regarding ExternE

The ExternE study is based on a Life Cycle Analysis approach to environmental impacts, which assessed categories of damage, and costs of impacts and effects. The impacts and effects were obtained from surveys of literature in the field. While this approach is reasonable, it relies on existing models of impact. These have largely concentrated on conventional sources of energy such as fossil fuel thermal energy conversion, i.e. combustion, or on nuclear energy. These sources are so dominant in electricity generation that approaches to them such as "Fuel Cycle" categorisation appear to be standard and are then applied to all of the sources. The application becomes increasingly tenuous when applied to renewable energy sources, which apart from biomass, are not fuel based. This emphasises the need for a different model of impacts. Indeed, the whole Life-Cycle approach, i.e. "from cradle to grave" implies a definite beginning phase, a use phase, and then an after use, or waste product phase. This is more applicable to fuel based sources of energy than to renewable sources which represent the harnessing of continuous flows of energy. Life-Cycle Analysis is more suited to products where clear system boundaries lines can be drawn. It is however, a very useful technique in determining e.g. energy payback accounts of discrete energy converter devices and equipment, and can be a powerful tool for assessing total impacts where they can be readily identified.

2.5 "Green" electricity Criteria

The advent of "green" electricity supply, sold as deriving from solely renewable sources and charging a premium, has led to some examination of the criteria for "green" generation and even what constitutes "renewable" (Clarke 2000). For instance, the question of whether waste sources are truly renewable and how "green" they are, can be posed, given that waste streams incinerated for energy purposes can include plastics and other fossil fuel based materials.

For an example of this as applied to hydropower, the EAWAG, Swiss Federal Institute for Aquatic Environmental Science and Technology Oekostrom Greenhydro project has issued international guidelines for Green Electricity using Hydropower (Bratrich et al, 2000). EAWAG has developed a certification procedure for green power from hydro sources using hydropower criteria, such as minimum (compensation) flow criteria, concerning the diversion of water, as well as storage. Also included in the criteria is interconnection between watercourses, groundwater, riparian zone, and floodplains, adequate water for fish migration, as well as preservation of natural river beds. The criteria extend to hydro peaking, i.e. the use for peak demands, also reservoir management, sediment transport bed load management, and power plant design criteria. Bratrich et al (EAWAG 2009), make the point about "green electricity" that "there is still a lack of credible guidelines for the certification of such products", and that such products have tended to concentrate on the new renewables, (excluding hydropower). Even where such sources are included, while the global criteria were met, local impacts to the river were frequently not considered. The Swiss situation is cited where some 80% of the technical resource capacity for HEP is already exploited. "The effects on the ecological integrity of many alpine river systems are dramatic". The interesting proposal here is to use the surcharge for "green" electricity to achieve higher standards in HEP generation, through the Ökostrom (eco current) project (EAWAG 2009).

The author has posed the question of whether some Green Energy Sources are greener than others, and if so by what criteria, in an article 'Buyer beware' (Clarke 1998).

As an example of particular land use problems, and the competition with existing uses of farmland, as well as the issue of target-setting in advance of research on the effects of a policy, the Biomass and Biofuels controversy is included here. Biomass is currently the largest source of renewable energy (Boyle 2004), but also has the lowest power flux density.

2.5.1 Biomass & Biofuels Controversy

The issue of target setting for renewable energy sources and for biomass and particularly biofuels policies had become environmentally controversial by 2008. Although there has been environmental scepticism concerning biomass energy usage ever since large scale policies were first proposed in the 1970s (Pimentel et al 1983), growth in the use of such sources has been gradual until recent policies were announced, e.g. the EU Biofuels Directive (EU 2003). Rising targets for "green" biofuels use were set for road transport, resulting from policies to increase renewable energy capacity overall, and has led to claims that competition for land area is driving up food prices, that forest is being cleared for e.g. palm oil plantations, and that the carbon savings from biomass energy are much lower than has been claimed (FoE 2008).

Several "Food versus Fuel" Reports were produced by different organisations.

A leaked World Bank draft report (Mitchell 2008) was said to claim that "Biofuels have caused 75% of the food price rise" (Guardian 10/07/2008).

In fact, when it was formally released, the report, by World Bank economist Don Mitchell, said that biofuels, low grain inventories, speculative activity and food export bans, had together pushed food prices up by 70-75%. So it was not just biofuels – it was also trade patterns. Also a study by New Energy Finance (Liebreich 2008), found that since 2004, biofuels were responsible for at most 8% of the 168% rise in global grain price and 17% of the 136% rise in edible oil prices.

Although the EU Biofuels Directive of 2003 (EU 2003) had encouraged farmers to set aside land for biofuels, there was not very much production in the UK, approximately 120,000t, which was small compared to whole world production.

A paper by Tan, Lee, Mohamed, and Batia, 'Palm Oil: addressing issues and towards sustainable development', in support of palm oil growers, defends the use of palm oil for biodiesel (Tan et al 2007). This is a riposte to WWF reports on the impacts of palm oil use for biodiesel production, which they claim include deforestation, biodiversity loss, orang-utan extinction and peatland destruction. Tan et al state that palm oil constitutes only 1% of biodiesel feedstock, but produces >4t per ha average compared to 1.5t per ha in the case of rapeseed oil, and at a lower price per ton. The claimed impacts of palm oil for biodiesel on deforestation are exaggerated, as out of 4050 m ha most are already cultivated, i.e. production has only shifted from other crops. Palm oil, the authors state, has better gross assimilation of CO_2/pa, than rainforest, with a high photosynthetic efficiency of 3.2% claimed. Other advantages are a low fertilizer requirement, relatively good biodiversity, with under-cropping possible. Tan et al also make suggestions for sustainability criteria.

The biofuels issue became increasingly urgent given the targets being set for renewable energy and transport fuels.

2.5.2 Targets

EU targets for getting 20% of EU energy by 2020 from renewables were instituted in 2007 (EREC 2007), (Europa 2008) and also 10% of transport fuels from biofuels by 2020. In the UK, Renewable Obligation targets of 10% electricity by 2010 (BERR 2007), and 15% by 2015 have been adopted. Government targets for road transport biofuels in UK were set at 2.5% of total initially, and then 5% by 2010, subsequently increasing to meet the 10% by 2020 EU Target (EU Biofuels Directive 2003).

A Policy Review undertaken by government, 'The Gallagher Review of the indirect effects of biofuels production' (Gallagher 2008) recommended reduced growth of biofuel use, effectively halving the rate of growth, pending use of marginal lands and advanced technologies such as enzyme "cracking" of cellulose (RFA 2008).

Subsequently, the government decided on a 3.25% target for biofuels in UK transport fuel from April 2009 to March 2010 - a reduction in the 3.75% target announced before the Gallagher Review. And subject to Parliamentary approval of the RTFO (Amendment) Order 2009, subsequent targets were:

3.5% for 2010/11;
4% for 2011/12;
4.5% for 2012/13;
5% for 2013/14

The Gallagher Review [of the indirect effects of biofuels production'], looked at the impacts of biofuels especially in land use change and rising food prices. However, although the review found that increasing demand for biofuels *'contributes to rising prices for some commodities, notably for oil seeds'* it could not provide estimates of how much since the data was *'complex and uncertain'*.

Some criteria for sustainability are nevertheless proposed so that biofuel production does not compete with food production and that carbon neutrality is achieved (Gallagher 2008). This policy report for government addresses concerns over biofuels policy in contributing to food price increases, deforestation and GHGs. The authors conclude that probably enough land area exists for both biofuel feed, and food production. Idle and marginal land should be used. Advanced technologies such as second generation biofuels using enzymes, should be stimulated. Biofuels do contribute to rising food prices for the poor, according to the authors, but a sustainable biofuel industry is possible. Lower targets, such as 5% not 10% of road fuel by 2020, and stronger controls are needed together with global enforcement to prevent deforestation, they state.

According to critical observers such as NGOs e.g. Friend of the Earth (FoE 2008), the emphasis on targets and rapid growth before proper sustainability criteria have been developed, has led to impacts. It would appear that sufficiently robust criteria, based on models incorporating quantitative data on e.g. soil carbon balances, are not yet available, leading to unrealistic expectations of biofuels.

2.6 General Environmental Impacts

While in recent years there has been no shortage of adverse and sometimes partisan commentary on local impacts of specific renewables, e.g. by groups opposed to wind farms, and there is a large literature on the issue of public reactions to renewables (Elliott 1994, Walker 1995, Elliott 2003, Bell et al 2005, Warren et al 2005, Devine-Wright 2006, Ellis et al 2006, Walker 1995*b*), there have been relatively few attempts at comprehensive comparative assessment of environmental impacts.

In a somewhat pejorative view of impact of renewable energy systems when applied on a large scale, which nevertheless makes some useful points concerning large land and water use, Abbasi & Abbasi (2000) review the negatives effects of renewable energy sources. In a paper titled 'The likely adverse environmental impacts of renewable energy sources', they state that all renewables have impacts, with solar heating and passive solar having least and wind few. Most types of renewable energy systems are reviewed. However, some of the material referred to is selectively chosen and out of date, such as the quoting of low frequency noise from the MOD-1 wind turbine of 1979. The authors write from a largely Indian perspective, in which hydro electric power is considered particularly bad, together with centralised biomass. The low overall photosynthetic conversion efficiency of biomass at 0.1% is cited. The authors state they are not against renewable energy, but caution wisely against it being seen as a "panacea".

The present author has however written in this field, and reviews several of his own works here.

2.6.1 Previous work by the author

This author has written a series of previous works, out of which the present thesis is developed. 'Comparing the Impacts of Renewables' (Clarke, 1993 & 1994) is a theoretical model and analytical structure for the assessment and comparison of impacts of different renewable energy sources. It suggests a predictive model for how impacts are caused based on power flux density, but also introduces other parameters such as proportion of the flow extracted, efficiency of energy conversion and number of conversions. A version as a paper was published in International Journal of Ambient Energy (Clarke 1994) as well as a report version. Although some preliminary figures are used in graphs and tables, the model is essentially uncalibrated, being a hypothetical structure for the mechanism of impacts.

'Environmental Impacts of Renewable Energy: a literature review, Thesis for a Bachelor of Philosophy Degree' (Clarke, 1995), aims to be a comprehensive review of the impacts of renewable energy organised by source, date and importance. It includes a review of general renewable energy impact approaches, as well as a section on the costing of impacts. It is a search for common themes in the impact assessment of the different and disparate sources. It is a critical and fairly comprehensive review and survey of a selection of literature up to 1994 of environmental impacts of renewable energy sources. One of the main conclusions is the need for a common framework in comparison of "apples and oranges". Other major points are the lack of reliable methodologies for comparison, the inadequacy of current definitions and analyses of natural environments, and that sensitivity to impacts is likely to result from the fact that natural energy flows power the environment. A characteristic, the diffuse energy density of renewable energy sources, is pointed out.

Since the work was carried out there have been advances in some areas as reviewed above, though the author believes many of the issues remain unresolved.

A criticism of Life Cycle Analysis techniques applied to renewable energy systems where complete cycles are required can be found in 'Life Cycle Assessment of Energy from Biomass Waste sources' (Clarke, 2000). There is a description of an analysis and model of impacts from renewables as applied to biomass and "green" criteria. The importance of soil carbon in determining CO_2 neutrality and 'sustainability' is emphasised. Another theme concerns the problems of employing combustion in energy conversion.

A version as a journal paper was produced 'An Assessment of Biomass as an energy source: the case of energy from waste', (Clarke 2002). The point was made of the need for thorough examination of the carbon balance.

Some of the literature on the impacts of hydro electricity, the main case study focus of this thesis, is reviewed below, in addition to the reviews of key issues in the literature, assessment techniques, green electricity criteria, biomass and biofuel controversy, and the author's own works.

2.7 Hydro Electric Power

Hydro electric power (HEP) is the oldest, most mature renewable electricity generating source and it has the largest installed capacity worldwide of the eight renewable energy sources that are used to generate electricity, as distinct from traditional biomass use for heating, cooking and lighting. There is as a result a considerable body of literature available on the subject of environmental effects and impacts from this source, and a selection is reviewed here. HEP has thus been selected as the most amenable source to use to investigate the hypothesis.

There has been considerable debate on the impacts of hydro, especially large Hydro, with opposition growing since the very large developments in the period 1930-1970. Such large schemes are now generally confined to developing continents such as SE Asia, Africa and S America. Hydro electric power developments have tended to lose their good reputation in developed countries and active opposition networks exist for example the Wild Rivers Campaign in the USA (American Rivers 2009). Opposition has also mounted to large hydro in developing countries, based in part of their alleged environmental impact (McCully 1996).

The political nature of the controversy over impacts of HEP can be seen in a paper on HEP and Environment in the subcontinent, "Hydropower and Environment in India" (Ranganathan 1997). This is a pro development debate / polemic which deplores adversarial decision making processes.

The potential environmental problems have of course not gone un-researched. A major work on hydro electric power impacts is that by Petts, 'Impounded Rivers. Perspectives for Ecological Management' (Petts 1984). This is an important book on the effects of dams and reservoirs including biochemical and biological issues, their geomorphology effects such as river and bed load, erosion, water stratification, and ecology. Petts raises questions over the degree of change rivers experience when dammed, and emphasises the 'river continuum' concept whereby changes continue to have effects downstream. He proposes a classification scheme and structure for addressing impacts and includes much detailed evidence and data.

That the HEP industry is trying to address criticisms can be seen in a paper by Trussart et al (2002), on the topic of environmental effects and solutions for HEP. Titled "Hydropower Projects: a review of most effective mitigation measures" it covers impact avoidance measures, mitigation measures, and compensation and enhancement measures (Trussart, et al 2002). A thorough checklist, together with discussion, is provided. The authors consider that effective measures can be taken to reduce impacts, but make the point that effectiveness of measures is not well known due to lack of comprehensive monitoring.

Support for HEP in fast developing countries can be seen in a paper on power generation in China which defends China's HEP programme. "Hydropower in China" by Li (2000) describes China's power situation, development demands, modernisation demands, the options available, fuel and pumped storage, and justifies the HEP programme. Li believes China's HEP policy is correct and western environmentalist criticisms are wrong.

The subject of social, environmental and economic changes as it applies to HEP development, and an explanation of changes in HEP development, is described in Oud (2002). This is a comprehensive account of past and present development and rationale. The author claims hydropower can adapt to sustainability requirements, economic liberalisation, and increased social demands and can compete economically. Methods by which HEP can adapt are included, e.g. design and flexibility features, such as multiple depth dam sluices.

The importance of HEP, hydropower developments worldwide and its potential in different regions of the world are the subject of a paper by Bartle "Hydropower Potential and Development activities" (Bartle, 2002). This is a market survey of expansion in different countries asserting that Hydropower is expanding especially in developing areas, due to its maturity, economy, long life, and abundance of the resource. The author's view is that environmentally and socially well planned hydropower has a major role to play in future world energy supply, despite the "recent wave of public opposition".

The evolving environmental regulation of HEP can be observed in: 'The environmental legal and regulatory frameworks: assessing fairness and efficiency' by Berube & Cusson (2002). The paper is concerned with hydro statutory environmental regulatory assessment, the influence of environmental assessments and Strategic Environmental Assessments. This is a legislative analysis, of policy, project planning, screening, and scoping. The authors make the point that there is confusion in the process, and believe that hydro electric power has lost out. They point to the need for strategic environmental assessments.

Sustainable hydro electric development proposals are contained in 'Environmental Assessments Recommendations for Sustainable Hydroelectric Development', (Klimpt, et al, 2002). This paper has a discussion and checklist for greener hydro procedures. The point is made that comparisons need to be made on a like for like basis; the benefits as well as impacts should be included in Life Cycle Analyses and environmental assessments. Klimpt's view is that hydropower has made much progress in the last 20 years and can be "green".

The research activities of the World Commission on Dams (WCD), a former industry association, on impacts of HEP are the subject of "WCD Cross Check Survey Final

Report" by C. Clarke. This is a survey of dams' performance, intended and actual developments, by the World Commission on Dams (Clarke C., 2000).

However the opposition has continued to press its case.

In 2004 the International Rivers Network, (IRN) produced a declaration calling for large hydropower to be excluded as a renewable energy option in the UN initiated 'Clean Development Mechanism' a green project support system for developing countries. The IRN claimed that large hydro projects have *"major social and ecological impacts"*, most obviously in terms of social dislocation resulting from the need to move people from the inundated areas, and said that efforts to mitigate local eco impacts typically fail. Moreover, it said, the alleged economic and social benefits of large hydro projects are often illusory (*"Large hydro does not have the poverty reduction benefits of decentralized renewables,"*) and while it supported small hydro, it claimed that including large hydro in funding initiatives would *"crowd out funds for new renewables"*.

2.7.1 HEP and GHG emissions

The IRN had also claimed that large reservoirs "can emit significant amounts" of greenhouse gases like methane, thus undermining hydro's claim to being 'climate friendly', this being one conclusion from an earlier report produced by the World Commission on Dams: 'Dams and Development: A New Framework for Decision-making' (WCD 2001). This looked at the emissions of greenhouse gases (GHGs) from dam reservoirs, due to the rotting of biomass trapped when the reservoir is filled and then brought down stream subsequently, and compared these emissions with those from other energy sources.

After two years work, the WCD concluded that *"All large dams and natural lakes in the boreal and tropical regions that have been measured emit greenhouse gases... some values for gross emissions are extremely low, and may be ten times less than the thermal option. Yet in some cases the gross emissions can be considerable, and possibly greater than the thermal alternatives".*

The WCD note that *"the flooded biomass alone does not explain the observed gas emissions. Carbon is flowing into the reservoir from the entire basin upstream, and other development and resource management activities in the basin can increase or decrease future carbon inputs to the reservoir".*

In response the International Hydropower Association (IHA), an industry non-governmental association, argued that the IRN's assertions about emissions were not properly backed up. Only a few studies had been done, and in any case, although HEP reservoirs can emit methane, what matters are the net emissions, i.e. the emissions with the dam in place compared with those that were generated from that area beforehand.

The IHA claimed that:

1. Tropical rivers, floodplains and wetlands, in their natural state, are large emitters of greenhouse gases.

2. Natural lakes and rivers, in boreal and temperate climate, have emissions similar to reservoirs older than 10 years.

3. Dams have little effect on overall emissions, because virtually all the carbon flowing in rivers tends to be emitted to the atmosphere and only a very small fraction will sediment permanently in the ocean.

4. In tropical forests, seasonal rain naturally floods huge areas that have similar ecological conditions to those of tropical reservoirs.

5. In boreal reservoirs, a few years after impoundment, aquatic productivity and water quality are similar to that in natural lakes.

The allegation that CO_2 emissions are raised by HEP reservoirs was also refuted by Gagnon in a paper titled "The International Rivers Network statement on GHG emissions from reservoirs, a case of misleading science."(Gagnon 2002).

Gagnon states that HEP emissions of GHGs are probably no more than those of rivers & floodplains in a natural state. His view is that comparisons have not been made on same basis, i.e. they have not assessed the net emission or increase due to the dam. He therefore proposes an improved methodology.

Richey states that carbon balances of tropical rivers may be neutral or even positive, in a paper on CO_2 emission and carbon transport of tropical rivers (Richey J. 2002). His paper "Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO_2" is a technical paper reporting on measurements and calculations of the carbon transport and CO_2 balances and emissions of Amazon Basin rivers. Richey states that linkages between land and water may be stronger than thought, with rivers representing a significant downstream translocation of carbon originally fixed by the forest.

On the same subject, an article (about a workshop meeting) titled "Cleaning up Hydro's Act" (Newman 2000) notes that while life cycle assessments have concluded that HEP can produce net emissions from reservoirs, so do natural lakes, and natural habitats may be either sources or sinks for carbon. Reservoirs cause "a net change in GHGs from pre to post impoundment". Boreal reservoir emissions were very low compared to tropical ones, but even there, the variation in GHG emissions from Brazilian HEP schemes ranged by a factor of up to 500.

However a number of physical characteristics of good and bad sites for GHG emissions are given. Good sites have a high power density per area inundated, bad sites have low "power density (in) kW/m^2"; deep reservoirs were found to be better than shallow ones in this respect, with canyon-like shapes better than dendritic (Newman 2000). Water residence time in the reservoir needed to be short rather than long. The size of the catchment area should be small rather than large. Temperature for a good site was cold and for bad sites warm. Nutrient and carbon input was low for good sites and high for bad sites.

However, simplistic impressions needed to be avoided since a reservoir will not necessarily emit more GHGs than a river before impoundment. The authors considered that more research was needed on the issues of pre-dam GHG emissions and sinks from natural habitats and the basin, as well as assessment of GHGs released from water passing through the dam, and observed GHG emission from the reservoir surface and inflows of carbon from upstream.

Some of the parameters given above for good and bad HEP sites associated with water quality, can be linked to changes to the energy flow and have been used in this study, see chapter five.

2.8 Land Use & Diffuseness

A persistent criticism of renewable energy's practicality by nuclear and fossil fuel industries has been that the land use, i.e. area required, is too great; that is renewable sources are too diffuse (Walker 1995). However, until fairly recently exactly *how* diffuse or concentrated sources are, has not been used as means of characterising the different sources.

Walker points to the importance of land use for renewable energy in a paper on planning issues 'Land Use and Renewables' (Walker 1995). He states that changes in energy policy have implications for land use, with "...interrelated themes of land requirements, environmental impacts and public opposition, and planning policy are identified". He notes the diffuse nature of renewable energy, stating that land availability is a potential constraint on renewable technologies.

Land use is raised as an issue by Gagnon et al, in a paper "Life Cycle Assessment of electricity generation options: the status of research in year 2001", (Gagnon et al 2002). Gagnon et al compare other electricity options with hydro. They claim that Hydro has the lowest land use per TWh. Their view is that shortcomings and omissions of assessments have militated against hydro. This work is discussed further in chapter 3.

Caetana de Souza (2007) makes the point that modern HEP plant use much less land per unit of dependable generation than older HEP schemes, in a paper titled 'Assessment of statistics of Brazilian hydroelectric power plants: dam areas versus installed and firm power define somewhere'. (Caetana de Souza, 2007). His HEP assessment technique involves an index system of environmental impact assessment based on land area compared to installed and firm power, in Brazil. A thorough survey of land areas and installed capacity and capacity factors, was carried out, and arranged in an index by region for Brazil, as criteria for environmental impact assessment. The index is based on land area compared with installed capacity. Caetana de Souza's view is that capacity factors can be a useful parameter for impact assessment, and that more modern development can reduce land take. Modern developments can have a higher environmental index based on firm power/land area. The author also suggests that electricity generation per unit of land area would be a useful parameter, and that calculated volume of reservoirs could be another basis for environmental analysis.

The issue of land use is considered by MacKay (2008), but in terms of the average power in watts per square metre, for renewable energy sources across the whole UK. Mackay (2008) assesses the renewable resources available to the UK in a wide ranging tour of energy options available for the UK, in a book 'Sustainable Energy – without the hot air'. He poses the question "whether a country like the United Kingdom, famously well endowed with wind, wave, and tidal resources, could live on its own renewables".

He assesses the available energy resources in comparison with the current energy demand, from all sources and not just for electricity. He states "all the available renewables are diffuse – they have small power density" (Mackay 2008 p181). For this reason he considers that it will be difficult for bulk renewable energy supply not to be large and intrusive. The method of determining the power flux density is to take the average resource on a country wide basis and this is then turned into W/m^2 and totaled up as kWh/m^2 per inhabitant per day. Certainly it is true to state that the power density, (the measure of intensity / diffuseness) is small on this basis.

However, whether like is really being comparing with like could be questioned, as for example, some of the space comparisons are for water areas, or the sea or estuaries, and some are land areas. This is acknowledged by the author as is the fact that some of these land areas will be available for several renewable sources simultaneously. For example for solar energy, panels allow no other renewable energy land use to take place below them at all (apart from geothermal), i.e. assuming the occupation in terms of interception of light, is 100%; but that for wind energy allows normal farming practices, either grazing or arable to continue. There could however, be solar panels on the ground occupying the same space as a wind farm, apart from the actual towers themselves. In fact the wind turbines should be described as being spread across the land area. That same land area is of course also acting as a catchment area for rivers which may be harnessed for hydro electric power.

However, MacKay does try to make a practical assessment of the different resources by incorporating some of the constraints of each renewable source in terms of collector characteristics, such as counting only south facing roofs for solar water heaters or photovoltaic panels.

His estimations for HEP land use are presumably averaged areas for the reservoirs, as opposed to "run of the river" or schemes with leats run along a valley side.

MacKay concludes that "it *would* be possible for the average European energy consumption of 125 kWh/day per person to be provided from these country-sized renewable sources" (2008a p3), provided that economic constraints and public objections can be set aside. However, he questions whether the scale of development would actually be acceptable and therefore has worked up a range of scenarios or energy plans involving substantial reduction of energy demand and different permutations of renewable sources, "clean coal" (with carbon capture and sequestration) and nuclear power.

2.81 Extraction of energy proportion from flows, in the literature

The concept of abstraction of the kinetic energy of natural energy flow, which is a key issue considered in this thesis, is pursued by Dacre, "Tidal Stream Environmental Impacts" (Dacre 2002), in a scoping study and generic environmental impact approach to tidal stream energy. This is a fairly thorough analysis, using some similar methodology to that used in this study. Among the conclusions and recommendations, the study identified some key environmental issues for tidal current energy development; in particular "the impact of extracting energy and the effects on tidal flow patterns, sedimentation processes and sea bed morphology". This, amongst other areas was highlighted as needing further knowledge. The development of a parametric model was another research area requiring further work.

The Pentland Firth tidal current energy project's environmental impact is the subject of the extended Executive Summary report "Pentland Firth Tidal Current Energy Feasibility Study - Phase 1", by Bryden et al, of Robert Gordon University and Scottish Enterprise Ltd (Bryden et al 2002). This impact assessment on the Pentland Firth tidal current energy scheme, identifies the likely impacts on the physical and ecological environment which include "possible changes in tidal patterns and wave climate through structure presence and through potential energy reduction and vorticity effects", as well as "changes in water turbidity and quality from seabed disturbance, gearbox leakages etc;"(p16). Other impacts are the disturbance to wildlife such as sea birds from cable laying and installation of the turbines, as well as noise and wildlife collision risk. Among the recommendations for further research on physical and ecological issues is "Further extensive research and hydrodynamic modelling..(..) ..to quantify the scale of likely effects in which devices may affect current patterns and velocities and thus local sediment movement"(p18). Overall the report's authors consider that impacts from tidal current energy devices are only moderate, despite some potential disruption to the environment.

A mention of the concept of 'proportion', a key factor explored in this thesis, is also made by Charlier in 'Sustainable co-generation from the tides: A Review' (Charlier 2003). He cites researchers suggesting that a "lower proportion of extraction may reduce impacts". This is a comprehensive review of tidal power around the world, including Russian and Chinese plants. The author states that tidal energy works, needs no new technology, and is environmentally more benign than fossil or nuclear alternatives. Capital costs of tidal remain high, but it has long life times, and low running costs are possible.

Related to the methodology used here and the concept of 'proportion', the cumulative effect of impact of wind turbines is to be taken into account in a updated government planning policy guidelines for renewable energy sources. "Planning Policy Statement 22: Renewable Energy" (HMSO 2004) itemises modified rules on planning policies as a result of about ten years' experience in facilitating new government renewable energy targets. A prescriptive, (restricting and directing) approach to renewable energy planning is disallowed; for instance no buffer zones outside designated areas are allowed, (but the effect on such zones is considered material). Also no urban (or other) prescriptive prohibition is allowed, but developments appraised are to be undertaken on their merits and impacts, on a case by case basis. No substitution of offshore capacity for onshore is allowed either.

2.9 Conclusion to chapter 2

Although much literature exists on the subject of the environmental impacts from renewable energy, and this has been a developing field, there are few systematic physical approaches that can allow comparison between and assessment of all the different renewable energy sources or provide a template for the assessment of possible future sources.

More progress appears to have been made on developing approaches that can unify the valuation of environmental effects into a generalised measure, e.g. cost, such as in the ExternE project, or on social decision making techniques such as Multi Criteria Analysis, (MCA) or Multi Attribute Decision making (MADM).

Due to the huge variation in characteristics of different sources, most studies concentrate on describing and modelling the environmental effects and impacts of individual sources and technologies. Most studies are concerned with itemising the various effects and then suggesting how they might be minimised. The result can be a check list with a range of potential actions taken in response. The disparity between the varied renewable sources and their impacts has been termed comparing "apples and pears" (Holdren et al 1980) and has been wide enough to forestall attempts to establish a common framework.

The response to this has been to compare the environmental damage from disparate sources and costing it, as has been done by the ExternE project, which uses an amalgamation of cost benefit and Life Cycle Analysis techniques. The latter may not be wholly appropriate for renewable energy systems, which utilise flows of energy, rather than products or processes having a definite beginning and end stage. The Fuel Cycle approach adopted is therefore considered by this author to be less appropriate to renewable energy.

With regard to hydro electric power, the review of key works in this area shows that the industry is well aware of environmental criticisms and is addressing them to an extent. The importance of HEP in world electricity generation, and its establishment as a major industry, is to some extent used to justify impacts, for instance on the basis of kWh per unit of impact, with claims made that this is lower than with other sources. This issue is pursued further in chapter 3, and in more detail in chapters 5-7.

While some common themes emerge from the literature on environmental impacts of renewable energy sources, these tend to be in the areas of minimum standards for e.g. noise or air and water pollution, connected to planning regulations. Alternatively issues of carbon saved or carbon neutrality emerge, for example in respect to biomass or hydro electric power. Common themes can be found in the approach comparing economic costs of impacts, as adopted by the ExternE project, although as the range of costs cited can be very wide, much uncertainty exists with this approach.

One significant common theme that does emerge is the topic of land use and hence the diffuseness of renewable energy sources. Few works have quantified the diffuseness in power flux density terms i.e. kW/m^2, and linked this to impacts, apart from e.g. Mackay in terms of land use and overall resource size.

There are, in the literature, some references to the concept of energy extraction from a flow, for example Holdren et al (1980) Dacre (2002), and Bryden et al (2002), and to the proportion extracted, especially latterly in the context of work on the impacts and constraints of developing tidal stream energy. It appears that quantification of these parameters is not complete. In part this is due to the need to model the baseline, i.e. pre-existing energy flow, before development of the renewable energy scheme modifies it. As Bryden et al point out, this is in itself a considerable challenge (Bryden et al 2002).

That natural energy flows power the natural environment is a point made by Holdren et al and that this becomes a significant factor when "large enough interventions in these natural energy flows and stocks ..." are made. This implies that proportion of energy extracted might be a significant parameter.

In 1990, the Watt Committee noted that no assessment methods they had seen work very well and consistently (Watt Committee 1990). That seems to be the case. This issue is pursued further in the next chapter and following chapters.

Chapter 3

Theory

3.1 Introduction

The previous chapter reviewed the literature of environmental impacts of renewable energy, concluding that few systematic physical approaches exist that can compare and help predict impacts for all of the renewable sources. This chapter discusses a theory proposed for such an approach.

3.1.1 How to Define Impact?

The definition of impact used here is one of step changes, the pushing of a stable system beyond its normal dynamic into a new state. These changes can be expressed numerically in terms of the extent, the frequency and the rate of change.

The state of the natural environment can be said to be maintained by energy flows as described in Chapter 1, table 1, and changes to these flows can be expected to result in environmental changes. Natural energy flows can be characterised in terms of their intensity, that is, their power flux density. This could be expected to relate to the amount of work that could be performed per unit area (perpendicular to the flow), and thus to the functions being performed in the natural environment, whether it is erosion and deposition, or bio-chemical processes such as photosynthesis.

If the definition of impact here is change to a given flow of energy, one of the significant changes is likely to be the interception and abstraction of the energy flow. The proportion of the flow that is intercepted and abstracted is likely to have a bearing on the changes to the flow.

Figure 3.1 below illustrates this conceptually for a natural energy flow, e.g. a river. Diagram showing energy losses from natural energy flow reducing energy available for functions.

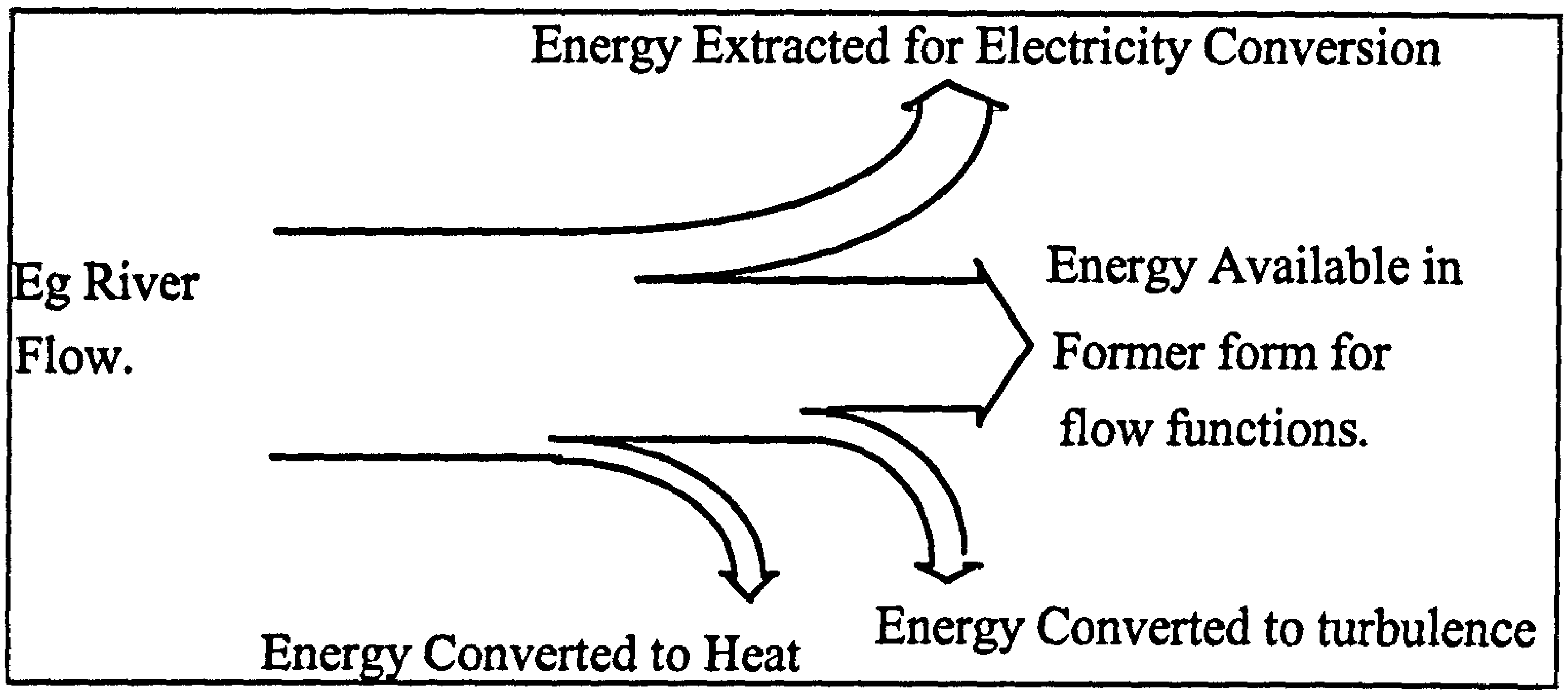


Fig 3.1 Sankey diagram showing energy losses from natural energy flows.

(Clarke 1993)

Interception of the flow is likely to cause changes or perturbation, while abstraction of energy will leave less available for the functions described above in chapter 1. These functions, such as erosion, transport of sediment, and nutrients, maintain the river's environmental conditions. For example the maintenance of deltas at the mouths of major rivers, depends on the supply of silt by the river, and loss of that supply can lead to the erosion of the delta by the action of the sea.

In terms of changes to the flow, and the degree of perturbation of the flow, the energy conversion device efficiency is likely to have an influence. Device efficiency is also likely to influence the proportion of the flow that is intercepted and abstracted.

An inefficient energy conversion device is likely to produce unwanted by-products, whether it is perturbation of a water flow or chemical by-products in the atmosphere or heat.

The mode of energy conversion itself is likely to relate to the overall impact. Since no energy conversion process, except ultimately that to low grade heat, can be 100% efficient, and unwanted by-products tend to be produced by left-over perturbed energy flows, the number of different energy conversion stages is likely to be related to the impact experienced, since each step is likely to involve a change to the flow and may generate impacts, cumulatively or independently. It is suggested that the more direct the energy conversion process, the lower the impact will tend to be, all other factors being equal.

3.1.2 Parameters

This interpretation leads to the suggestion that a limited number of parameters could be used to measure these factors and thus provide an assessment of the likelihood of impacts.

i) Power flux density is the first parameter identified here, which might indicate the degree of activity or work performed on or in a certain area. The extent or size of the natural energy flow will indicate the total extent of work done, which might be related to the cross sectional area of a river, or air flow, or of solar radiation flows. However, it is the intensity of the work performed per unit of area, or the force × distance applied, that can indicate the degree of work performed.

ii) Secondly, the proportion of the flow intercepted and then abstracted should be a significant parameter, in terms of the effect on the functions performed by the energy flow in the natural world.

iii) A third parameter to consider is the converter efficiency, since this may have a bearing on the degree of perturbation of a natural energy flow, in terms of unwanted by-products.

iv) A fourth parameter, the number of conversions involved in the energy conversion process, could prove to be a significant parameter of impact.

In this thesis four variables are labelled:

d Power flux density
p Proportion of the flow intercepted and then abstracted
e Efficiency of the converter device
n Number of energy conversions

3.2 Energy / Power Flux Density

How intense or diffuse is the renewable energy source flow? This is a fundamental question with wide reaching implications.

3.2.1 Terminology

Some confusion or debate may arise concerning the terms employed here and the units of measurement used. The term *energy* flux might be used because energy is usually defined as "the capacity to do work". The flows of energy described here represent the capacity to do work. Since what is being described here is a flow of energy, the unit of measurement would be joules per second; but there is already a unit for that, i.e. the watt. Watts are used to describe *the rate at which work is done*, that is a measure of power. A flux or flow of necessity involves the dimension of time and this is therefore the *rate* of flow. However, doing work implies a conversion of energy from one form into another. But that is not the issue here; the 'work' or transformation of the energy form has either already occurred and / or is about to occur again. The result is that the energy flows are measured here in watts per square metre, which purists may argue is the wrong term, or alternatively requires the term 'power flux density'. In the literature this term is often used and in practice and in this thesis, watts are used somewhat interchangeably with joules per second. However, for the sake of clarity the term 'power flux density' is used here.

3.2.2 Power flux density

The concept of power flux density is defined here as the rate of energy flow per square metre across a hypothetical plane across the energy flow perpendicular to it, as shown in the figure 3.2 below.

The eight primary renewable energy sources identified earlier vary considerably in how diffuse or intense they are. All of these energy flows are ultimately derived from the sun, apart from tidal and geothermal flows, which are derived respectively from the gravitational pull of the moon (and sun) and the radioactive decay of rocks as well as residual heat from the formation of the earth (Alexander in Boyle 1996).

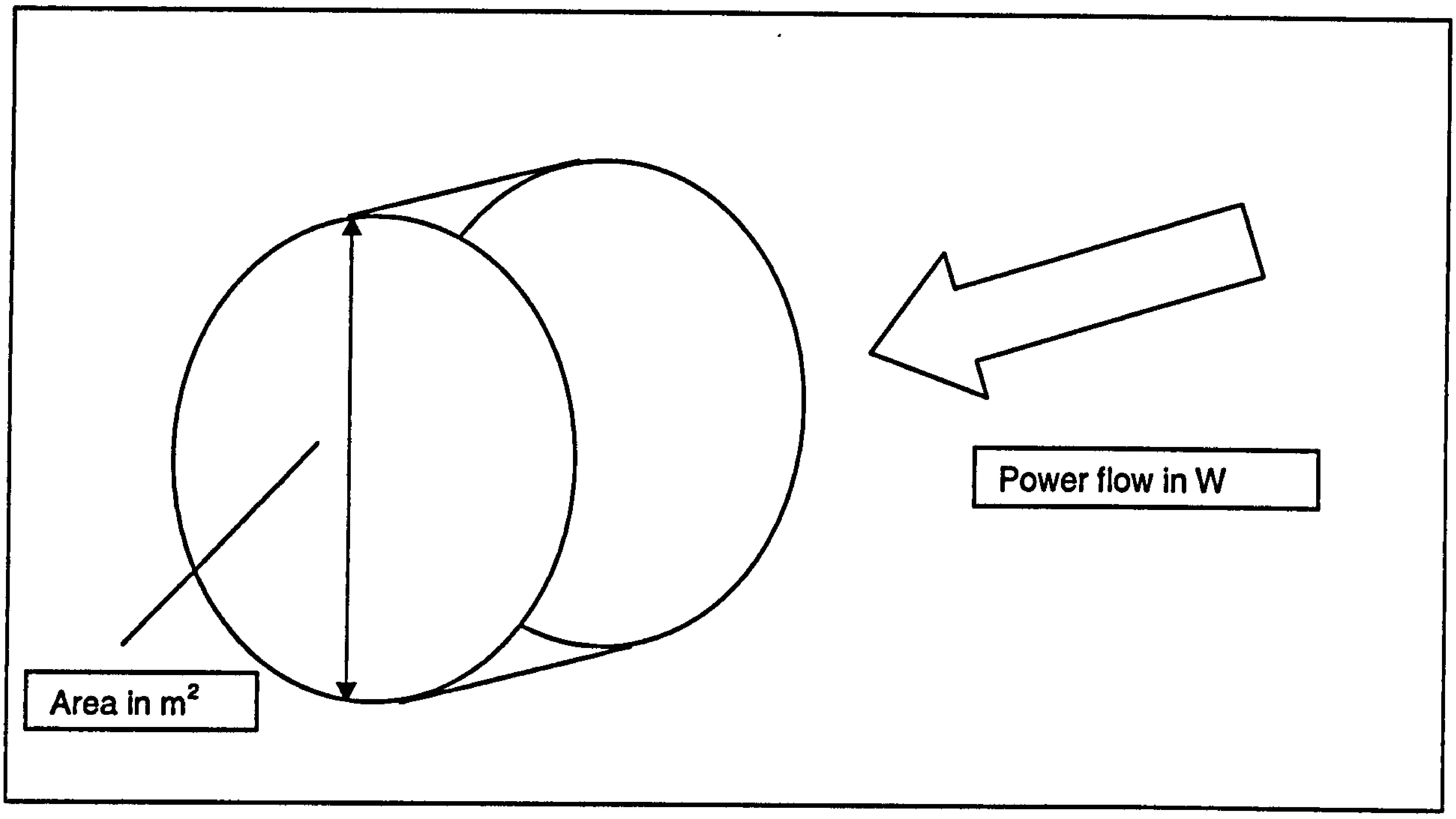


Figure 3.2. Diagram showing components of power flux density of natural energy flow.

It is evident then that solar energy arriving at the earth's surface at a maximum of ~1kW/m^2, is then concentrated through successive conversions into flows that are generally more intense (though smaller in size of total resource), starting with wind derived from heat from solar radiation, and pressure differences across the world, going on to ocean waves, derived from wind, and further to wind and thermally driven ocean currents. Solar radiation heating the atmosphere and the earth's surface evaporates water in the hydrological cycle, which through falling water can provide hydro electric power.

Biomass energy is somewhat of an exception here, since on the one hand, at the conversion stage in a plant, it has very low power flux density, being only ~0.5% efficient in conversion and storage of solar energy (Ramage & Scurlock 1996 p145), and on the other hand, the stored carbohydrates themselves represent flows in the soil with a potentially higher power flux density.

Ocean currents, mentioned above can be wind derived, e.g. the Gulf Stream, but also thermo-haline in origin, produced by temperature and density variations due to salt concentration differences (Brandon & Smith 2003 p215). An example here is the North Atlantic Conveyor current. Closer to land, the tides are the main cause of currents and these currents can become amplified by the shape of coastlines and estuaries, as they are "squeezed" into narrow channels, or resonate in funnel shaped estuaries (Charlier 2003).

Geothermal energy has very low average background power flux density of 0.06W/m^2 (Brown 1996), but can have high power flux density at naturally occurring vents such as geysers.

Since the power flux density of the different sources varies very considerably, by up to a factor of at least ~1750, this has profound implications for the area required and potentially for land use. See figure 3.3 and table 3.1 below for the power flux densities of eight different primary renewable energy flows. The intensity and variability of different natural energy flows is distributed unevenly geographically and in time, as well as between the different sources. Some examples of this are given below in a section on intensity of natural energy flows on page 78.

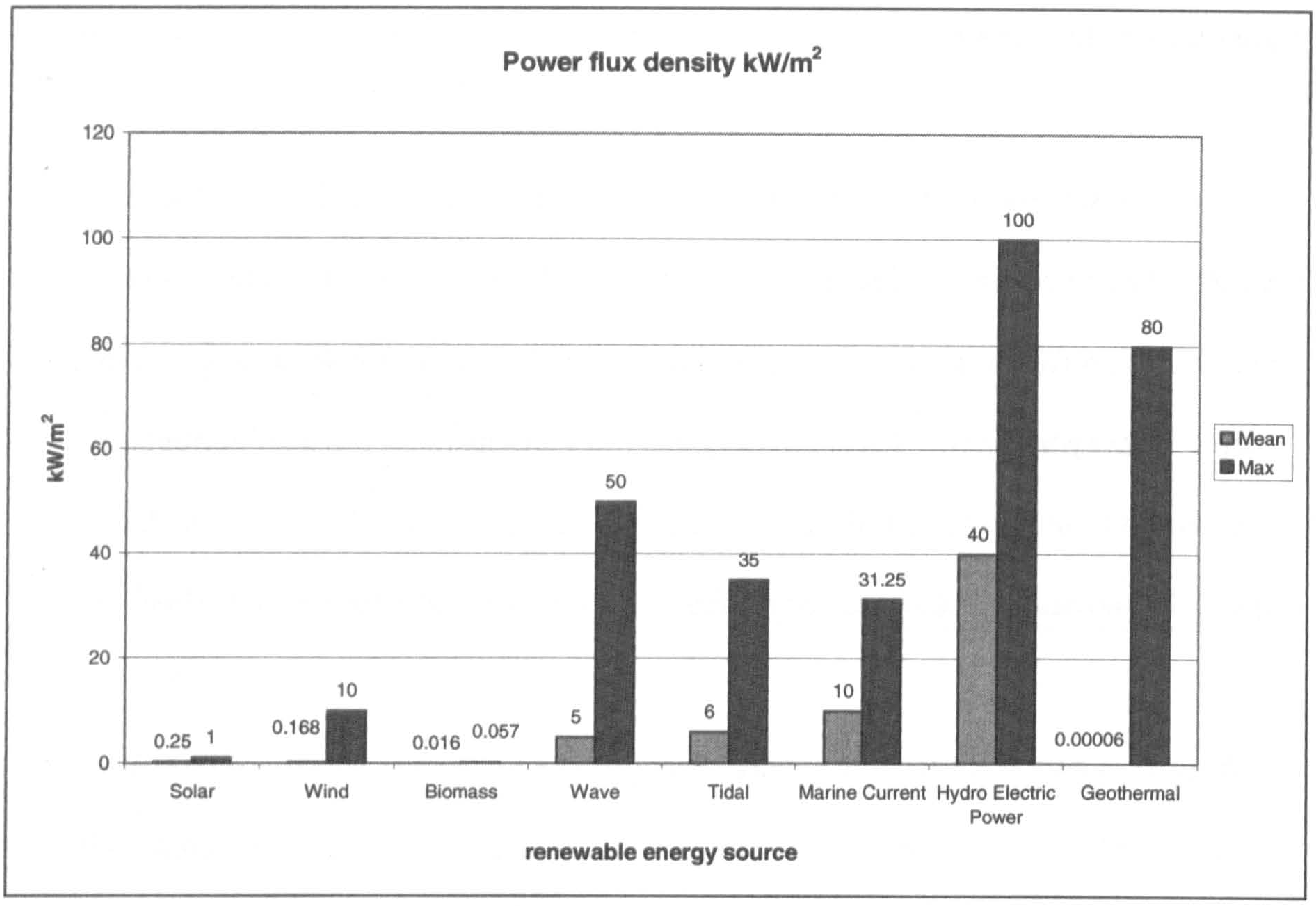


Figure 3.3. Renewable power flux density before concentration at the converter.[1]

(Source Clarke 1993)

---

[1] Refs: Solar: Twidell & Weir (1986) 1 kW/m^2,

Marine Current 10 MW/km^2 (Fraenkel 2007).

figures are indicative as there may be wide individual variations.

Solar: 3-30MJ m^{-2} per day mean, < 1kWm^{-2} max.

Wind: 6.5ms^{-1} mean, and 25ms^{-1} max.

Biomass: Assumed 320W solar radiation max absorption, <0.5% efficiency, remainder of energy used in evapo-transpiration, and heat. 16Wm^{-2} leaf surface mean energy flow in sunlight.

Wave: 20-40kWm^{-1} mean, N. Atlantic, assuming wave depth is 10m, max wave height e.g. once per 50yrs, may be up to 50 times height, but depth of <100m. Energy density also dependent on sea depth.

Hydro Electric Power (HEP) assumes medium-high head site.

Geothermal: 0.06Wm^{-2} mean earth surface value, max e.g. Geysers.

	Mean Power Flux Density	Maximum Power Flux Density
Solar	100W-250Wm^{-2}	1000Wm^{-2}
Biomass	0.016Wm^{-2}	0.57Wm^{-2}
Wind	168Wm^{-2}	10kWm^{-2}
Hydro	40kWm^{-2}	100kWm^{-2}
Wave	3kWm^{-2}	50kWm^{-2}
Tidal	6kWm^{-2}	30kWm^{-2}
Marine Current	10kWm^{-2}	31.25kWm^{-2}
Geothermal	0.06Wm^{-2}	80kWm^{-2}

Table 3.1. Power flux density for renewable energy sources, at the converter

Note: figures are indicative only and cannot represent the wide ranges at individual sites.

Intensity of natural energy flows:

The intensity of natural energy flows varies in nature both spatially and temporally. Natural variability in the intensity of such energy flows (i.e. the power flux density), can be compared with other examples of concentrated energy flows for illustration.

For example whereas normal sunlight intensity has a maximum of ~1 kWm^{-2} at the earth's surface and 1.365 kWm^{-2} at the top of the earth's atmosphere (Boyle 1996 p96), light can be concentrated in laser light beams with a power flux density of up to and beyond, for example 10^6 kWm^{-2} (Key et al 1972). Visible light wavelengths vary from ~0.3 μm to ~3 μm, with peak energy transmitted at ~0.45 μm -5 μm (Boyle 1996 p44). Ultraviolet wavelengths of light with a shorter e.g. 0.3 μm wavelength have more energy than visible frequencies. The atmosphere and ozone layer shield the surface from higher ultraviolet fluxes, though these are experienced at higher altitudes. As the angle of the sun and cloud cover change, the energy flux changes, decreasing to zero at night.

Wind energy also varies considerably, from an ~40W m^{-2} average based on $4ms^{-1}$ average wind speed (at the converter) across the earth (WEC 2004), to locations with 615 W m^{-2} at an average speed of 10 ms^{-1}, and up to e.g. 56 kW m^{-2} at 45 ms^{-1} [2] or greater in storms or hurricanes. At such power levels considerable damage can be caused.

Similarly, rainfall varies both spatially and temporally between ~0mm pa and ~10,000 mm pa (Brandon & Smith 2003); many rivers have cyclic flood flow periods, when flows can be several magnitudes greater than continuous flows. As the gradient of rivers is not constant, the intensity of the energy flow will depend on the gradient at any location along the river. The example of a waterfall can be considered compared to a river in its flood plain, with e.g. high head hydro electric schemes compared to low head hydro power and resulting differences in intensity of energy flows.

---

[2] Based on power P (in watts) = 1/2 x 1.23 x A x V^3

3.3 Land-use

One of the most evident relationships between power flux density and environmental impact may be the issue of the area required by any renewable energy source, per unit of energy produced, or on a larger scale the use of land or space required. Land use is the term usually applied to the type of land use by humans. Here it is applied to the amount of land used by each source and technology per kW of power.

The land used and some of the factors and issues involved are discussed below for these sources:-

Solar
Biomass
Wind
Hydro
Wave
Tidal
Marine Current
Geothermal

For solar, the power flux density, or intensity can be fairly easily related to the area of collector required, and also to general notions of land use. Since power flux density is here defined as the watts per square metre (Wm^{-2}), of an imaginary collector perpendicular to the ambient energy flow, it is apparent how the density is related to collector area; a greater power flux density will require less collector area per energy unit. If the flow is horizontal to the earth's surface, then the collector angle will be perpendicular, i.e. vertical, and the area it occupies will be in a vertical plane. Hence land use will tend to be less. Where the renewable energy flow's angle relative to the earth's surface, is greater than zero degrees, i.e. tilted, the collector angle will occupy space in a horizontal plane in addition to a vertical one.

Solar and geothermal flows are generally from a vertical (though varying in the case of solar) direction, or perpendicular to the earth's surface, while water flows, and air flows are generally horizontal or parallel to the earth's surface. So it would follow that direct solar, biomass and geothermal collectors occupy horizontal areas i.e. using land area; and wind, hydro, wave and tidal collectors in occupying space in a vertical plane, may not relatively speaking, occupy very much land area. Of course the associated ancillary conversion and energy storage facilities e.g. reservoirs, may well occupy considerable land area.

3.3.1 Land use and power flux density

Do typically quoted land use values for each renewable tend to bear out the relationship with the power flux density? Those cited by Gagnon et al (2002*a*), shown below in figure 3.4, only do so to an extent, in that biomass plantations require the largest land areas and have the lowest power flux density, and the hydro run of river requires the lowest land area, and has a relatively high power flux density, as might be expected. The figures for hydro with reservoir, range from ~5-200 km^2 / TWh, a surprisingly large figure considering that wind power is allocated a ~30 - 130 km^2 / TWh range, and again surprisingly and questionably, this is higher than the figure for Solar PV ~30 - 45 km^2 / TWh.

Some of these results would contradict the hypothesis here, being inverted in relation to power flux density at the converter and may be averaged over total land areas.

Unfortunately due to the paucity of references and lack of explanation of methods used to generate this data, only suggestions can be made for the difference in results. The authors do however caution against simple interpretation of the data, as ..."it does not consider the intensity of impact nor the degree of compatibility of generation options with other land use."

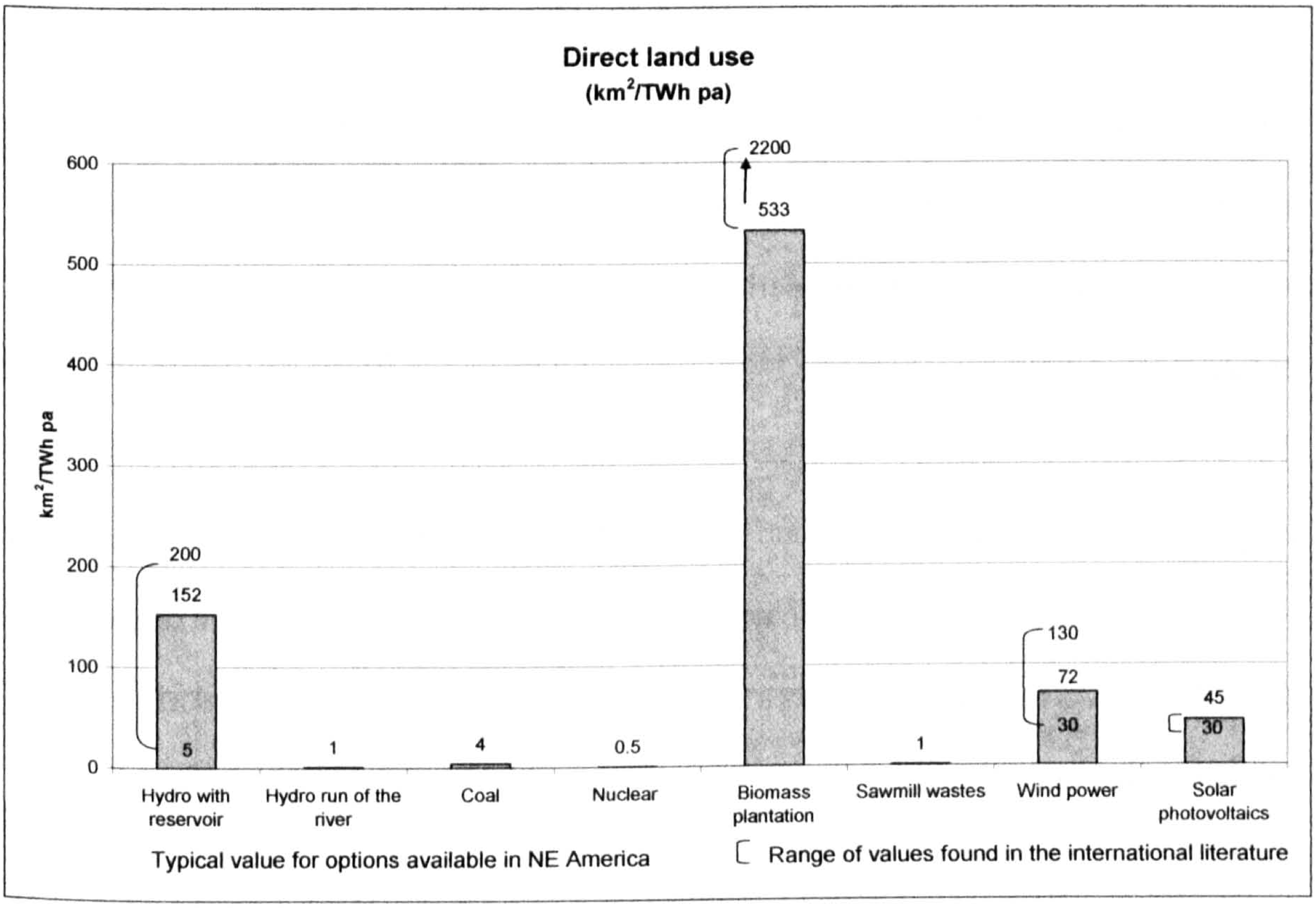


Fig 3.4 Land use of renewable and conventional energy sources data from international literature. (Gagnon et al 2002a.)

Notes (Gagnon 2002a) *Range of values found in the international literature:*

1. *Hydro with Reservoir for Base & Peakload options : ~5-200 km² / TWh*
2. *Hydro Run of river:* *1 km² / TWh*
3. *Coal:* *4 km² / TWh*
4. *Nuclear:* *0.5 km² / TWh*

5.Biomass plantation:	*533-2200 km^2 / TWh*
6. Sawmill wastes:	*1 km^2 / TWh*

Intermittent options that need backup generation:

Wind Power:	*~ 30- ~130 km^2 / TWh*
Solar photovoltaic	*~30 - 45 km^2 / TWh*

(Gagnon et al 2002 *a* Fig 4 p1274).

Moreover the authors point out that only the direct use of land is considered and that accounting for indirect land "use" e.g. from acid deposition from coal burning, or the longevity of nuclear waste storage periods can alter the land use figures by one or even two orders of magnitude.

Hydropower's results vary significantly due to site specific conditions, they state, as well as the multi-purpose nature of many schemes, together with the storage function of the reservoir. However, as few references are given, the data sources and method of calculation are not apparent.

The high figures for wind energy at 72 km^2 per TWh pa, or ~2.3m^2 per W (0.44W m^{-2}) may be due to using land area across which turbines are spread, rather than actual land occupied. The authors state that "for wind power the land around the windmills can still be used for agriculture,... that solar energy can be developed on rooftops or arid areas without agriculture,.. and that hydropower can be developed in mountainous or cold climate areas". It would appear that a rather imprecise interpretation of "land used" may account for the figures provided. Possibly no distinction has been made between land actually occupied and land affected, by a renewable collector device or scheme.

3.3.2 Diffuseness

MacKay in his estimation of UK renewable energy resources cites the power per unit land or water area, and argues that "renewable facilities have to be country sized because all renewable sources are so diffuse" (MacKay 2008a). MacKay 2008 cites land use in W/m^2 for different renewable energy sources as shown in Table 3.2, below.

Here MacKay is citing the estimated land area for each source, and averaging the power density over the estimation of practically available land from the UK's 245,670 km^2. This method differs from that of this thesis which considers the power flux density per m^2 of that part of the flow which is harnessed and the power density per m^2 area at the converter itself.

Power per unit land or water area

Wind	2W/m^2
Offshore wind	3W/m^2
Tidal pools	3W/m^2
Tidal stream	6W/m^2
Solar PV panels	5–20W/m^2
Plants	0.5W/m^2
Rain-water (highlands)	0.24W/m^2
Hydroelectric facility	11W/m^2
Solar chimney	0.1W/m^2
Ocean thermal	5W/m^2
Concentrating solar power (desert)	15W/m^2

Table 3.2 Average overall power per unit of area of total resource.

(MacKay 2008a Table 3, p3)

MacKay's concern is to estimate the overall resources available for the UK as a whole, and its population, as opposed to comparing the power flux density at the converter, with the resulting environmental impacts.

These two objectives are related in that the practical resource size is determined by constraints resulting from environmental impacts. MacKay does not investigate the link between power flux density at the converter and environmental impacts and constraints. The assumption is that this is relatively fixed; his objective appears to be to produce viable plans at a certain moment in time, hence the "state of development" is taken as read. However, the estimations of power per unit area are relevant to this study in terms of the maximum packing density of energy converters over a larger area. This topic is discussed for wind energy later in chapter 9.

3.3.3 Land Use for HEP schemes

Land use per TWh might be expected to be inversely related to power flux density, in that the higher the power flux density, the lower the area required. However, land use for HEP schemes, comprises mainly the reservoir area, which is a function of the head height chosen and the river gradient which will determine how long the reservoir is, as well as the topography of the valley, together with breadth and steepness of the sides. Together with flow rate, these factors then determine the land use per unit of energy generated. It is mainly the need for large storage capacity to even out the high seasonal flow variation, as well as achieving a head height, that results in large land area use per unit of energy production.

A proposed formula for land use for hydro electric schemes might be:

$$A \,/\, \text{unit of power (e.g. TWh p.a.)} = B \times (H / H (s \times g \times Q \times \rho \times \eta))$$

Where A = land area

B = reservoir breadth

H = head height

s = slope or river gradient

g = acceleration due to gravity

Q = flow rate

ρ = density

η = coefficient of performance (overall conversion efficiency)

Dimensional Analysis:

Area is expressed in m × m or $[L]^2$

Unit of energy produced per unit of time is expressed as power or $[M] \times [L]^2 \times [T]^{-3}$

Breadth is expressed in m or $[L]$

Head is expressed in m or $[L]$

Slope is expressed as m / m or $[L]\,[L]^{-1}$

Acceleration due to gravity is expressed as m / s^2 or $[L]\,[T]^{-2}$

Flow rate is expressed as m^3 / s or $[L]^3\,[T]^{-1}$

Density is expressed as $\rho = kg/m^3$ or $[M]\,[L]^{-3}$

η = dimensionless

So:

$$[L]^2 / [M] \times [L]^2 \times [T]^{-3} = [L]\,[L] / [L]\,[L]\,[L]^{-1}[L]\,[T]^{-2}[L]^3\,[T]^{-1}[M]\,[L]^{-3}$$

This shows that the equation balances in terms of dimensions.

It might be expected that land use per unit of energy will be lower for schemes with greater river gradients, higher mean flow rates, as well as narrower valleys, and higher coefficients of performance.

3.3.4 Space Occupation

Energy converters take up space not just in the horizontal plane but also in the vertical planes. However, the different technologies and sources require varying volumes. For instance the very thin converters of solar PV technology can be contrasted with wind turbines that occupy a spherical volume (in order for the blades to be oriented or yawed through 360°) some metres above the ground. Other technologies with multiple stage conversion equally require a volume of space. As a consequence, solar PV panels can be substituted for roof tiles or slates, with very little effective impact despite the low power flux density of solar radiation (ETSU 1994).

3.4 Proportion

There are different ways of employing the concept of proportion of energy flow extracted; for example at different scales. The concept could apply to a technology, e.g. wind energy, or it could apply to the design for a single development, e.g. an HEP scheme, or to a whole river. Alternatively the concept of proportion can refer to the fraction of a total resource in a region, or a nation, or a whole continent.

If it is accepted that natural energy flows power the natural environment, then extracting energy from those flows might be assumed to affect processes in the natural environment. It could be expected that the proportion of energy abstracted will be related to the impacts.

As an illustration of impacts from intercepting energy flows, one might consider the impacts from interception of the total flow. For instance the effect of 100% interception of light for solar PV could be considered so that no light reached the earth's surface. Some examples of the concept of interception of *proportions* of the energy flow, are given here, illustrated through some extreme polarities.

Solar: Solar radiation flows arrive at the surface of the earth providing light in the visible waveband. This radiation flow is moderated by the ozone layer, by the atmosphere, cloud cover, dust, and finally by vegetation (e.g. 1.365kWm^{-2} maximum outside the earth's atmosphere and up to 1kWm^{-2} max. on the surface) (Boyle 1996 p96). Solar collectors intercept a proportion of this flow. If the total solar flow interception were to be 100% (i.e. a 100% efficient back body absorber) covering 100% of the earth's surface, the result would be darkness at the surface of the earth, thus preventing photosynthesis, the primary basis for life, from occurring. 100% earth surface coverage would result in permanent darkness, versus normal conditions. A 100% interception rate can be compared with the natural moderation by the atmosphere, i.e. the spectral power distribution, as a result of air mass distribution (Boyle 1996 p96), cloud cover, and dust absorption. Even if a lesser area were to be covered, sufficient light could be intercepted to prevent plants growing in an area. At still lower percentages coverage, the result would merely be shade, and a decrease in light intensity with resulting heat decrease too.

Biomass: Biomatter carbohydrate flows through the biosphere, via decomposition and soil, but can be intercepted by harvesting for combustion. If *all* the bio matter were harvested, including the roots, and combusted so that no organic carbon reached the soil, the result would deprive soils of organic nutrients, carbon, hydrogen, and nitrogen particularly. A process akin to this can occur when deforestation occurs in hot dry tropical areas, leading to desertification.

Wind: Wind turbines function through slowing down the wind slightly. If the air flows of weather systems could be entirely halted, there would be considerable impact on the weather system rendering the air flow and circulation component inoperative.

Water Flows: Flowing water under the influence of gravity is exploited by HEP systems, which abstract some of the kinetic energy, by slowing down the water speed. If the water speed could be entirely halted, very considerable changes to the flow and water system would be experienced. For an example, the freezing of an entire river system, as occurred in the ice ages, has major impacts on the ecology of the surrounding eco- system, and the relevant part of the hydrological system, aside from changes in temperature. However, it is apparent that if the water speed were entirely halted, then that part of the hydrological system would cease to function. More realistically it might be assumed that if a high proportion of the flow energy is abstracted, there will be considerable changes in the river system. Since the river is an integral part of ecological systems and has a wider longer term influence on whole environments, this change can be defined as environmental impact.

The concept of *Proportion* might also be employed in relation to the fraction of a total resource developed. For example Bartle (2002) in a paper on HEP and development, cites Africa as having developed only 4% of the technical resource.

3.5 Efficiency

The efficiency of energy conversion is defined as the electrical, fuel or heat energy output from the converter divided by the theoretical energy available to the converter, in a given flow. This can be significant to environmental impact in several ways, affecting the proportion of energy that can be abstracted, the possible perturbation of the flow and in some cases the formation of by-products. High efficiency conversion capability enables a large proportion of a flow to be abstracted, an example of which is the conversion efficiency of high and medium head hydro electric plant of up to ~90%. By contrast wind turbines and marine current turbines are subject to a theoretical maximum efficiency limit of ~59 %, known as the Betz limit (Twidell & Weir 1986) (Betz 1920), since such turbines are sited in an extended fluid stream. Slowing down the flow further would be counter productive, since the flow at the converter would be eventually halted and would by-pass the obstruction created. In practice, actual conversion efficiencies will be lower still than the 59% of the Betz limit. In addition wind and marine current turbines need to be spaced out from each other to avoid being in each other's wind or current "shadow". As a consequence, the overall proportion of the energy flow that can be intercepted and abstracted is much lower than that of hydro electric schemes.

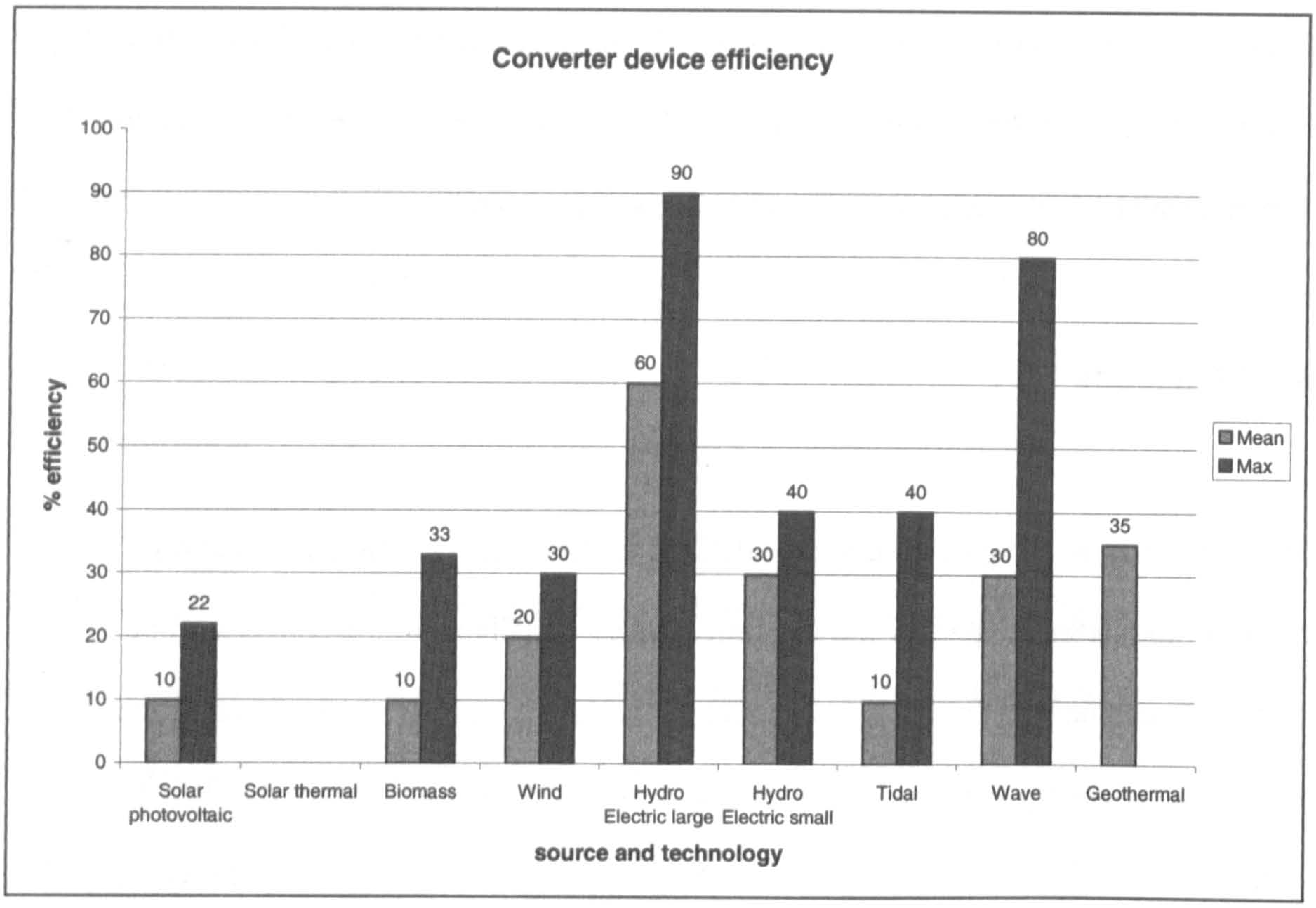


Fig 3.5 Renewable energy converter device efficiency.[3] (Clarke 1993)

Similarly, the efficiency of wave energy converters could be related to the energy left in the wave once it had passed a converter, and thus the size of the wave that for example reaches the shore. Different operational principles are employed in the different wave energy converters, with resulting varying efficiencies. Figure 3.5 above shows indicative renewable energy converter efficiencies for the main sources.

3.6 Number of conversions

The number of conversions describes how many times the energy flow is transformed into other forms, for example from kinetic energy to potential energy, or from thermal energy to rotational kinetic energy. This variable appears to be related to the form of the energy flow rather than the power flux density. The reason that transformations of energy form,

---

[3] Note that definitions of efficiency vary with technology.

such as from kinetic to potential, are likely to be significant in environmental impact, is that they represent discontinuities in the energy flow functions. For instance the transport of sediment by the kinetic energy of flowing water will be interrupted when that kinetic form is converted into potential form in a reservoir. The water speed will drop and the sediment in suspension will be deposited.

Such conversions of energy form, and ensuing interruptions to functions, are not just limited to hydro electric power, but are likely to occur in some of the other renewable energy source conversion technologies. For example concentrating solar thermal power stations convert the radiant solar beams to heat form and then to potential energy in raising steam.

At this stage a distinction should be made between the number of conversions enacted on a natural flow such as a river, before extraction of energy, and those conversions carried out to the energy extracted from a flow which are contained within the "black box" of the converter device. The number of conversions enacted on the natural energy flow may be more significant, since this part of the flow continues to perform functions in the natural environment.

3.7 High and Low Grade energy sources

Of relevance to the parameters proposed above is the concept of high and low grade sources (Alexander 1996 p7-8). "High grade" energy sources can be thought of as highly organised, low entropy, lending themselves to efficient conversion into other high grade forms, such as electricity. "Low grade" sources can be conceived of as less organised, high entropy, resulting in low energy conversion efficiency to other higher grade forms, for example heat energy, where the energy is contained in the random oscillatory kinetic motion of atoms. The latter thus requires multiple conversion stages to be transformed to the "high grade" form electricity, with resulting loss of overall efficiency. This is governed by the Second Law of Thermodynamics (Clausius 1856). However, when comparing conversion efficiencies of energy flows of forms as different as solar radiation, flowing water, or thermal energy, this raises issues as to the extent to which thermodynamics can be applied at the quantum level, which is beyond the scope of this thesis.

The term "high grade" can also, in the case of heat sources, e.g. geothermal energy, refer to the power flux density for flows of energy -the higher the power flux density the higher the grade. This usage of the term relates essentially to thermal energy conversion, where increases in temperature difference Δ T increase the efficiency of conversion.

For static stores of energy such as fuels or steam, "high grade" forms refer to the energy density or energy per cubic metre or per unit of mass, i.e. $J\ m^{-3}$ or $J\ t^{-1}$.

The importance of the concept lies in the conversion efficiencies possible resulting from the grade of energy. Conversion from one high grade source to another high grade form is often possible at high efficiency, for example falling water (HEP) to electricity. Conversion from a high grade source to a lower grade is also possible at high efficiency, but conversion from a low grade source to a higher one will only be possible at low efficiency. Thus thermal conversions to electricity are rarely above 50% efficient, usually~30%, or less depending on the temperature difference. To achieve a theoretical 80% conversion efficiency would require temperature differences of over 1000 degrees which is unlikely, in most cases as yet, to be a practical option.

As stated above, if lower efficiencies are likely to result in more unwanted by-products, i.e. the likelihood of environmental changes and hence impacts, then limitations of conversion efficiency are key to explaining impacts.

3.8 Conclusions to chapter 3

The hypothesis proposed in this thesis holds that power flux density of a natural energy flow is a significant variable in determining the environmental impact from renewable energy sources. This is due:

i) to the intensity of the functions performed in nature by the energy flow; the higher the power flux density the higher the rate of work of the functions performed.

ii) to the relationship between power flux density and land use: the higher the power flux density, the lower the land use; fewer collectors are required per unit of energy, resulting in less usage of land area.

While power flux density is proposed as a fundamental factor in characterising impact from renewable energy sources, it cannot serve to explain all impacts or the degree of impact.

Therefore in addition to this variable, the proportion (or ratio) of energy extracted from a natural energy flow is proposed as a parameter. The degree of impact caused from extraction of energy from a natural energy flow could, it is suggested, be related to the proportion of energy extracted. Impacts would then result from the changes caused by reduced energy available for natural functions.

Following on from the proportion of energy extracted, another related parameter proposed here is the efficiency of conversion.

iii) The relationship between power flux density and efficiency: higher power flux densities can lead to greater conversion efficiencies, e.g. in the case of thermal energy conversion.

The parameter of proportion extracted can explain the limits to the proportion of energy that it is possible to extract, and also help account for aspects of impact due to unwanted by-products.

While these further parameters can help to explain impacts, they still cannot provide a full model of environmental changes caused. Many changes can be effected to natural energy flows without energy actually being extracted from the system. These changes are to the form of energy, e.g. conversion from kinetic to potential, or from radiative to thermal. Such conversions can cause discontinuities to the functions of the natural energy flow resulting in impacts. The number of such conversions to the form of the energy flow is thus proposed as another parameter.

While four different variables are described here, they are not independent of each other. In addition, natural energy flows normally drive more than one function, e.g. rivers transport sediment, and also perform drainage functions. Both of these functions depend on flowing water, i.e. kinetic energy caused by the influence of gravity. Again some of these functions are more energy dependent than others. But power flux density, it is argued, might be the most significant variable since the proportion of energy capture from a particular renewable source appears to depend in part on the power density of the flow. Figure 3.6 below shows the typical proportions of flow intercepted / captured compared to power flux density, assembled by the author.

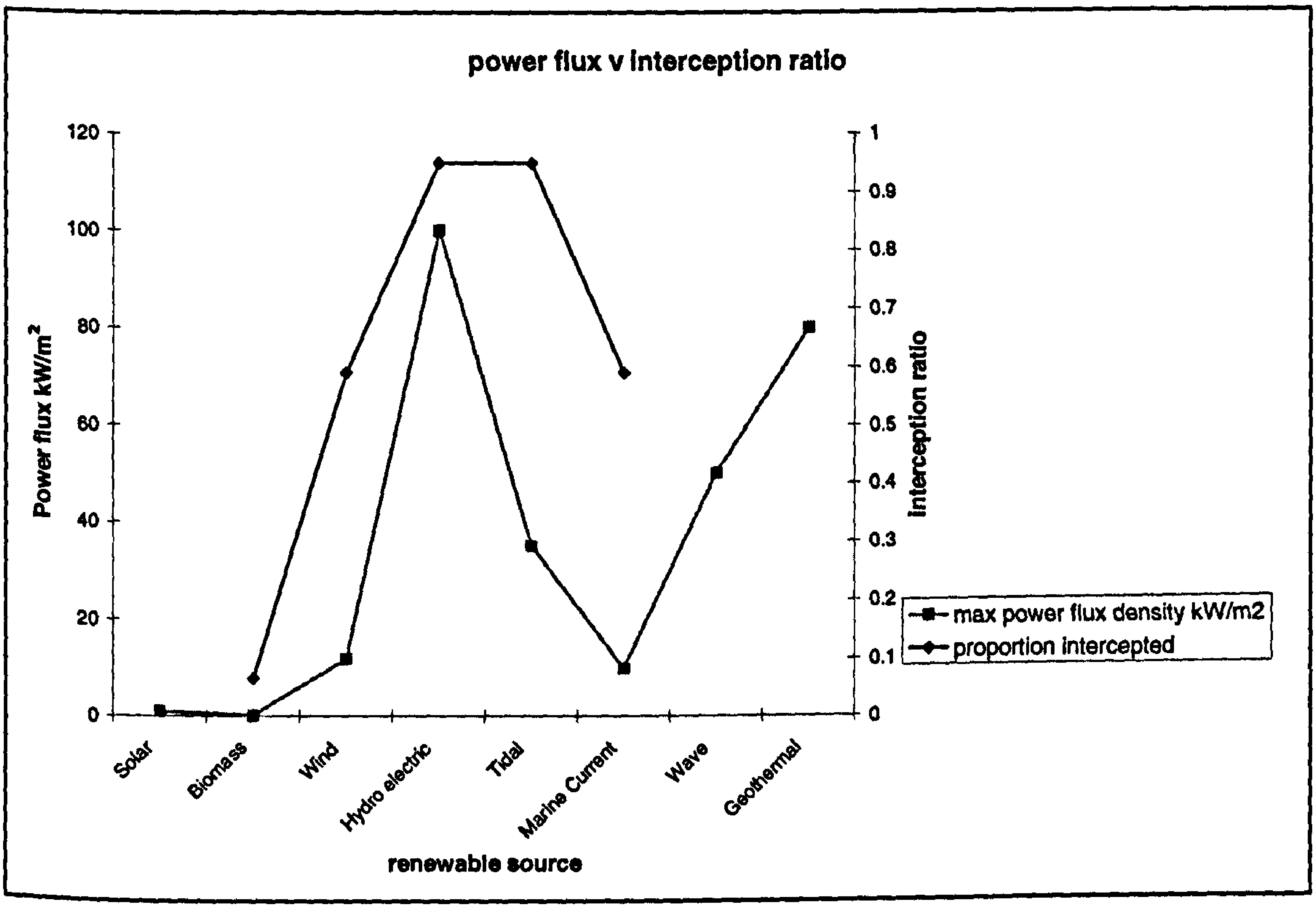


Figure 3.6 Power flux density and interception ratio for renewable energy sources.

The proportion appears to be highest for the highest power flux density sources, e.g. HEP where the proportion intercepted can be 100% of the flow and the portion captured can be 80-90%, as shown in figure 3.6. The nature of the well defined flows that constitute rivers can be contrasted with much broader flows of air currents, which will by their nature be less able to be fully intercepted.

For wind energy the maximum theoretical efficiency is expressed by the Betz limit, at 59.3% (Betz 1920 & 1966). This is the theoretical limit of energy abstraction in a continuous flow. If a higher proportion of abstraction is attempted then the flow itself is slowed to such an extent that overall still less energy can be abstracted. This limit also applies to marine current turbines.

A fifth new parameter can be added here; that is the changes i.e. increases / decreases in the power flux density of the natural energy flow. Such changes could lead to alterations to the flow functions.

The parameters described above, 1) power flux density, 2) proportion extracted, 3) efficiency, 4) number of conversions and 5) changes in the power flux density may then provide a more complete and satisfactory model of environmental impact from renewable energy sources.

Chapter 4

Questions raised by hypothesis

4.1 Introduction

The central research question of this thesis is:- *Is the environmental impact of renewable energy sources related to the power flux density?* The hypothesis is that a relationship exists, but that it may not be a simple one in all respects.

The conclusions to the last chapter outlined the proposed parameters of the hypothesis. From these parameters the primary questions can be posed.

Relating directly to power flux density:

-Does higher power flux density of a natural energy flow result in a higher rate of work of functions performed?

-Does higher power flux density result in lower land use per unit of energy?

Relating to the proportion of energy abstracted from a renewable energy flow:

-Do impacts result from the reduced energy available for natural functions?

-Is the degree of impact related to the proportion of energy extracted from a natural energy flow?

Relating to efficiency of conversion by the converter device:

-Does the efficiency of energy conversion affect the proportion that can be abstracted?

-Does the efficiency of energy conversion affect the production of unwanted by-products?

Relating to the number of energy conversions:-

- Are the impacts proportional to the number of conversions to the form of the energy flow?

These questions can be further broken down into the different forms of impact, the different renewable energy sources, and the type of relationship with power flux density.

As described in chapter 2 there is a considerable literature on the effects and impacts of renewable energy sources. Summaries of impacts for the different sources are given in later chapters. The relationship of these impacts to the power flux density might be revealed by ascertaining in some detail the mechanisms whereby the existing environment is powered and maintained by the flows of energy through it. The degree of interception of, or interference with, these energy flows, might reflect the impacts experienced.

However it would require a major data gathering and analysis effort to try to explore and fully test this relationship in detail for all renewables. This thesis focuses in detail on one example HEP, attempting to test whether the hypothesis applies in that case. It then assesses whether this can provide generalisable results, which can hold for other renewables.

4.1.1 Rationale for use of HEP to test the hypothesis

The choice of example was based on the need for extensive existing accessible data, backed by a large body of theoretical understanding and operational experience.

It was concluded that such characteristics could be represented by hydro electric power (HEP). This renewable energy source is the most mature of the new renewable energy sources and technologies, having been first used in the 1880s (Ramage 1996). As well as over one hundred years of experience, it is the most widely used of the new renewable energy technologies, supplying some ~2.2% of world primary energy, and ~ 16% of world electricity (IEA 2006). Hydro Electric Power has been described as the only mature renewable energy technology in widespread use (Bartle 2002). HEP developments have been carried out all over the world in a variety of different environments and conditions. HEP has also been deployed on a hugely varying scale from just several kW capacity, to the largest power stations in the world at 18GW capacity (Freer 2001) with head heights from ~1-2m to several hundred to a thousand metres. Furthermore much research, modelling and theoretical work has been carried out on the subject of rivers as well as on hydro electric power's environmental effects.

The task could be aided by the fact that river flows have been reliably recorded for over one hundred and thirty years, while there are flow records dating back thousands of years in the case of the Nile. Extensive flow data exists for a variety of rivers and watersheds worldwide.

4.2 Central Question Formulation Applied to HEP

The central thesis question "Is the environmental impact from renewable energy sources related to the power flux density?" could be applied to the test case of HEP in a number of ways.

As stated earlier, the first and most apparent way to show this could be through the land use or area required by different renewable energy sources, or more particularly HEP. Land use can then be equated with environmental impact; the greater the use of land, the greater the impact. For example Egree & Milewski, cite the area inundated as a rule of thumb measure of impact for HEP schemes (Egree & Milewski 2002).

This should be relatively straightforward to show albeit with some complications, for example the land area actually occupied as opposed to land affected, though not directly occupied.

A question arising from HEP as a test case would be whether impact increases in proportion to the size of development or not? I.e. does impact scale linearly or non linearly as the power flux density increases? This could be considered for HEP, where one large scheme with high head could be compared with a series of smaller schemes with lower heads.

4.2.1 Is there a relationship between the power flux density and functions in the natural environment?

The hypothesis proposes that the power flux density of any renewable energy source may characterise the environmental impacts, due in part to the reduced energy available for natural functions. This central thesis question is based on the idea that natural energy sources power natural processes in the environment. Another way of expressing this is that a natural energy flow performs a number of *functions* in the environment. These functions could be important to the maintenance of any environment. For example, river systems are responsible for erosion, transport and deposition of sediment. Such processes can maintain bank shapes and for example deltas which would otherwise be eroded by the action of waves and sea currents. Further general functions of natural energy flows were given in Table 1 chapter 1.

So a number of basic questions can be asked.

Following on from the theory in chapter 3, but in more detail:-

-Is it true that the greater the power flux density, the greater the number and intensity of the functions performed by the flow?

-Does a lower power flux density result in fewer functions being performed by the flow?

-Is the relationship linear or geometric, exponential or some other?

-What limits might apply to this relationship?

4.2.2 Impacts and changes: discussion on the effects of Hydro Electric Power.

The impacts of HEP, which have been well documented, need to be measured. Earlier in chapter 1, a definition of "impacts", was given as changes. Most environmental conditions are in a state of dynamic equilibrium (Petts 1984), and are constantly changing within a certain range, but overall maintaining their relatively steady state. Impacts by contrast can be defined as changes which push a system from one equilibrium state to another; that is they are changes of sufficient magnitude and rate to alter the state of dynamic equilibrium (Catlow 1976). An example of this for river systems would be the adoption of a new channel course after major floods.

Such changes can be contrasted with the more continuous but damaging unwanted by-products such as chemical pollution, e.g. gaseous emissions from fossil fuel combustion or noise emissions from energy conversion processes. These environmental effects can be considered more as chronic effects, for example chemical pollution such as acid nitric oxide emissions may not be sufficient to cause the cessation of animal or plant life, but imposes continuous damage to respiration and metabolism, reducing health and growth.

Rivers are also responsible for continuous processes such as erosion and transport and deposition of sediment, which over time will affect the morphology of the areas they flow through. Slow but continuous changes such as the building up of deltas are then another natural function of the energy flow; in this case interrupting the flow and halting the processes of geomorphology, (i.e. sediment transport here), would constitute the change. So the halting of an existing process of slow stable change would be defined as an impact.

Applying the question of whether the power flux density is proportional to the functions, for HEP, some questions can also be posed:-

The general question, -whether impacts from HEP are wholly site specific or are generalisable into a set of principles, can be posed. In the literature Trussart et al (2002) indicate that each scheme is considered to be unique in its impacts.

For the test of the hypothesis, the question of how the impacts are to be measured in the case of HEP can be posed. Impacts could be measured quantitatively from the data of individual impact categories, where available, and qualitatively through literature and possibly case studies.

Specifically for the test of the hypothesis the primary questions posed are:-

-What is the power flux density?

-Is there any link between this power flux density and the impacts, in particular sediment transport and land use?

-What proportion of the flow is intercepted? (i.e. the interception ratio).

-What proportion of the energy of the flow is abstracted?

Applying the parameter of proportion of energy flow abstracted to rivers and hydro electric power schemes poses certain problems. For example the straightforward abstraction of energy from a flow can be considered, and hence a reduction in flow energy downstream would occur. Alternatively, the flow might be substantially changed and modified, in the process of abstracting a proportion of the energy, in such a manner that the whole of the flow had been affected, although only a proportion of the energy had been extracted.

In the case of hydro electric schemes, dams can either intercept the whole of the river bed and thus the whole of the flow, or alternatively, in the case of smaller schemes, smaller dams or weirs might be used to allow a leat (an almost-level channel) to be run along the valley side, taking a proportion of the river flow, to achieve sufficient head height, further along as the valley drops away.

In this latter case the abstraction of the water flow away from the main river channel is manifest, and the energy abstracted could be calculated. However, most large HEP schemes have dams which intercept the entire valley, and thus the entire river flow, although not all of the river's energy which has been concentrated at the dam will be converted to electricity and abstracted; some of it may still be available to the river albeit in an altered form.

Most HEP schemes pass some of the flow over the spill ways or around the dam, and only a proportion of the flow is routed via the sluices and penstock to the turbines to generate electricity. This may, in the case of some large schemes be a high proportion, or in others a lower proportion.

4.3 Hydrology and Hydraulics

In the fields of hydrology, the study of water on the earth's surface, and hydraulics, the science relating to the flow of fluids (Chambers 1974), concepts and techniques have been developed to explain and predict the behaviour of river flows in erosion and deposition, i.e. where the river's energy is directed as work. The subjects of hydrology and hydraulics are both extensive and highly specialised and only certain aspects can be touched upon here.

The scope of this study does not extend to a comprehensive review of these fields but uses some concepts and techniques from them. In particular Manning's (1889) equations governing flow prediction in open and closed channels, and Bagnold's Stream Power (1966) concepts are relevant here. Stream Power is one of the more important concepts, which has been widely used as a basis for river flow effects quantification and prediction.

4.3.1 Flood Erosion: Alluvial Channels

Baker et al (1988) state that "Erosional effects in alluvial channels do not correlate directly with hydraulics, for example, mean velocity or discharge is a consequence of regime behaviour. Adjustments in sediment concentration and bed roughness are the variables that are most difficult to evaluate in predicting alluvial channel erosion. The only effective procedure derives from the tendency of alluvial rivers (a) to conserve adjustments that lead to equilibrium and (b) to dissipate adjustments that do not." (Maddock 1976b) cit in (Baker et al 1988).

This observation on regime expressions suggests that in terms of functions, the different forms that power flux density can take under different river bed conditions, (e.g. shallow, broad beds, as opposed to deep narrow beds), merely alter the type of function (e.g. erosion or deposition or increased flow velocity), not the overall magnitude of the generalised effect. In other words it may be of no consequence (to the thesis) that a river is eroding, depositing or in / decreasing sediment transport as all of these, qualify as functions. These actions are components of a larger process, i.e. the tendency of rivers to shape landscapes, smoothening and flattening, but in a continuum through the balanced equilibrium of the three processes: erosion, transport and deposition. The regime equations by Baker et al (1988) describe some of the dynamics of equilibrium states. Each equilibrium state then has a threshold value at which it will change to a new equilibrium value.

4.3.2 Concept of Stream Power

A suitable already developed concept has been used in hydraulics to describe the power of streams, namely 'Stream power'. Stream power expresses the power available to the river in watts, as a consequence of the specific force of gravity on water, expressed as a flow rate in m/s, and the slope or gradient expressed as a fraction. Stream power can be used in a variety of ways; per length of river reach termed Total Stream Power, per metre of river termed Cross-sectional Stream Power or per defined unit of bed area. This concept, originated by Bagnold (1956), (1966), "describes the force exerted by a mass of water moving over and across a single cross section per unit time", and is used by hydrologists (Fitzgerald & Bowden 2006). It is used to study sediment transport, bedload movement, and to determine whether a stream is aggrading (accumulating sediment) or degrading, (losing sediment or incising).

Equation: $\Omega = \rho g Q S$ (Bagnold 1966)

where Ω = Stream power per unit measure of bed (W/m)

ρ = density of water (kg/m^3)

g = acceleration due to gravity (9.81m^{-2})

Q = discharge (m^3/s)

S = slope (dimensionless)

The term "Stream Power" has also been defined as the "rate of energy supply at the channel bed which is available for overcoming friction and transporting sediments". (McEwen, 1994: 359, cit in Barker 2004). Flowing water performs work as potential energy is converted into kinetic energy, and can be said to have the properties of mechanical power. When this occurs within a channel, most of the mechanical energy is dissipated as friction with the channel boundary. However, a portion is left over for eroding and transporting sediment, i.e. geomorphic work. The concept has been used widely in the literature to calculate sediment transport, to explain channel incision, and channel pattern and bank side habitat development.

General physics equations traditionally describe force per unit area, when calculating mechanical power (for example watts and horsepower), as has been done here in formulating this hypothesis, however the Stream Power concept uses the slope and gradient profile to calculate theoretical power. The apparent suitability of this concept for measuring and testing the hypothesis on HEP leads to the following question:

Could the use of the concept of Stream Power provide a means of testing whether the environmental impacts of hydro electric power developments are proportional to power flux density?

4.4 Which impacts are unrelated to energy?

If the purpose here is to relate impacts to the power flux density and energy flows, it is worth identifying some of the impacts which are not related directly to energy. For example it could be argued that the extent of population displacement by a hydro electric scheme depends on the population density of the area, rather than an energy-related factor. This is partly true as the example of the Three Gorges HEP scheme in China demonstrates (Ziyun 1994). The very high population density of the valleys affected by the reservoir has indeed resulted in a high displacement. However, another factor contributing to this is the length of the reservoir, at 600km (Greeman 1996), which in itself is due to the low gradient of the river and the head height. So while a non energy related factor is the main reason for the large population displacement, energy related factors also play a role.

Rare or valued wild plant or animal populations in the area endangered by inundation by the reservoir might also constitute impacts that are unrelated to energy. There have been examples of endangered species being threatened by HEP reservoirs. However, once again the extent of land used per unit of energy harnessed, which could relate to power flux density could be a significant factor. A point worth noting here is that river valleys can be rich in biodiversity and some, such as the Three Gorges have provided habitats for rare species (Ziyun 1994), partly due to their micro climates or unique conditions. These may be partly energy related. To some extent then, some impacts could be described as "accidents of geography", and be relatively unrelated to energy factors.

Another impact not directly related to energy is that of the barrier to migratory fish such as salmon and trout that are formed by dams and weirs for HEP schemes. Fish passes can be designed to by-pass such obstacles and the turbine in-take and outlet. Crucially the efficacy of fish ladders depends on water flows being adequate to attract the fish rather than the flows at the weir or turbine duct (Environment Agency 2008). Minimum flows need to be established during the spawning period, even if this means less flow via turbines and hence reduced generation. This illustrates an example of the concept of proportion of flow, applied to maintaining conditions in a river.

Impacts from construction might be considered to be unrelated to energy. Apart from the impact of erecting large structures, where the bigger the structure the bigger the impact might be expected to be, there may well be ways of reducing the impact of construction which are unrelated to energy. One example here is the use of a coffer dam for a rock barrage, when building the Rance tidal barrage in France, as opposed to modern techniques of floating in caissons, which can lower the impact significantly (Baker 1988). Impacts from construction such as noise, fumes, dust or debris, relate more to the techniques employed as opposed to any energy factor.

4.5 Wider relevance of the hypothesis to other renewable sources

The question of whether the hypothesis applies to other renewable energy sources apart from hydro electric power can be posed. Do the parameters identified earlier, i.e. *power flux density*, *proportion* of the flow intercepted and energy abstracted, *efficiency* of conversion and *number* of conversions apply to environmental impact elsewhere, for example to tidal energy, or wave energy, or moving further from hydro electric power, to wind, solar and biomass sources?

These sources differ in a variety of ways, but can be ranked in terms of power flux density. Is this parameter then related to impacts and in what manner?

Since these sources diverge increasingly in their principles of operation, from the starting position of hydro electric power, can their flows be assessed in a similar manner? If this is possible, are the proportion of the flow intercepted and the proportion of the energy abstracted significant in the impact caused? Whether or not this relationship can be demonstrated for all sources of renewable energy constitutes a further question.

The parameter of efficiency of energy conversion devices and processes, can readily be applied to the different renewable energy sources; its links to impacts and whether this can be shown, is a separate question.

Related to efficiency of energy conversions is the number of conversions that occur in the converter device, which should be identifiable, through close description of the processes and principles involved. To what extent these energy conversions account for some of the environmental effects through for example changes or discontinuities in the functions in nature of those energy flows is another question.

In Clarke 1993, the present author suggested that the relevance of the hypothesis lay in part in the characterization of impacts from renewables, such that impacts did not just increase proportionately to the amount of development, but depended on the power flux density of the source flow as well as the proportion of energy abstracted, and also on the category of the environment.

A summary table outlining the expected impact level from either diffuse or dense flows on different environmental categories is shown below in Table 4.1. Until tested this must remain hypothetical, though the pattern of impact placement is consistent with the reasoning provided above.

Environment Category	Diffuse flow		Dense flow	
	ratio of energy abstracted		ratio of energy abstracted	
	low	high	low	high
Human	medium	big	small	small
Animate	small	big	medium?	big
Inanimate	small	medium	medium	big

Table 4.1 General levels of impact from diffuse or dense renewable flows on environmental categories. (Clarke 1993)

4.6 Conclusions and summary of chapter 4

The central questions concern the power flux density:-

-whether a higher power flux density results in a higher rate of functions performed

and

-whether less land is used per unit of energy by higher power flux density sources

Next, questions concerning the proportion of the energy flow abstracted or energy extracted were posed:-

-whether impacts result from reduced energy available for natural functions.

-whether the degree of impact relates to the proportion of energy extracted from a natural energy flow.

Following on, questions concerning the effects of efficiency of conversion were posed:-

-whether the efficiency of energy conversion affects the proportion that can be abstracted.

-whether the efficiency of energy conversion affects the production of unwanted by-products.

Finally, questions concerning the number of energy conversions of the flow were posed:-

-whether the number of energy conversions is reflected in the impacts

These primary questions raised a number of other issues concerning methods of measurement and how the relationships would be identified. The requirement for a single source to be chosen as a test case was discussed. Hydro electric power was chosen due to its maturity, long experience and widespread application, as well as availability of data.

The applicability of the parameters and questions posed to HEP were considered, for example in regard to power flux density and land use. The issue of how impacts from HEP increase with scale, whether it is linear or non linear was raised. Issues of how the functions performed by natural energy flows were possibly related to power flux density were then debated. The manner in which natural energy flows maintain natural environments was illustrated using the example of river flows. Energy flows resulting in a balance of forces maintain the environment, in this case the river, in a state of dynamic equilibrium. Impacts can then be defined as changes that push a stable system into a new equilibrium state. Existing processes of slow stable change, which are interrupted, reversed or terminated, would then be considered as impacts.

Some considerations in applying the concept of proportion diverted to HEP developments were considered, for example the need to distinguish between diverting water, changing the nature of the flow and actually extracting energy from the flow. In most cases of large HEP development, the entire valley is dammed and the entire flow intercepted, with resulting changes. However, some schemes do not intercept the whole flow. The actual proportion of energy extracted is a related but distinct factor.

The relevance of analysis techniques used in the subject area of hydraulics was considered. Two techniques that have relevance here are Manning's equations for open channel flows and Bagnold's Stream power concept. Some regime expressions for flood erosion in alluvial channels are outlined.

Those impacts not directly related to energy were discussed; for example population displacement from HEP schemes, aesthetic reactions to wind energy and biodiversity issues for biomass energy sources. Accidents of geography may result in particular impacts, but others are unrelated e.g. manufacturing impacts.

The question of the wider relevance of the hypothesis to other renewable energy sources, as well as HEP might be considered, since other sources such as tidal, wave, solar, wind, or biomass differ from HEP in such respects as power flux density and the nature of their flows. This is left to later sections in the Appendix.

The suggestion that impacts occur not just in relation to the size of developments, but also dependent on the nature of the energy flow as well as the category of the environment, was considered. Impacts from diffuse or dense flows may be experienced disproportionately by certain environmental categories.

A number of further questions raised by the hypothesis that cannot all be answered in this study but could form part of further research are included in the conclusions in chapter 10.

Chapter 5

5. Constructing the Test

The previous chapter has described the main questions raised by the theory, in particular as applied to hydro electric power. The central question of whether a higher power flux density results in a higher rate of work, (i.e. water flow eroding and transporting sediment), in relation to functions performed by the natural energy flow, was posed. Further questions raised were whether a higher power flux density source uses less land area per unit and whether reduced energy available for natural functions leads to impacts. Moreover it was asked whether these impacts were in proportion to the energy extracted, whether the efficiency of conversion is a factor in impacts, and also whether this was influenced by the number of energy form conversions. This chapter describes the setting up of the test of the hypothesis by exploring these questions in relation to hydro electric power.

5.1 Introduction

This chapter investigates the issues and feasibility of designing a test to investigate in broad terms the environmental impact associated with HEP. Some of the impacts of HEP schemes have been outlined and are briefly discussed below, as the author has reviewed these in Clarke (1995). In order to test the hypothesis, initially a set of hydro electric schemes which have become known for environmental effects were selected and their dam and reservoir parameters were researched, to examine whether these could be linked to impacts. Following this, the river courses below the hydro electric schemes in question were investigated in terms of the energy available, and gradient profiles plotted for four of the rivers, where data was available. The concept of Total Stream Power was applied and modelled for four of the rivers, the Danube, the Nile, the Columbia and the Colorado. Where data was available, the available energy in the river before and after the HEP scheme was modelled. This loss of energy, and in particular the power flux density, could then be linked to impacts downstream of the scheme. The environmental effects associated with hydro electric power have been generally described, as well as those linked to specific schemes, and there are descriptions of the four individual river systems which have been considered in more detail.

5.1.1 Impacts of Hydro Electricity

Hydro electric power has existed for over a century (Ramage 1996), and is the largest source of renewable electricity supplying ~16 % (IEA 2006) of world electricity. The world's largest power stations are hydro electric, for example, the 18GW Chinese Three Gorges scheme or the 12GW Brazilian & Paraguayan Itaipu scheme, (International Water Power & Dam Construction 1996), though hydro electric power can be developed at almost any scale, from ~ 1kW to 18GW, provided the resource is available. It is considered to be a mature technology which is well known and understood. HEP schemes, especially large ones, are acknowledged to cause substantial change to rivers which result in a wide variety of environmental effects and impacts (Petts 1984). See Table 5.1 below.

Hydroelectric power impacts

High head dam & lake	Low head / run of river, / weir
Lacustrine Environment.	
Loss of river gradient	Smaller change to river gradient
Land Use	Small/no land use
Population displacement	Little/no population displacement
Incompatibilities	Few / no incompatibilities
Reduced water speed	Smaller speed reduction
Wildlife flora and fauna change	Smaller changes to flora and fauna
Silting	Smaller silting
Nutrient loss downstream	Little nutrient loss
Water quality reduction	Lower water quality reduction
Supersaturation possible	Supersaturation unlikely
Eutrophication	Eutrophication unlikely
Reduced species diversity possible	Species diversity reduction unlikely
Changed species	Species little changed
Water table effects	Little/no water table effect
Drainage effects	Fewer drainage effects
Flow changes downstream	Less flow change downstream
Increased erosion downstream	Less erosion downstream
Water temperature changes	Water temperature changes unlikely
Fish migration barrier	Reduced obstacle to fish migration
Fish turbine strikes	Reduced risk of fish turbine strikes
Fish damage from pressure changes	Pressure change fish damage less likely
Flood protection (+)	Less flood protection
Flow regulation	Less flow regulation
Often raised levels for navigation	Raised levels for navigation

Table 5.1 Summary of impacts from different types of hydro electric power scheme.
(Clarke, 1995)

There is a considerable body of literature on its environmental impacts. All HEP schemes will have some effects, since energy is abstracted from the flowing stream, and changes are made to the channel by dams, and in many cases water is diverted (Petts 1984). Flow changes downstream can result from reservoirs, which can affect the transport of sediment. Most commentators believe the impacts downstream from the dam to be more serious than those at the reservoir and dam reach (Petts 1984). "The most serious problems resulting from the construction of hydropower facilities are the disruption of the longitudinal continuity of the rivers, and dramatic changes in the rivers' hydrological characteristics". (Joint Danube Survey 2006). The present author has written on this topic, see above the table 5.1 of general impacts that HEP schemes can result in.

5.1.2 Selection of case sample

A selection of environmentally significant HEP plant was made, based on some of the best known examples around the world. These are all large schemes, based on seven different major rivers, in five continents: the Gabcikovo and Iron Gates schemes on the Danube river in Central and Eastern Europe; the Columbia River schemes in N.W. USA; the Colorado River's Hoover and Glen Canyon schemes in S.W. USA; the Itaipu scheme on the River Parana; and in Africa, the Aswan High Dam on the Nile, and the Kariba and Cabora Bassa schemes on the Zambezi; and finally the Three Gorges scheme on the Yangtze in China. A list of these schemes is shown below in Table 5.2.

Of these HEP schemes, it is probably fair to describe the Aswan High scheme as the best known for its environmental impacts downstream. The Nile is one of the best studied rivers in the world, and together with the Danube there are good flow records going back to the 19th century.

5.1.3 Definition of environmentally significant dams

Environmental significance is defined here as due to number and severity of environmental impacts as reflected in literature citation such as the number of scientific journal papers, or the number of Google citations. Controversy and political disputes are other signifiers of notoriety, as are campaigns by Non-Governmental Organisations. The impacts cited and their severity, provide further indications. While this definition is not an objective one, it should reflect the sensitivity of perceived environmental impacts, socially and in terms of the physical environment, to some extent. This sensitivity to impacts is likely to have had the effect of inducing greater scrutiny, resulting in more research being carried out and more publications.

5.2 The river systems characterised

In attempting to compare dams and HEP plants on different river systems, the individual and unique characteristics of each river system need to be taken into account. Each of the seven different rivers considered here flows in different latitudes, climates, terrains, and geology. Each has its own flow characteristics, e.g. fairly regular seasonal flow variations, reflecting the climate and precipitation in its catchment area, as well as soil and geological rock types which influence run-off and flow. Each river system has its own individual gradient pattern, as well as catchment vegetation (that is, biomes), due to latitude, climate and altitude. For each river a unique human population settlement pattern will exist, as also populations of flora and fauna. In short, each river system has a unique combination of factors making up its particular environment. This will result in particular individual sensitivities. Despite this apparent site specificity, it is proposed that there could be

-Aswan High
-Kariba
-Cabora Bassa
-Itaipu
-Hoover Dam
-Glen Canyon
-Bonneville Dam
-Grand Coulee
-Gabickovo
-Iron Gates I & II
-Three Gorges

Table 5.2 List of HEP schemes in this study.

enough common factors to enable different rivers to be compared by using common parameters. However, the unique characteristics of each river system need to be identified and then the data set needs to be normalised. They are described in the following section for the four rivers whose gradient and energy profile has been plotted.

5.2.1 Nile

The Nile is (arguably), the world's longest river with a length of 5611km, not including the river Kagera section, the largest tributary of Lake Victoria. The University of New Hampshire / Global Run-off Data Centre UNH/GRDC flow station networks cite the total length of the main stem as 5964 km, to basin outlet (UNH GRDC 2007 & 8). The Nile has been thoroughly surveyed and studied and records of its flows extend back to 3000 years BC, in some form (Sutcliffe & Parks 1999). Since 1869, records have been kept at Aswan and, although not entirely continuous and consistent, are fairly complete compared to other major rivers. The river's flow direction is South to North (Northwards) from a latitude of 3° S - 32° N, from south of the equator to the Mediterranean, though its catchment traverses only 8° of longitude. Its theoretical drainage area is three million square kilometres, though of this about 44% does not contribute any rainfall (Rzoska 1978). Of all the world's major rivers, the Nile has the lowest specific mean discharge per area of catchment, at 0.98 m^3 per km^2 (Mamdouh, 1985). The Nile descends from a height of 1134m on the East African plateau, to 457m on the Sudan plains, over 800km, and then drops to 372m by Khartoum flowing on for 3000km through desert and a series of rocky sills known as cataracts, to reach the Mediterranean at a great delta. Below Cairo, the river splits into two main branches, the Damietta and Rosetta. The Nile's unusual catchment shape is thought to be the result of a merging of several separate river systems, in the final phase of the Pleistocene. This was caused by the tectonic tilting of the E African plateau, which contributed to the formation of Lake Victoria. Large scale faulting has formed the Rift Valley, and affected the direction of the Nile.

The Blue Nile, the main tributary and its other two main tributaries, the Sobat and the Atbara, flow down from the volcanic high Plateau of Ethiopia, probably formed in the Oligocene, about 20 million years ago. Evidence from sediments indicates that these rivers flowed north independently from upper parts of the river and only joined up relatively recently (Rzoska 1978). The Blue Nile produces much of the flow and most of the flood flow, as its catchment area has one wet season. Being a steep river with its flow unattenuated by the lakes which occur on the White Nile, it also contributes the majority of the crucial sediment load, estimated as 140m tons per year at el Deim (Sutcliffe & Parks 1999).

The shape of the Nile basin has been caused largely by the slopes of the rivers, with layers of alluvial soils spread across central Sudan, resulting from Nile floods. The Nile has been heavily influenced by climatic changes over the last 30,000 years with considerable shifts of rainfall, with a series of wet and dry phases, which have affected North Africa and Egypt and the present Sahara region. Especially over the last 20,000 years, changes of climate and vegetation have occurred.

There are a great variety of biomes, i.e. of rainfall and temperature and the resulting vegetation, over the great latitudinal extent of the river. Rainfall varies from 1500mm per year at Lake Victoria, with two annual peaks, to 25mm and then nil, over the last 1,500km through Sudan and Egypt. The East African lake plateau has a temperature of ~25° C throughout the year and vegetation is mixed savannah-woodland. Ethiopia was originally covered in mountain vegetation, now very altered by man. The Blue Nile gorge has a unique habitat with specific climatic zones, influenced by successive flooding and aridity, with fringe forest and scrub. In Sudan the river environs have belts of lowland forest, with small areas of montane vegetation, followed by savannah woodlands, swamp, and wetland savannah, then thorn savannah and finally semi desert and desert, as a result of the diminishing rainfall downstream (Sutcliffe & Parks 1999). The alluvial cultivated valley of the Nile in Egypt and that formerly in Nubia, are surrounded by desert. The narrow river valley widens out into the "great riverain oasis of Faiyum" and then the delta (Sutcliffe & Parks 1999).

Dams on the Nile

Since ancient times, barrages have been used to intercept the Nile's waters for irrigation purposes. Today there are five major dams on the Nile, with only the Aswan High Dam being of the impoundment type. Excluding the barrages for irrigation, and the first Aswan

Dam of 1904, the dams on the Nile are the Owen Falls dam in Uganda, at the exit to Lake Victoria, used mainly for electricity generation, which raises the height of Lake Victoria slightly, by 3m (Marndouh, 1985); the Roseires dam of 1966 in Sudan where the Blue Nile enters the White Nile; the Gebel Aulia dam of 1936 which is on the White Nile; and the Senner dam of 1925 on the Blue Nile in Sudan. The Aswan High dam, of 1964, is used for electricity generation, irrigation and water supply and the reservoir hosts a fishery. A former dam still exists at Aswan, built by the British government in 1904 (Rzoska 1978).

Below this on the Nile are a number of weirs and barrages associated both with navigation with locks and water supply for irrigation and for domestic and industrial consumption. These are the Esna barrage, the Nag Hammadi barrage and the Assuit barrage and finally the Delta barrage and then the Edfina Barrage (Marndouh 1985, Dickenson H. & Wedgewood.K.F, 1982). Between the Aswan dam and Cairo the river can thus divided be into four reaches.

Sensitivity of the Nile's Environment

Two countries, Sudan and Egypt, both of which have desert climates, rely almost completely on the waters of the Nile since rainfall is either very low, in northern Sudan, or almost completely absent in large parts of that country and in Egypt. Irrigation has been practiced for thousands of years and over time, river flows have been reduced by water abstraction for irrigation and water supply as well as increased evaporation losses from wider channels, and reservoir surfaces (Sutcliffe & Parks 1999). These losses are estimated to have increased from 2.2×10^9 m^3 to 3.2×10^9 m^3 in the period of records 1911-1995 for the Atbara and main Nile between Khartoum and Wadi Halfa (Sutcliffe & Parks 1999).

It is also the silt and sediment washed down by the Nile that forms all of the useable soil in Egypt, and most in Sudan. In Egypt a narrow corridor of fertile land on each bank of the river, much of which is only 16 – 32km wide, comprises the only useful agricultural land, until it widens out into the delta, below Cairo. The annual flooding of the Nile in Egypt was used in ancient times to determine the tax levied, as the amount of silt, and degree of soaking of the fields on either side of the river, determined the size of the harvest (Marndouh 1985). The delta itself was formed by the deposition of silt and sediments brought by the river.

The particular sensitivity of the environment concerns the water supply, which is a vital resource for the millions of Egypt's population, and secondly the silt and sediments which brought nutrient rich replenishment to the country's soils. The delta is dependent on silt replenishment to replace coastal erosion by the sea. Since 1964, some 98% of the 125m tons (El-Moattassem 1994) of sediment transported by the river has been trapped in Lake Nasser which has led to the near cessation of the replenishment of the delta. Impacts linked to the Aswan High Dam are shown in Table 5.3 below.

However, since the High Aswan Dam was built in 1964 and Lake Nasser formed, a constant all year round flow has been maintained on the river, to supply water for domestic, industrial and particularly irrigation use, as compared with the seasonal drought and floods in September. In addition, an annual average of 8 TWh (Dubowski 1997) of electricity has been supplied enabling much development in Egypt.

The normal pool level of the reservoir is 175m, and the maximum is 183m (El-Moattassem 1994). At 175m the reservoir volume is 120 x 10^9m^3, while at 183m, it is 164 x 10^9m^3. Reservoir capacity comprises three parts, live storage of 90 x 10^9m^3 between elevation 147 and 175m, flood control capacity of 47 x $10^9 m^3$ between 175 and 183m and dead storage capacity of 31.6 x $10^9 m^3$ for use as a silt trap for 500 years (Amin 1994).

Sedimentation in the reservoir.
Loss of sediment below the dam.
Evening out of flow downstream of dam, losing the flood discharge and sediment transport.
Erosion of the delta.
Loss of water by evaporation from Lake Nasser.
Land area lost to reservoir.
Population displacement.
Sedimentation and formation of a delta at the mouth of Lake Nasser.
Fishery impact: loss of sardine fishery off the delta coast.

Table 5.3 Impacts linked to the Aswan High Dam.

5.2.2 Danube

The Danube is Europe's second longest river at 2857km, with a catchment area of 817,000 km^2 (Joint Danube Survey 2005 Ch3). It rises at an altitude of ~690m in the Black Forest in Germany, latitude ~48° N, and longitude ~8° E and flows generally eastward or East South East, through Germany, Austria, Slovakia, Hungary, Serbia, Romania and Bulgaria, to reach the Black Sea at a delta in Romania, of which part borders the Ukraine, at latitude 45° N and longitude 27.7 ° E. Its major tributaries drain the North Eastern and Eastern Alps, e.g. the Lech, Isar, the Inn, the Drave, then South West Czech Republic, i.e. the Morave, and much of Slovakia, the Vah, the Nitra and Ipel Ipoly. The Drave and the Save rivers drain respectively the Hungarian plain and Croatia and Serbia while the Tisa flows south from the Carpathians through Hungary. The Morava River flows north, draining

South East Serbia and the border of Macedonia. A number of rivers flow south into the Danube from Transylvania in Romania, the Olt being one of the largest, also the Jiul, the Vedea, the Arges, and the Dambovita. The major tributaries the Siret and the Prut join within 250km of the mouth, flowing from the north and the Prut forms the border between Romania and the Ukraine. As the river approaches the low reaches towards the delta it splits into several channels with three main ones in the delta area.

The river was classified into three main sections, by Lasloffy (1969 cit in Joint Danube Survey 2005), the upper about 900km long, from source to the "Hungarian Gate" where it breaks through the end of the Little Carpathians and drops down to the Hungarian Plain, then the Carpathian Basin section of about 925km, as far as the "Iron Gate", where it breaks through the Southern Carpathians, with the lower section following, of about 885km, through Romania and Bulgaria to the delta. These three sections are characterised by their gradients from 1.1 to 0.43% in the upper section, to 0.17 % to 0.04% in the middle, and 0.04% to 0.01% and 0.004% near the mouth (Lasloffy 1967, cit in Joint Danube Survey 2005). The gradients are steeper at the Hungarian Gateway and the Iron Gates section, both having "cataracts", which were pronounced at the Iron Gates. The Hungarian Gateway section is characterised by a braided stream, a steeper gradient and finally an inland gravel "delta". The gravel beds are very deep at this location. The Iron Gates consists of two sections of river gorge, of steeper gradient for ~150km, with great water depth and in the past, submerged rocks and fast flowing stream, now inundated by the two hydro electric scheme reservoirs.

The mean flow rate varies from 359m^3/s in Germany at Oberndorf (GRDC 2008) to 1463m^3/s at Linz in Austria, and 2047m^3/s by Bratislava, to 2354 m^3/s by Mohacs south of Budapest, and 5500 m^3/s by the Iron Gates, and 6415 m^3/s by Ceatal Izmail along one of the streams near the mouth. The hydrograph at Bratislava is characterised by a single peak in early summer in June, of ~ 2800 m^3/s from melted snow in the mountains, and a minimum of ~1500 m^3/s in November. This seasonal variation is less pronounced downstream by the Nagymaros flow station. The river has been an important artery for Central and Eastern Europe for thousands of years, and is navigable for 2600km from Ulm (Joint Danube Survey 2006).

Dams on the Danube

There are 59 dams for Hydro Electricity along the upper Danube (Joint Danube Survey 2006) upstream of the Gabcikovo dam, as the steep gradient makes this suitable. There is a dam on average every 16km now on the upper section, and few reaches are free flowing. The largest HEP scheme is the Iron Gates, I (1970) & II (1984), in Romania/Serbia, and second largest the Gabcikovo in Slovakia. The Iron Gates I scheme has a head height of 26m and Iron Gates II a head height of 7m (Stankovic 1960), with the two reservoirs cited as extending some 270 km upstream (Joint Danube Survey 2006). Despite the relatively modest head height, by comparison with the world's largest, the Iron Gates I is Europe's largest hydro electricity scheme with a rated capacity of 2136 MW, due to the considerable flow rate.

Gabcikovo Scheme

The Slovakian Gabcikovo HEP scheme, completed in 1992, was originally intended to be the first part of a dual dam scheme, together with the Nagymaros dam in Hungary. The Nagymaros second dam was never built, as the Hungarian government pulled out in 1989 on the basis of environmental objections at the time of democratisation (Borsos 1991). The Gabcikovo-Nagymaros scheme was intended as a "peaking" power plant, and the second lower dam, was intended to absorb the resulting wave, from peak generation.

Improvements to navigation were another prime objective, since the old course of the river was subject to low water in drought periods, limiting the draught of shipping over this reach.

The Gabcikovo dam in Slovakia is relatively unusual in that a huge "leat" or artificial raised canal causeway takes water off 20km from the main reservoir to provide the required head height, as the land and former main river stream fall away. Its head height is 21.5m and with a mean flow of 2047m^3/s this provides for a rating of 720 MW. The Gabcikovo scheme diverts 80% of the water flow into the 20km leat (Zinke 2004), leaving the old main channel and the multiple braided channels either drought prone or with sluggish water flows after weirs were installed, as opposed to the former dynamic flood flows. This area forms an inland "delta" of deep gravel beds, where the steep gradient ceases at the entrance to the Hungarian Plains and contains protected wetlands (Zinke 2004). Another point of contention is that the old course of the river is also the international border between Slovakia and Hungary and most of the water has been diverted away from the Hungarian bank. Slovakia has defended its continuation of the project alone, with some modifications, and has claimed that without the Nagymaros dam, about 2000 GWh per year of electricity has been lost, worth six billion Crowns, or about 200m $ US (Liska, 1993 p35). The unilateral decision to pull out of the scheme by Hungary provoked an international crisis which required third party mediation. A summary of impacts for the Gabcikovo and Iron Gates I schemes is shown in the tables 5.4 and 5.5 below.

Neither of these schemes are impoundment dams and both have to be operated on a "run of the river" basis; that is, they cannot store more than a small fraction of the river flow.

Loss of water flow in the old main channel
Loss of water supply to wetlands around old main channel
Degradation of side channel flushing
Side channel siltation
Disruption of sediment transport
Eco-system changes and degradation in wetlands area due to drying out
Lowering of ground water table in surrounding area due to diversion of main water flow (Zinke 2004)

Table 5.4. Impacts linked to the Gabcikovo HEP scheme.

The remainder of the dams upstream have relatively low heads, and are run of the river dams, for hydro electricity and navigation purposes. According to Joint Danube Survey (2006), about 30% of the Danube's length is impounded for HEP schemes. Some 80% of the river is regulated with dykes or flood protection works, which have been built since the 16th century.

Reduction of sediment transport
Bio silicate deficiencies at delta area
Nutrient changes at Black Sea (Humborg 1997)
Inundation of river banks
Settlement and population displacement
Reduction of sturgeon fisheries
Irrigation

Table 5.5 Impacts linked to the Iron Gates I & II HEP scheme.

These include straightened sections, canals cut e.g. in the delta area and embankments cutting off the flood plains from the river. Only one fifth of the former flood plain exists now compared to the 19th century.

The Danube Delta

The Danube delta occupies an area of variously 3446 km^2, 6264 km^2, or 7990 km^2 (WWF 2008) and is protected under the Biosphere UNESCO programme, the Ramsar Convention and also as a World Heritage Site, with 650 km^2 in Romania strictly protected (WWF 2008). The delta straddles the border between the Ukraine (20% area) and Romania with 80% area. The Romanian protection dates from 1991, the Biosphere Reserve designation, shared between the two countries dates from 1998. The Ukraine established the first protection in 1973 as part of the Black Sea State Reserve, then in 1981 as a Natural Reserve of the Danube stream.

The silt carried by the river resulted in an expansion each year of the Delta making it a dynamic region (Schwarz 2008). Recent commentators consider the Delta overall to be declining in area. Schwarz states that only 34%, or 18m tons pa of sediment reaches the delta, compared to 53m tons pa before the construction of the Iron Gates dam (Schwarz 2008). Three main channels carry the waters to the sea and a multitude of small channels, though historically seven main channels existed. There are also two canals which cut across the delta with a third one started by the Ukraine in 2004. This latter canal has caused controversy as it increases flows resulting in less silt accumulation and may have deleterious effects on the delicate ecosystem, which depends on water levels being maintained. The vegetation of the delta area consists of areas of forested islands that are regularly flooded, marsh areas, and reed areas, with lagoons and lakes. It is an important bird roosting site, on migration routes for millions of birds, as well as a nesting and breeding site. There are 45 species of freshwater fish, three hundred species of birds, and one thousand two hundred species of plants (WWF 2008). There are also fifteen thousand inhabitants in the delta area, many of who live off fishing.

5.2.3 Colorado

The Colorado rises at an altitude of 2746m, in the Rocky Mountain National Park, and flows for 2365.6 km, through six different States, to reach the Gulf of California and the Pacific (Kammerer 1990). Its catchment area is approximately 626,780 km^2, and includes areas of Colorado, Utah, some of New Mexico, Arizona, Nevada, California as well as Mexico. The river flows largely through desert areas, and its main flow is derived from melting snow in the Rocky Mountains, and some summer thunderstorms. For a large proportion of its length, it flows through canyons, carved from the arid rocks, the largest being the Grand Canyon, at 446 km in length. Its average gradient over its whole length is one in 861, or 0.11608%, though in its upper reaches it has steeper gradients (Encyclopaedia Britannica 2009).

The flow direction of the river is from NE-SW and then N-S, from latitude 40°-32° N. The natural flow of the river has a very marked seasonal peak, and is quite variable with a relatively low flow. Since the building of a number of large dam structures in the upper, middle and lower sections, the natural variability of the flow has been evened out, by controlled discharges, with long water storage retention periods. Lake Powell, the reservoir for the Glen Canyon dam, stores water for almost a year, and Lake Mead, the reservoir for the Hoover dam, for 2.8 years. Impounded volume of the reservoirs is about four times that of the river's average flow per annum (IWBC 2001, p33).

The International Boundary and Water Commission (IBWC) says that "The operating criteria include three modes that govern releases from the dam. There is a minimum release of 8.23 million acre-feet (10.152 x 10^9 m^3) (per annum) to meet downstream demands.

There are equalization releases to balance the amounts of water in Lake Powell and Lake Mead, though under certain conditions, equalization releases are not made. Additionally, spill avoidance is practiced whereby if high inflows are expected, water is released prematurely in order to create storage space." (IWBC 2001 p32).

The dams have multiple purposes, the primary ones being water supply for irrigation, flood control and hydro electricity supply. So much water is abstracted that the Colorado loses most of its flow by the time it reaches the Gulf of California, with just $23 m^3/s$ mean flow by 1975, at Yuma near the US-Mexico border down from 875 m^3/s at Glen Canyon (USGS 2004). The major water supply is to the Imperial Valley for irrigation of citrus fruit groves, but water is also abstracted to supply the Las Vegas area, and other regions. The irrigation canal the 'All American Canal' takes off 450-850 m^3/s, much of the river's flow in a normal rainfall year, to irrigate the Imperial Valley. Several major cities in the West including Las Vegas, Los Angeles, San Diego, Tucson and Phoenix rely either wholly or partly on the river for water supply, with aqueducts taking water off. About 90% of the water of the river is used for irrigation and water supply.

Under the 1944 Water Treaty, the US has an obligation to deliver 1.5 million acre-feet (or $1.8502 \times 10^9 m^3$) of water, ~10% of river flow, to Mexico (IWBC 2001, Flessa 2001). By the mid to late 1980s an average flow of 18 m^3/s, and only $567.65 \times 10^6 m^3$ pa, or ~30% was delivered. Post 1991, to 2001, more water has been supplied from the US to Mexico, after recognition of issues surrounding water supply (Colorado River Delta Bi-National Symposium Proceedings 2001).

It has been noted that "Most of the years, the river below the (international) border is dry." (Colorado River Delta Bi-National Symposium Proceedings 2001, p39) "About 20 percent of the total river flow in the past 20 years (since Lake Powell filled) have been flood flows and these typically come with El Niño events." (Colorado River Delta Bi-National Symposium Proceedings 2001, p46). "In January 1997, there was a release of approximately 250,000 acre-feet of water over a three month period." (op cit p46).

A population reduction of bi-valve mollusk from 34 to 95% has taken place since diversion of the Colorado River water (Colorado River Delta Bi-National Symposium Proceedings 2001, p49). "In 2001, about ten million acre-feet of water will be released from Hoover Dam to meet the needs of downstream users. None of that water is released for ecological purposes and instead is used to meet contracts, agreements and the 1944 Water Treaty. Ten million acre-feet is one million acre-feet more than was needed to be released five years ago. Uses in the U.S. continue to grow and the states continue to use more of their entitlements" (Colorado River Delta Bi-National Symposium Proceedings 2001, p55).

It was also noted that "Alternatives for providing the water needed to meet ecological needs should be determined. These could include recognizing the Delta as a legitimate user of Colorado River water; buying or giving water rights to the Delta; or using agricultural irrigation surplus from both sides of the border." (Colorado River Delta Bi-National Symposium Proceedings 2001, p56 & 57). "The shrimping crisis at the end of the 1980s and into the beginning of the 1990s, resulted in a 50 percent reduction in shrimp catches. This crisis corresponded with the five consecutively driest years of Colorado flow to the Gulf. Likewise the collapse in the totoaba fishery in the early 1970s followed the opening of Glen Canyon Dam." (IWBC 2001, p57). "Internationally, the vaquita was acknowledged in the 1980's and the importance of the Delta in the 1990s. The Mexican federal government, through the Secretariat of the Environment, began elaboration of the management program starting in 1996." (IWBC 2001, p59).

Colorado River Delta

The Colorado River forms a delta where it flows into the Gulf of California, which once covered 8612 km^2 and supported fertile plant, animal and aquatic life (Alles 2006). Sediment from the high desert areas was transported down the river to build up the delta until the damming of the river in the 20th century trapped it in the reservoirs. With most of the water abstracted for irrigation and urban water supply, the means of sediment transport are no longer available. The delta is now largely dried out with much of the former vegetation reduced and the formerly fresh water is brackish and saline (IWBC 2001), as mudflats; coastal wave action is now eroding the area. The delta area has been very considerably reduced and Alles cites the area as only 10% of the former (Alles 2006). The delta area is protected under a range of designations, such as the UNESCO biosphere reserve, since 1993 (IWBC 2001 p58) together with the upper Gulf of California area, also a 2500 km^2 Ramsar Wetland under the UN Convention on Wetlands for areas of international importance in terms of species, ecology and hydrology.

The amount of water estimated to sustain the delta, would be approximately 436×10^6 m^3 over four years or 40×10^6 m^3 per year, and 316×10^6 m^3 every fourth year, or less than 0.5% of the total runoff for the Colorado River over this time (IWBC 2001, p41).

The Colorado River's environmental characteristics can be summarised as:

-Peakiness of flows

-Variability of flow

-Relatively low mean flow

-Extreme dependence on river by many categories of 'environment'.

-Sensitivity of environment to changes to river regime.

-Multiple purpose use of water resource

-International nature of water issue

-Large number of dams

-Highly managed river

A summary of impacts for the Colorado River is given in Table 5.6 below.

-Loss of seasonal flow variations
-Attenuation of high and low flows
-Pulse releases below dams e.g. Glen Canyon (Petts 1984, p266)
-Trapping of sediment
-Channel degradation, e.g. 2.6m below Glen Canyon (Petts 1984 pp121, 123-125, 30)
-Channel sedimentation below tributary confluences (Petts p133)
-Vegetation changes due to loss of flood flows and sedimentation (Petts 1984 p138)
-Loss of indigenous fish species below dams due to bottom discharge cold water releases (Petts 1984, p214, 216)
-Water quality changes
- Change from warm turbid water quality to cold clear water, changes fish habitat and range
-Abstraction of water
-Evaporation losses
-Saline water quality in lower reaches and delta
-Barriers to fish migration
-Erosion of delta due to sediment transport loss

Table 5.6. Impacts linked to the major Colorado River HEP schemes.

5.2.4 Columbia River

The Columbia River rises in western Canada in British Columbia and flows between latitudes 55°- 47° N for 1931 kilometres (Lang 2007). It springs from two lakes between the Continental Divide and the Selkirk mountain ranges, at a height of 807 metres (Lang 2007). It flows north for over 321 km, before turning south to the border with the USA, then flowing southwest skirting one of the Columbia plateau's massive larva flows. The river turns south east and cuts through the volcanic shield in a gorge, towards the confluence with the main tributary the Snake River. From here it flows westward to the Pacific.

The river catchment basin of 670,810 km^2 with its ten main tributaries drains a variety of climatic and ecological areas, from temperate rain forests to semi-arid plateaus (Lang 2007). Precipitation ranges from 2.79m to 0.1524m. Melting snow contributes much of the discharge, and this fluctuates seasonally with the highest volumes in April to September and the lowest in the winter months from December to February. The average river gradient is over 0.038%, but in some sections over double this. There are several former falls and rapids sections such as the Celilo falls and Cascades Rapids, now inundated by reservoirs for the HEP schemes (O'Connor 2004).

The Columbia River, together with its main tributary the Snake River and smaller tributaries, drains "an area the size of France" and was once one of the most prolific fisheries of Salmon and Steelhead migratory fish -so much so that the wild salmon of the NW area of the USA covering several States, was central to native populations' economy, traditions and culture, as a totem. After the Second World War the Federal Government together with the individual States' administrations carried out a development programme for the area with HEP development of the large rivers central to the plan. Other purposes of the dams were to raise water levels for navigation, so that ocean going ships now reach Portland, and barges can reach the inland port of Boise in Idaho. Also the reservoirs are used considerably for irrigation purposes and have contributed greatly to agriculture in the dry plateau areas. The cheap hydro electricity has aided industrial development to a large extent, e.g. aluminium smelting and the Hanford nuclear site are powered from it.

The Columbia River has been described as the most hydro-electrically developed river system in the world (Lang, 2007). The river's gradient profile has been turned into a series of steps, with only the Hanford reach and the tidal reach below Bonneville remaining free flowing in the US section, unimpeded by impoundments. This can be seen from the gradient profile.

Today the Columbia River has a series of fourteen large dams in Washington State USA and in British Columbia, with a combined installed capacity of ~24-25 GW forming a significant part of the total HEP capacity of the USA (FCRPS 2003). There are a further twelve dams on the large tributary, the Snake River, mostly with power generation installed.

There has been a considerable decline in the populations of migratory fish, especially in the period since the dams were constructed. Only ~2% of the former numbers of fish now migrate up the runs (Joint Staff Report 2006). This has become a major environmental and political issue since the fish are protected in a Treaty of 1855 between the USA and the Nez Perce Tribe, Confederated Tribes of the Umtilla Indian Reservation, Confederated Tribes of Warm Springs of Oregon, and the Confederated Tribes and Bands of the Yakama

Nation (North West Council 2002) with the Native American Indian population. This issue is the focus of much work, study and expenditure as well as considerable controversy.

Considerable efforts have been made to equip the dams for passing migratory fish. Fish ladders, turbine tube intake barriers, diversionary channels, trucking and barging the small fry and smolts around dams, are some of the main methods. However, the success rate has not been high. The changes effected to the river, from a free flowing state with a series of fast flowing shallow rapids with the occasional falls, and quieter pools, to a succession of wide, deep, slow flowing lakes, confined by hazardous dam passages, has so altered water conditions for migratory fish as to "wreck their original habitat" (Lang 2007).

A table summarising the main impacts of the Columbia River HEP schemes is shown below in Table 5.7.

Loss of salmon habitat
Disruption of salmon migration
Blockage of salmon migration routes
Fish Barrier effects
Fish Damage
Degradation of water quality
Evening out of seasonal flood flows
Flood Control
Inundation of land
Displaced land use e.g. farming

Table 5.7 Impacts linked to the Columbia River HEP schemes.

5.3 Methods of Analysis

The next section describes the methods of analysis of data from the cases studied, as applied to the hypothesis. Firstly the hypothesis was tested against the parameters of the dam and reservoir, and then secondly against the flow regime of the river below the dam, for periods before and after the dam, where data was available to perform this.

5.3.1 The HEP Reservoir and Dam Parameters

Quantitative data for a list of environmentally significant HEP plants was collected, in order to test for correlation with the proposed key parameters for environmental impact. A spreadsheet was constructed with key HEP data such as head height, mean flow rates, and annular area of turbine tubes, to provide a figure for maximum power flux density. The aim was to discover whether any linkage could be found between the power flux density and the impacts.

As part of this, the aim was to compare the power flux density of the HEP plant with that of the river in an "unchanged" state, i.e. its former power flux density. This would demonstrate the magnitude of the change in power flux density terms for the river over that part of the course now "flattened out" by the backwater from the dam impoundment.

A set of data parameters for the HEP schemes was selected, based on head heights, rivers flows, and reservoir and dam characteristics. A list of the data parameters for the HEP schemes is shown in table 5.8 below.

List of data parameters used

Parameter	Unit	Comments
Reservoir area	km^2	
Basin volume	$10^6 m^3$	
Dam height	m	
Head height	m	
Turbine flow rate Q (max)	m^3/s	
Flood river flow rate	m^3/s	
Mean river flow	m^3/s	
River minimum discharge	m^3/s	
Compensation flow (mean)	m^3/s	
Spillway	m	
Dam crest length	m	
Installed capacity	MW	
Turbine type		
Turbine diameter	m	
Number of tubes		
Annular area of tubes	m^2	
Annual average electricity production	GW h	Annual average electricity production
Energy	TJ	
Power flux (river) at dam line	kW	Power flux (river) at dam line
Production factor	ratio	(derived calculation)
Capacity factor	ratio	(derived calculation)
Installed capacity per reservoir area	kW/m^2	(derived calculation)
Power flux density	kW/m^2	(derived calculation)
Energy flux across converter	TJ/m^3	(derived calculation)
Sediment trap efficiency of reservoir	ratio	(derived calculation)
Reservoir length	m	
Old river course mean gradient (reservoir)	ratio (m/m)	(derived calculation)
Mean water residence time	years	(derived calculation)
Sediment load	10^6 t per annum	
Mean reservoir cross-sectional area	m^2	(derived calculation)
Mean reservoir fluid velocity	m/s	(derived calculation)

Table 5.8 List of data parameters used in test.

The parameters for each hydro electric scheme were used to test for the proportion of energy abstracted from the available energy in the flow, to discover how this varied between the different schemes, and whether it might be a significant factor in the impact experienced. Comparisons between the different schemes could be made on this basis.

The variable, proportion or ratio, could then be tested for a link to impacts and the specific impacts experienced. In this study "proportion" of the energy flow abstracted and converted to electricity, has been given the term 'Production Factor'.

5.3.2 Definitions of Parameters

Basin Volume

Values for basin volume have been obtained from data sources. However, the volume will depend on pool operating height for the reservoir. Ideally an average operating height and thus volume should be cited. A difficulty arises in comparing reservoir volumes with river basin volumes in 'run of the river' schemes, which leave the river bed relatively unchanged apart from some increased depth and width. The modified river basin may still exhibit some characteristics of river beds, though without very appreciable gradients, due to bed friction and available energy balances, as compared with the reservoir which will be level.

Mean River Flow m^3/s, has been taken wherever possible from flow at dam line. In certain cases, *inflow* into the reservoir has been the measured parameter included (e.g. Glen Canyon). In other cases e.g. Hoover Dam, Lake Mead, water is abstracted from the reservoir for irrigation or water supply, and dam line flow figures can be misleading.

Flood River Flow Rate m^3/s, has been taken from the maximum recorded flood in the measurement period. Other possible representations are yearly maximum average, or ten year maximum flow rate or hundred year maximum flow rate.

Mean Former River Gradient

The mean former river gradient has been derived by dividing the head height by the length of the reservoir. The reservoir is level and since the method takes no account of the depth of the river at the reservoir inflow point, which may be substantial, or downstream of the dam, it is assumed that the gradient is that of the water surface. Using the mean gradient for the Belgrade -Iron Gates reach cited in the Joint Danube Survey (2005), of 0.04%, and taking the head height of the scheme as 34m, gives a level reservoir length of 85 km. Elsewhere, the length of the reservoir is cited as 112km (Cioranescu 1980). This may be explained by varying water levels and the effects of the scheme extending further upstream than the reservoir itself. Where possible, data for river and reservoir elevations should be cited in preference to this approximation. Data for gradients on the Danube are taken from the Joint Danube Survey (Joint Danube Survey 2005 Ch3 p23), also GRDC data and elevation data obtained from published papers and from Google Earth satellite images.

For the Nile, data for the gradient slope profile was obtained from Rzoska, (1978) and also Marndou (1985) and Sutcliffe & Parks (1999). Gradients have been cross checked wherever possible by using elevation data from sources such as Google Earth aerial and satellite images. The resolution level obtained is of necessity somewhat coarse, and subject to seasonal variations in the case of water levels.

Mean reservoir cross-sectional area has been derived by dividing the reservoir capacity at mean pool elevation, by the reservoir length, which is an approximation used by the US ACE Army (1989).

Mean reservoir fluid velocity has been derived by dividing the inflow rate by the cross-sectional area, a technique used to approximate reservoir fluid velocity by the US ACE Army (1989).

The data for the parameters for eleven cases of HEP schemes and a further six cases was assembled into a spreadsheet.

5.3.2 Details of Analysis Method

The land area of the HEP scheme has been obtained from the reservoir area. This can then be compared with the annual average generation output, to provide a watts / m^2 value. The annual average generation can be divided by the installed capacity to provide a value for the capacity factor.

By using the equation:

$$P(in\,kW) = 10 \times Q \times h$$

Where P = power

10 = approximation to $9.81 ms^{-2}$ (acceleration due to gravity)

Q = $m^3 s^{-1}$

h = head height (Ramage 1996 in Boyle 1996)

the theoretical average power in the HEP scheme can be calculated from the average flow rate, which can then be compared with the average annual output of the scheme, and allowing for an efficiency factor, this can be used to calculate the proportion of the energy abstracted for conversion to electricity.

5.3.4 Possible Impact Parameters

-Land Use or Land Take:

- m^2 per kW installed i.e. power
- m^2 per kWh produced i.e. energy
- km^2 per TWh p.a. i.e. average power

higher = more impact

-Population Displacement:

-capita numbers

-Flow Changes:

-river course to reservoir difference

Water Speed Changes

-river to reservoir changes upstream of dam ms^{-1}

-reservoir to river changes downstream of dam ms^{-1}

-Sedimentation:

Sediment originates not just in the upper reaches of rivers but all along the bed, and is generally in dynamic balance between processes of erosion, transport and deposition (Petts 1984). It has been estimated that reservoirs trap about 25-30% of the global sediment being actively transported in rivers (Vorosmarty et al 2003, cit in Owens et al 2005). Suspended sediment transported to the global ocean has been estimated to be of the order of 15-20 x 10^9 t per year with the larger proportion being discharges by rivers in mountainous areas (Milliman & Syvitski, 1992; Farnsworth and Milliman 2003; Syvitski, 2003, cit in Owens et al 2005).

Sedimentation might be measured in rate of deposition tonnes per year, or in loss of deposition downstream tonnes per year, or as a percentage of the river's load. Alternatively the reservoir trap efficiency might be measured (Toniolo 2007). Reservoir sedimentation is dependent on three factors: size of the reservoirs drainage basin, characteristics of the basin which affect the sediment yield, ratio of the reservoir's storage capacity to the river's flow (Petts 1984).

Sediment transport depends on water speed. Langford (1983) notes that below 0.2 m s^{-1} water movement, silt and mud will settle out, while at velocities of 0.2-0.4 m s^{-1} stream beds would comprise sand among the stones and gravel. Sediment transport increases as the water speed increases, and also larger diameter particles are transported. Settling velocity versus particle diameter equations of both linear and non linear form have been proposed (Graf et al 1966, cit in Graf 1971, Fig 4).

The efficiency of a reservoir as a trap for sediments has been described by the Brune Curve (ICOLD 1989). The Brune curve is an empirical tool describing how the longer the residence time in a reservoir, (volume/ inflow), the greater the sediment trap efficiency (Brune 1953). However, it does not describe the physical principles involved. Other methods of estimating trap efficiency have been developed by Brown, (1944) and Churchill (1948), (US Army ACE 1989).

Brown's method of sediment efficiency calculation employs reservoir capacity and watershed area and is useful where the only parameters known are the storage capacity and the watershed area. Brune's method is considered more accurate than Brown's but should only be applied to "normal ponded reservoirs, not desilting basins or semi-dry reservoirs"

(US Army ACE 1989). Churchill's method uses a parameter, the sedimentation index, which is the period of retention divided by the reservoir mean velocity (Churchill 1948). The reservoir length needs to be known for this.

Brune's curves, empirically derived, assuming a median curve and some additional data, were described in this predictive equation by Dendy:

$$E = 100 \times \left(0.97^{0.19^{\log C/I}} \right)$$

Where E = reservoir sediment trap efficiency
C = reservoir capacity
I = inflow rates per year

By contrast Brown's Curve is described by the equation:

$$E = 100[1 - 1/91 + (KC/W)]$$

Where E = reservoir trap efficiency (percentage)
C = capacity (in acre-ft)
W = watershed area (in square miles)
K = coefficient ranging from 0.046 to 1.0, with median value 0.1 . K increases for regions of smaller and varied retention time (calculated using the capacity-inflow ratio). (US Army ACE 1989).

Churchill's method (Churchill 1948)

Churchill's method of estimating trap efficiency uses a sedimentation index, which is the period of retention divided by the reservoir mean velocity. The retention time (R in seconds) can be estimated by the reservoir capacity divided by the daily inflow rate. The reservoir mean velocity is obtained from either field data or approximated from the average daily inflow rate divided by average cross-sectional area. The average cross sectional area can be obtained by dividing the capacity by the reservoir length.

So $S.I. = R / V$

$$R = C / I$$

$$V = I / A$$

$$A = C / L$$

$$S.I = CA / I^2 = (C / I^2)(C / L) = (C/I)^2 / L$$

Where $S.I.$ = sedimentation index

R = retention time in seconds

V = mean velocity in ft per second

C = capacity in cubic ft

I = inflow rate in cubic ft per second

A = average cross-sectional area in square ft

L = reservoir length in ft at mean operating pool elevation

(US Army ACE 1989)

Following on from these impact parameters, caused by flow changes, are other effects which could be included as parameters:

-Water Quality Reduction:

-Temperature change °C

-Chemical e.g. Total Dissolved Gasses (TDG)

-Oxygen dissolved: %

-Nutrient Loss:

-Organic materials carbohydrate flow

-Changed Species:

-Indigenous species change

-Introduced species change

-Biodiversity:

-% species reduction

The barrier of the dam itself creates impacts and possible parameters are, for example:-

-Fish Barrier effects:

-% Rate of passage as proportion of pre dam passage

-Fish Damage:

-Strikes by Turbine proportion

-Pressure Changes

However, regulating the flow has some positive effects for human use too:-

-Flood protection:

-Incidence / severity of flooding.

-Flow Regulation:

-Navigation:

-Increased water depth and draft.

5.3.5 Test for hypothesis parameters

The sample has been tested for power flux density, using head height plus flow rate, for each HEP scheme. Hydrostatic pressure was also estimated. A test for the proportion of the energy flow extracted was carried out, where known compensation flows were taken into account. A test for the efficiency of energy conversion was made by comparing the Production Factor with the theoretical energy available from the average river flow. The number of conversions of energy form was determined.

These parameters were assessed for correlation, and causal linkage with impacts.

The parameters above were tested against the following measures of impact.

- -area occupied (land use),
    - -i.e. reservoir area
- -lacustrine environment created,
    - -i.e. flow rate change / residence time
    - -reduced load transport downstream
        - -i.e. flow rate change (decrease)
- -sedimentation
    - -i.e. sensitivity to mechanical energy loss, (dependant on sediment load and decrease in water current).

- -flow changes downstream
    - -i.e. losses, abstraction, and flow fluctuation.
- -increased erosion downstream
    - -i.e. flow fluctuations,

Other parameters could be tested but were beyond the scope of this study:

- -water quality changes
    - -i.e. changes in temperature, chemical changes
- -eutrophication

-i.e. water quality, oxygenation.

residence time.

-barrier to migratory fish,

-fish ladder by-pass?, head height.

-upstream / downstream

-compensation flows.

-fish damage from pressure changes

-i.e. pressure changes across turbine converter.

-turbine fish strikes

-i.e. turbine design,

5.3.6 Testing the hypothesis against the river flow regime below the dam, before and after the HEP scheme.

Stream Power

This concept described in chapter 4, was originated by Bagnold (1966). He states that "The available power supply, or time rate of energy supply, to unit length is clearly the time rate of liberation in kinetic form of the liquid's potential energy as it descends the gravity slope S." Bagnold denotes this as:

$$\Omega = \rho g Q S \qquad (1)$$

where Ω = Stream power (W/m)

ρ = density of water (kg/m^3)

g = acceleration due to gravity (9.8ms^{-2})

Q = discharge (m^3/s)

S = slope (dimensionless)

Stream power represents the rate of energy dissipation through friction and work, with the bed and banks, per unit length of a stream. It is assumed that the water is not accelerating and the channel cross section remains constant. These are reasonable assumptions for an averaged reach over a fairly short distance. If there is no acceleration of the water flow and the cross section remains constant, it follows that the energy of the water flowing down a slope must be being dissipated in friction and in work done. The work done would be channel incision or sediment transport, while friction with the bed and banks would convert energy to heat.

Bagnold's concept can be employed in a number of different ways, and various forms of the general power equation have been developed. Stream power is used to study sediment transport, bedload movement, and to determine whether a stream is aggrading (accumulating sediment) or degrading, (losing sediment or incising), as well as for channel pattern and bank side habitat development.

Stream power can be used to calculate the power of the stream per unit length, as above or per unit bed area as below. Bagnold states that "The mean available power supply to the column of fluid over unit bed area, to be denoted by ω is therefore:"

$$(2) \qquad \omega = \frac{\Omega}{\text{flow width}} = \frac{\rho g Q S}{\text{flow width}} = \rho g d S u$$

Where ω = available power per unit length and unit width

$\rho =$ density of water

$d =$ channel depth

$g =$ acceleration due to gravity

$u =$ average fluid velocity

$S =$ slope

$Q =$ flow rate

(Bagnold 1966)

Bagnold equates the rate of doing work with the available power multiplied by the efficiency. The available power ω is then the supply of energy to overcome friction and for the transport of sediment.

With the increasing use and development of the Stream power concept, the wide variety of different terms and expressions used became confusing, leading Rhoads (1987) to propose a standardised nomenclature. This nomenclature is employed in this thesis. Two specific uses of the Stream power concept are employed in this study, i) Stream power per length of river reach, termed 'Total Stream Power', and ii) Stream power per metre of river termed 'Cross-sectional Stream Power'.

Stream power used to define the power of a defined reach of a stream channel, in watts, known as 'Total Stream Power' or TSP (Rhoads 1987), is defined as:

$$p = \rho g Q S X \tag{3}$$

where $p =$ Total Stream Power in W

$\rho =$ density of water in kg

$g =$ acceleration due to gravity in $\mathrm{ms^{-2}}$.

$Q =$ flow rate in $\mathrm{m^3 s^{-1}}$

S = slope h/l in mm^{-1}
X = length of reach in m

Stream power per unit length of a defined reach (Wm^{-1}) termed Cross-sectional Stream power or CSP, is defined as:

$$\Omega = \gamma Q s \quad (4)$$

where Ω = Cross-sectional Stream power (Wm^{-1})
γ = specific weight of water (=9810 Nm^{-3})
Q = water discharge (m^3s^{-1})
s = the energy slope (mm^{-1}) which may be approximated by the slope of the channel bed.

(Rhoads 1987)

Using the equation (3) for Total Stream Power, this was calculated for the sample rivers and hydro electric schemes, over the extent of old river course now occupied by the reservoir, to give a value in kW. The results are contained in the next chapter. This concept can be used for finding out the total power available over the average gradient of the former river bed, and could provide an indication of the amount of energy available for performing the river functions, e.g. sediment transport, albeit at a coarse resolution level. The Cross-sectional Stream Power was then calculated for the old river course now occupied by the reservoir, using equation (4).

Averaging out the former river bed gradient over the reservoir length will mask the many likely small scale gradient variations, such as falls and rapids that are frequently drowned by the reservoirs of hydro electric schemes. However, the technique could give useful indications of the energy and functions balance of that section of the river bed now changed, in terms of inputs and outputs. As far as the author is aware, this use of Total

Stream power concept and Cross-sectional Stream power in connection with environmental impacts from HEP schemes and reservoirs is novel.

5.3.7 Applying Stream Power concept to the data set

Methods of deriving approximations of unknown parameters of reservoir bed and flow are as follows:

The known parameters are:	Q	flow rate	(cubic metres per second)
	S	slope gradient (fraction)	
	γ	specific weight of water (=9810 Nm^{-3})	

the unknown parameters:	B	channel width	(metres)
	D	depth	(metres)
	u	average fluid velocity	(metres per second)

Methods of deriving approximations for unknown parameters are as follows:

For D depth in reservoir, we can assume an even gradient along the former river bed as far as the reservoir river entrance. The gradient will be the head / reservoir length. The depth at any given point in the former river bed will then be the proportion of the head height given by the distance to the reservoir entrance, to the reservoir length. However, this method assumes that the river bed had effectively no depth at the reservoir entrance, though this may be cancelled out by the fact that the head height does not incorporate the (downstream) river depth. Average approximate reservoir depth can be found by dividing the volume by the surface area.

For *u,* the average fluid velocity, the inflow rate divided by the cross-section square area of the reservoir bed section is required. The cross section area is obtained from the width and depth. Where these are not known, the average cross-sectional area can be approximated by dividing the reservoir capacity by the reservoir length (US Army ACE 1989), at the average operating pool elevation. The average fluid velocity is the inflow rate divided by the average cross- sectional area. However, this method will only provide the average velocity for the whole reservoir, which may be hundreds of km long and vary greatly in width and depth.

For *B* width, if this parameter is unknown, then the average width can be obtained in the following manner.

The equation (2) $$\omega = \frac{\rho g Q S}{\text{flow width}} = \rho g d S u$$

Can be expressed as $$\omega = \frac{\gamma Q S}{B} = \gamma D u$$

Where γ = specific weight of water (=9810 $\mathrm{Nm^{-3}}$)
B = breadth
D = depth
u = average fluid velocity

Rearranging the equation $$\omega = \frac{\gamma Q S}{B} = \gamma D u$$

will provide $$B = \frac{Q}{Du}$$ (note that there is effectively no slope)

i.e. Breadth = Flow rate / depth × water velocity

However this can only provide an average breadth for the reservoir, and only an approximation at that. Even so, this could be a useful guide to the values to be expected, in the absence of the actual data. Where possible these approximate values should be validated with actual data.

5.3.8 Manning's Equations

Another widely used equation in hydrology is that of Manning (Manning 1889), based on empirical observation and testing. Manning's equation is used to predict the behaviour of open channel flows. This is a partly empirical equation used for modelling water flows which are open to the atmosphere and are not under pressure and though superseded by more sophisticated models, is still employed today. Manning's equation for velocity is as follows:

$$V = (1.49/n)R^{2/3}S^{1/2}$$

Where V = velocity m/s

n = channel roughness (value obtained from table)

R = hydraulic radius m^2/m (R = cross sectional area / wetted perimeter)

S = slope m/m

R hydraulic radius is found by dividing the cross-sectional area of the water by the wetted perimeter.

Manning discovered by experiment that the flow velocity varies as a square root of the slope of the channel, the shape of the channel, i.e. its depth and width, and the roughness of the channel. The slope of the channel determines the gravitational force exerted per metre of bed. The shape of the channel, its depth and breadth, determine the degree of friction incurred by the flow. The roughness determines further the flow efficiency and the degree of laminar flow achieved.

5.3.9 Dimensional Analysis

This test brings together different concepts concerning river power density, i.e. W/m^2, in the hypothesis with the W/m of the Stream power concept. It is therefore very important to check rigorously that consistent dimensions are being used in the parameters employed. This is done by dimensional analysis (Sleigh & Noakes 2009). The units employed have been analysed below in terms of the basic physical dimensions of which they are comprised, to ensure that like is being compared with like. This is particularly important as units and terms used in the literature tend to vary quite widely.

The prime units used here are those of flow rate *Q*, expressed as m^3 cubic metres of water, per second.

$Q = \frac{m^3}{s}$ $[L]^3/[T]$

Acceleration due to gravity
is expressed as $g = m/s^2$ $[L]/[T]^2$

Velocity as expressed in $v = \frac{m}{s}$ $[L]/[T]$

Where L = length
T = time
M = mass

Power is expressed as $p = kW$ $[M] \times [L]^2 \times [T]^{-3}$

Density is expressed as $\rho = kg/m^3$ $[M]/[L]^3$

Slope is expressed as $S = m\,m^{-1}$ $[L] / [L]$

Length of reach expressed as $X = m$ $[L]$

Therefore for the TSP equation $p = \rho g Q S X$ Equation (3) (Rhoads 1987)

$$[M] \times [L]^2 \times [T]^{-3} = [M]\ [L]^{-3}\ [L]\ [T]^{-2}\ [L]^3\ [T]^{-1}\ [L]\ [L]^{-1}\ [L]$$

This balances the equation in dimensional terms, making it consistent.

5.3.10 Application of Stream Power to the Nile, Danube, Columbia and Colorado below major HEP Schemes

The longitudinal gradient profiles for the seven rivers were plotted downstream of the HEP schemes in the sample, from a variety of sources. (Global Data Run-off Centre, GRDC 2008, Google Earth, Joint Danube Survey 2005) This process involved a total of four spreadsheets in detail and three further ones.

Flow data was obtained from GRDC, downstream of Khartoum for the Nile, and downstream of Vienna for the Danube. This data, covering the period 1871-1984 for the Aswan Dam, and 1901-1997 for Bratislava on the Danube, was then reassembled in the form of monthly mean flow hydrographs. This could then be used to show the flow regimes both before the major dams were constructed and after, and the associated changes. This process was repeated for the River Columbia downstream of the below the Canadian border to the sea, a distance of 1449 km, with monthly hydrographs assembled including, where possible, the period before the major impoundment dams and the period after. The River Colorado was similarly treated, subject to availability of flow records for the relevant period. This process involved a total of fifty one spreadsheets.

Where flow data was available, the gradient profile spreadsheets were then extended to monthly mean flows and a calculation of the monthly mean Total Stream Power for that particular reach. This could then show the difference in Total Stream Power available to the river before and after the dam construction, and hence the loss of power available to perform erosion and transport of sediment.

Spreadsheets were assembled to show the Total Stream Power (TSP) and Cross-sectional Stream power (CSP) for the Nile, the Danube, Columbia, and Colorado rivers according to the theory above. Mean flow rates were obtained from eleven GRDC measuring stations (Dornblut 2000) corresponding to seven reaches of the Danube, as surveyed by the Joint Danube Survey (2005). The gradient profile of the Danube River was obtained from the same source and checked using elevation readings from Google Earth satellite photographs. The resolution level is of necessity somewhat coarse as the dates of the composite aerial and satellite photographs are not known, and water levels can vary by several metres depending on the season. However, it is considered that a broad agreement of the figures has been obtained to produce a fair representation of the gradient profile within ~ 2m in most cases.

Hydrographs, showing mean monthly river flows over periods ranging from 100 years to 40 years were produced for the Danube. Between 480 and 1200 data readings have been used per flow monitoring station, which is considered to be a fair sample. The effect of the two dams on flow rates was then assessed by calculation of the maximum and minimum flows, as well as the standard deviation, before and after the dam and reservoir construction. Total Stream Power was calculated for each of the seven reaches of the Joint Danube Survey, and also Cross-sectional Stream Power per metre, at a coarse resolution.

5.4 Conclusion of chapter 5

The conclusion is that it is possible to set up a test to investigate in broad terms the environmental impacts of HEP. The setting up of the test has consisted of the selection of a set of cases of well known environmental impact from HEP schemes, the identification of a set of parameters by which to measure the features of the reservoir reach and dam, the identification of impact parameters and the plotting of gradient profiles downstream from the schemes for four of the rivers, with energy flows estimated where data was available. The case sample is necessarily not a statistically representative one, in that the sample is too small, at eleven main cases, with a further six included.

The parameters of impact have been used where quantitative data was available, though this was not always possible. Sediment load data was not available for all the cases, and water quality, biodiversity changes and fish migration barrier data have been outside the scope of the test. The study has concentrated on the main energy parameters of land area and power flux density, flow rate changes and by extension its effects on sediment transport.

Only four of the rivers the Nile, Danube, Columbia and Colorado, have had gradient profiles plotted due to the extent of the task and the availability of data. River gradients have only been plotted below the HEP schemes in question, since this is considered the major area of impact and because the rivers involved are some of the world's longest.
A variety of tests have been applied to the sample of selected HEP schemes and rivers, aiming to test the hypothesis that the power flux density is related to the environmental impact. In particular, parameters of the dams and associated reservoirs have been

investigated, as well as the river gradient and flow regimes downstream from these installations. The tests aim to compare and contrast the energy parameters of the river before and after installation of HEP schemes with the incidence of environmental effects and impacts. The power flux density, the land area used, the proportion or ratio of energy extracted from the flow, as well as the number of energy conversions involved are some of the primary parameters here, as applied to the reservoir reach and the dam. Flow rate changes are significant measures of power flux density changes and these have been identified for the reservoir reaches. Sedimentation and sediment trap efficiency has been another parameter used where practical. Further possible impact parameters were proposed but have proved to be beyond the scope and resources available in this study.

The Total Stream Power concept has been applied using the equation (3) $TSP = \rho g\ QSX$ and equation (4) $CSP = \gamma Qs$ (Rhoads 1987), to reaches of the four rivers that have had gradient profiles plotted below the major dams in the case study, in order to identify changes in Total Stream Power and Cross-sectional Stream power from periods before dam construction to afterwards. Flow data from thirty river flow stations was collected, covering periods of up to 130 years in the case of the Danube. As stated earlier, to the author's knowledge, the use of the concept of Total Stream Power and Cross-sectional Stream power for determining impacts from HEP as a result of changes in power flux densities is novel. The complex and interrelated nature of these parameters has necessitated some considerable amount of detail and description here. The results are presented in the next chapter showing the uses and application of the hypothesis in practice.

Chapter 6

First Results

6. Introduction

The previous chapter described the setting up of the test of the hypothesis for the case of hydro electric power. This entailed the selection of a sample of well known hydro electric schemes on seven of the world's major rivers. A selection of data parameters was made for the reservoir reach and dam, and data collected for each. For the testing of the hypothesis downstream of the hydro electric scheme, gradient profiles were assembled in spreadsheet form. Flow station data was then collected from thirty measuring stations so that the concept of Stream Power could be applied in the same spreadsheet as a test of the hypothesis. This chapter reports the initial results of the test and then considers their main features.

The first results for the reservoir reach and dam parameters of the case sample are shown below in chart form and described in figures to allow comparison. Short descriptions of the main features are included, and how these might relate to impacts. The expected results, if the theory holds true, should correlate mechanical energy effects of water speed and thus power flux density, e.g. sediment load transport, with changes to power flux density e.g. from energy extraction, and sedimentation. Water quality could be expected to correlate with residence time (Petts 1984), as a result of reduced water speed and thus changes in the power flux density. Biological effects on flora and fauna could be expected to correlate with changes in water quality and speed, from changes in power flux density.

6.1. Results

Parameter results

6.1.1 Head heights

The power flux density could be closely related to head height and also to the flow rate, though limited by design to avoid cavitation effects. In this sample the highest head height is that of the Hoover dam at 158.5m, closely followed by the Glen Canyon dam at 155.45m, as shown in figure 6.1 below. Then in descending order come the Cabora Bassa at 120.5m and slightly lower the Itaipu at 118.4m, with the Three Gorges following at 102m, then the Grand Coulee at 100.6m, and the Kariba at 95m with the Aswan High

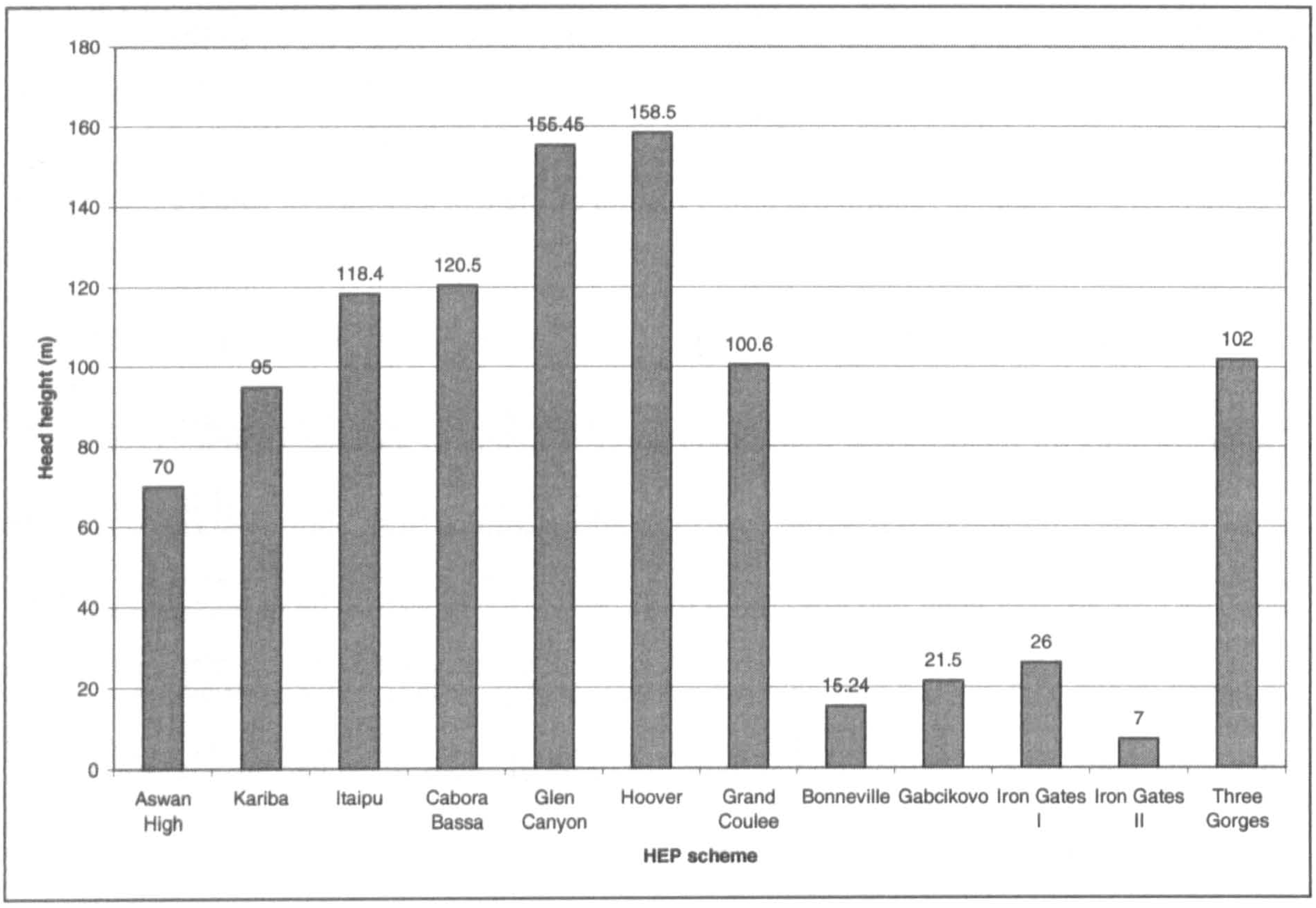


Figure 6.1. Sample HEP scheme head height.

scheme at 70m. The Iron Gates I & II, Gabcikovo and the Bonneville plant are run of river schemes, with low heads of 26m, 7m, 21.5m and 15.24m respectively. See figure 6.1 above.

The head height may be used to describe the power flux density of the river's flow as a function of the acceleration of the mass of the water under the influence of gravity of water.

The available energy will be:

$$PE = mgh$$

Potential Energy = mass × acceleration due to gravity × head height

Therefore the highest power flux densities will be those with the highest head heights as shown in figure 6.2 below. Assuming constant penstock and turbine dimensions, the power flux density can be described in hypothetical terms of the head height and one cubic metre of water under the influence of the force of gravity acting on one square metre. On this basis the Hoover dam with a head height of 158.5m has a power flux density of 1554.88 kWm^{-2}, the highest in the sample, followed by Glen Canyon dam at 1524.96 kWm^{-2}. Next comes the Cabora Bassa at 1182.105 kW m^{-2}, then the Itaipu with 1161.50 kW m^{-2} and these are followed by the Three Gorges with 1000.62 kW m^{-2} and then the Grand Coulee with 986.88 kW m^{-2} and the Kariba with 931.95 kW m^{-2}. The High Aswan has 686.7 kW $m^{-2}$and this is followed by the Chief Joseph with 532.19 kW m^{-2} and then John Day with 337.45 kW m^{-2}. All of the lower head dams in this selection have power flux densities of below 300 kW m^{-2}. These are mainly run of river schemes.

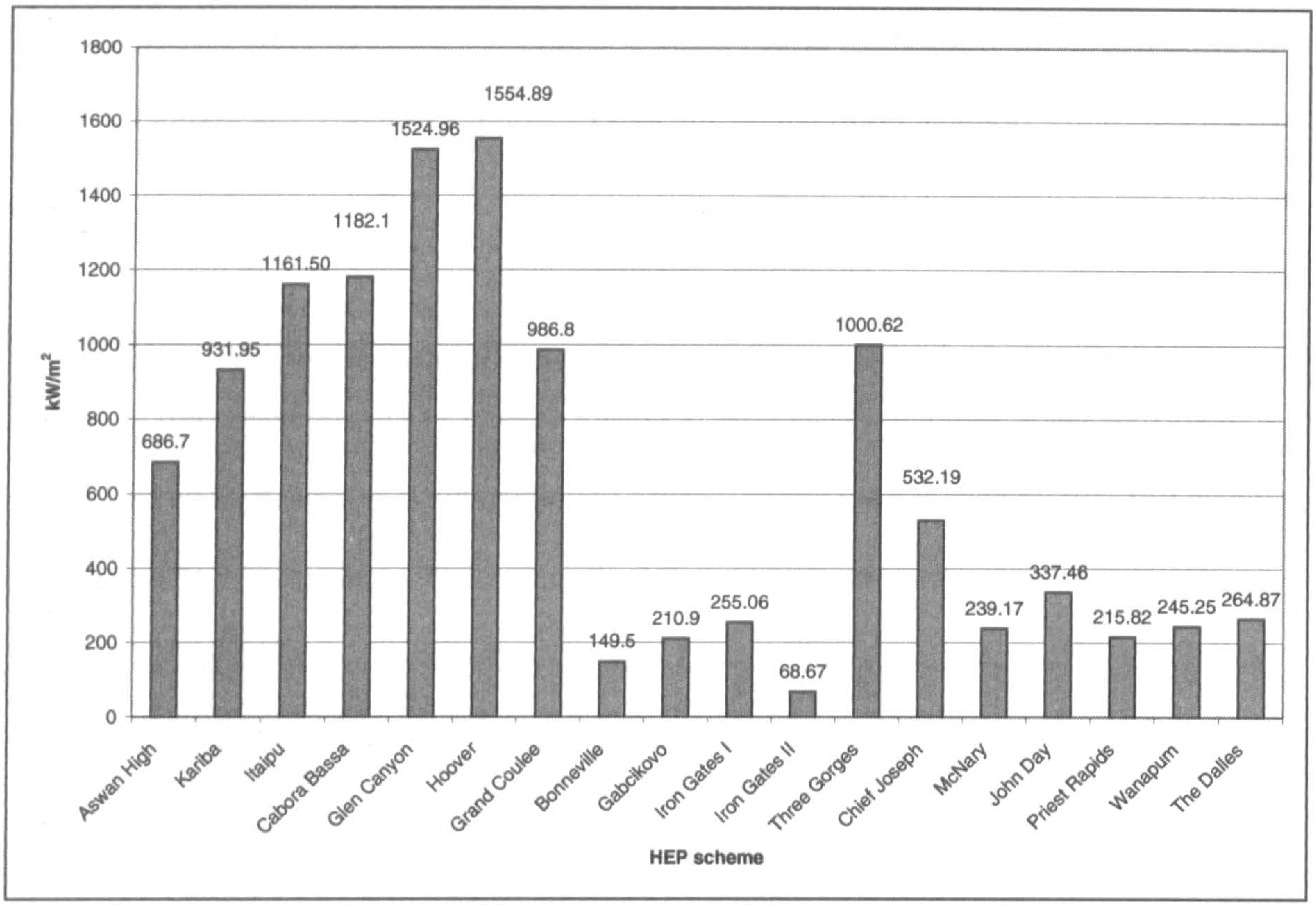


Figure 6.2. Hypothetical power flux density, based on head height kWm^{-2}, for selection of HEP schemes.

The Iron Gates II with 68.7 kW m^{-2} has the lowest power flux density, followed by Bonneville with 149.5 kW m^{-2}. Gabcikovo with 210.92 kW m^{-2} follows, then Priest Rapids with 215.82, and McNary with 239.17 kW m^{-2}, Wanapum with 245.25 kW m^{-2} and Iron Gates I with 255.06 kW m^{-2} and finally The Dalles with 264.87 kW m^{-2}.

The power flux density of HEP schemes is also limited by the phenomenon of cavitation, the explosive coming out of solution of dissolved nitrogen when the water pressure is suddenly dropped, e.g. at the turbine blades.

However, to determine the actual power flux density of HEP schemes requires the flow rate, head height and square area, either at the converter or some other cross sectional point.

The power of an HEP scheme can be calculated by using the equation:

$$P(in\,kW) = Q \times g \times h \times \eta$$

Where: $Q = \mathrm{m^3s^{-1}}$

$g = 9.81\ \mathrm{ms^{-2}}$ acceleration due to gravity

h = head height

η = efficiency (Ramage in Boyle et al 1996 p188)

Head height and flow rate are the two major variables. Efficiency of energy conversion tends to be in the range of 65 to 90 % (Twidell & Weir 1986 p194), reflecting penstock friction losses and the turbine and generator efficiency.

There is a linear relationship between head height and power flux of an approximate factor of 9.81 due to the acceleration due to gravity, ignoring the efficiency losses.

As stated, for the potential energy of the static reservoir water mass stored at a height

$$PE = m \times g \times h$$

is the equation used, i.e. the potential energy is equal to mass multiplied by the acceleration due to gravity multiplied by the head height.

In the penstock, pipe or the reservoir, the static mass of the water exerts a force on the bottom, comprising the mass of the column of water, which can be expressed in Nm^{-2} or more commonly in pascals, the unit for pressure 1 newton per square metre. The standard value of atmospheric pressure at sea level is 1.01325×10^4 N m^{-1} (Chambers 1974). Water is 813 times denser than the air at sea level, 1000kg m^{-3}, as compared to 1.23 kg m^{-3}.

Therefore at one metre depth, water pressure will be:

$$1000 \times 9.81 + 1.01325 \times 10^4 \text{ N m}^{-1}$$
$$= 1.99 \times 10^4 \text{ pascals}$$

At 50m depth pressure $= 5.00 \times 10^5$ Pa

And at 100m depth pressure will be $= 9.91 \times 10^5$ Pa

The highest head height in this sample of HEP schemes is that of the Hoover Dam, with 158m head height, which would result in a maximum static pressure of ~1.56 MPa at the reservoir bottom, or penstock inlet.

In operation, however, as the water flows down the penstock and accelerates, and potential energy is converted into kinetic energy, the high pressures found in high head reservoir bottoms and penstock bottoms will be reduced; resulting instead in high water velocities. Bernoulli's law states that " the sum of the pressure, kinetic and potential energies per unit volume is constant at any point in a tube through which liquid is flowing, pressure being smallest at points of greatest velocity." (Bernoulli cit in Chambers 1974), and conservation of energy equations relate water pressure, velocity and potential energy.

Of the three most common types of hydro electric turbine, the Pelton, Francis and Kaplan, only the Pelton operates at atmospheric pressure (Twidell & Weir 1986 p189). Reaction turbines, i.e. Francis turbines and Kaplan turbines operate immersed and under pressure and there will be pressure changes across the turbine. Twidell & Weir state that pressures can be lower than atmospheric pressure and below the vapour pressure of water, so that bubbles of water vapour form a process called cavitation; as pressure increases downstream these bubbles collapse explosively causing damage such as pitting to mechanical parts (Twidell & Weir 1986 p192). Gas supersaturation due to high pressures can be another phenomenon of high head dams (Petts 1984).

6.1.2 Average River Flow Rate

River flow rate is the other parameter relating to energy flux, shown in figure 6.3 below. Of the sample, the Three Gorges scheme has the greatest average river flow rate at 14300 cubic metres per second, with the Itaipu scheme the next largest average flow at 9000 m^3s^{-1}. Following this, comes the Bonneville scheme at 5660 m^3s^{-1} followed by the Aswan dam scheme at 2760 m^3s^{-1}, and then the Cabora Bassa at 2457 m^3s^{-1}. The Hoover dam scheme has the lowest average flow at 395.6 m^3s^{-1}, followed by Glen Canyon scheme with 875 m^3s^{-1}. The next lowest average flow in the sample is the Kariba scheme at 1775 m^3s^{-1} while the Gabcikovo scheme has a average flow of 2047 m^3s^{-1}.

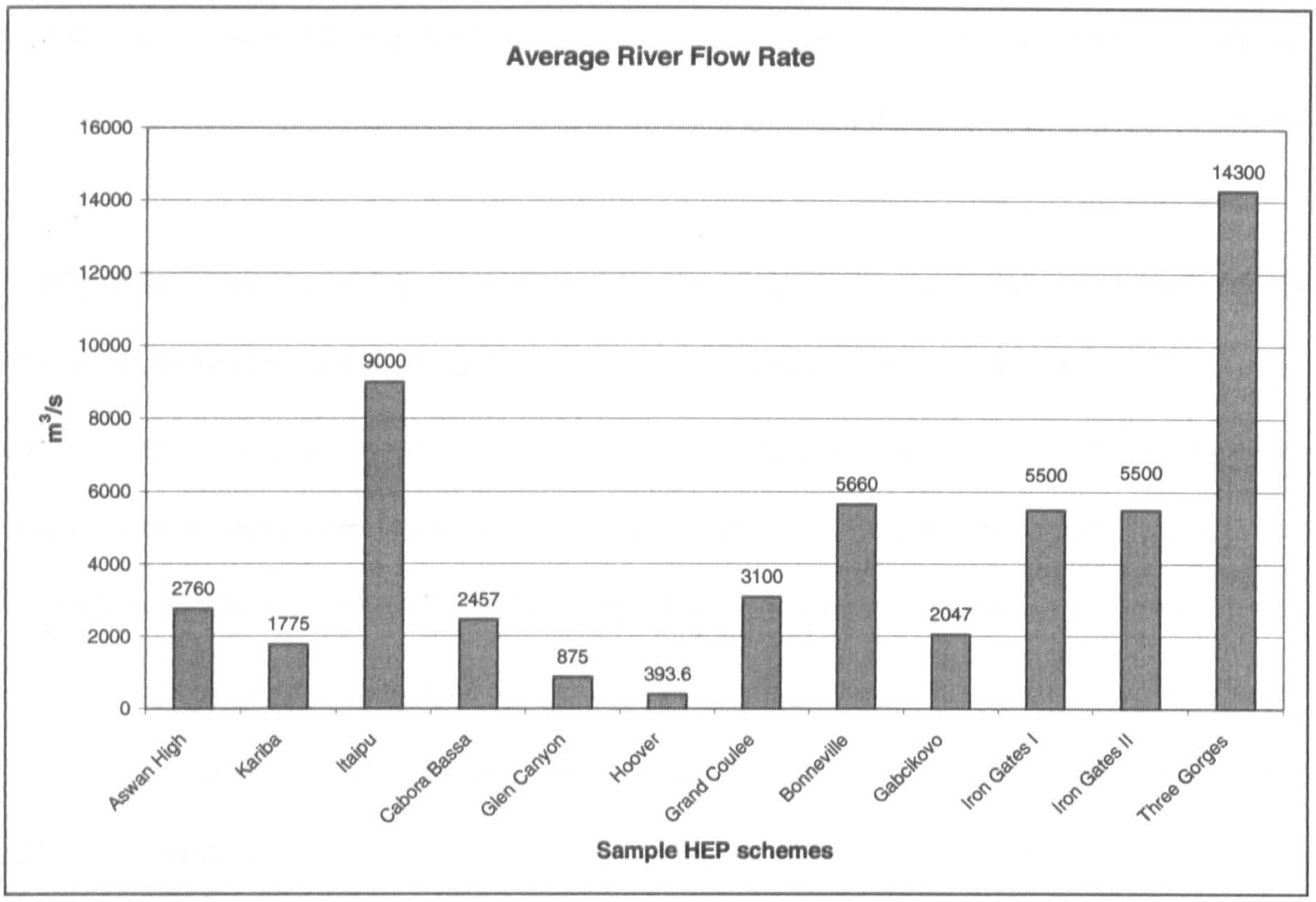


Fig 6.3 Average long run river flow rates at sample HEP dam sites.

6.1.3 Production Factor - Proportion

The Production Factor is defined by this author as the proportion of the river's energy (at the HEP site) that is extracted for electricity production, as shown in figure 6.4 below. In the sample the Iron Gates has the highest extraction of river energy for electricity generation, with the proportion being 83%. The Itaipu follows at ~ 80%. This value varies to the lowest in the sample, 30% for the Glen Canyon, and Cabora Bassa dam, which had previously been operating at 19%, operating well below its designed capacity, now at 51%. Other HEP schemes which take a high proportion of the available power are the Gabcikovo scheme at ~78%, the Grand Coulee at 76.8% and the Hoover dam scheme at 73%, with the Three Gorges scheme following at 68%, and then the Bonneville scheme at ~66%. The next lowest production factor after the Glen Canyon at ~30% is the Aswan High dam scheme at ~ 48%, followed by the Cabora Bassa at ~51%, and then the Kariba at 55%. Since at best the efficiency of conversion into electrical energy, will be in the region of 85-90% (Ramage 1996), the above figures should be multiplied by ~ 1.11, to take account of energy conversion losses, for a more accurate indication of the amount of energy abstracted. This would raise the energy extraction for the Itaipu scheme to ~91%, a high value.

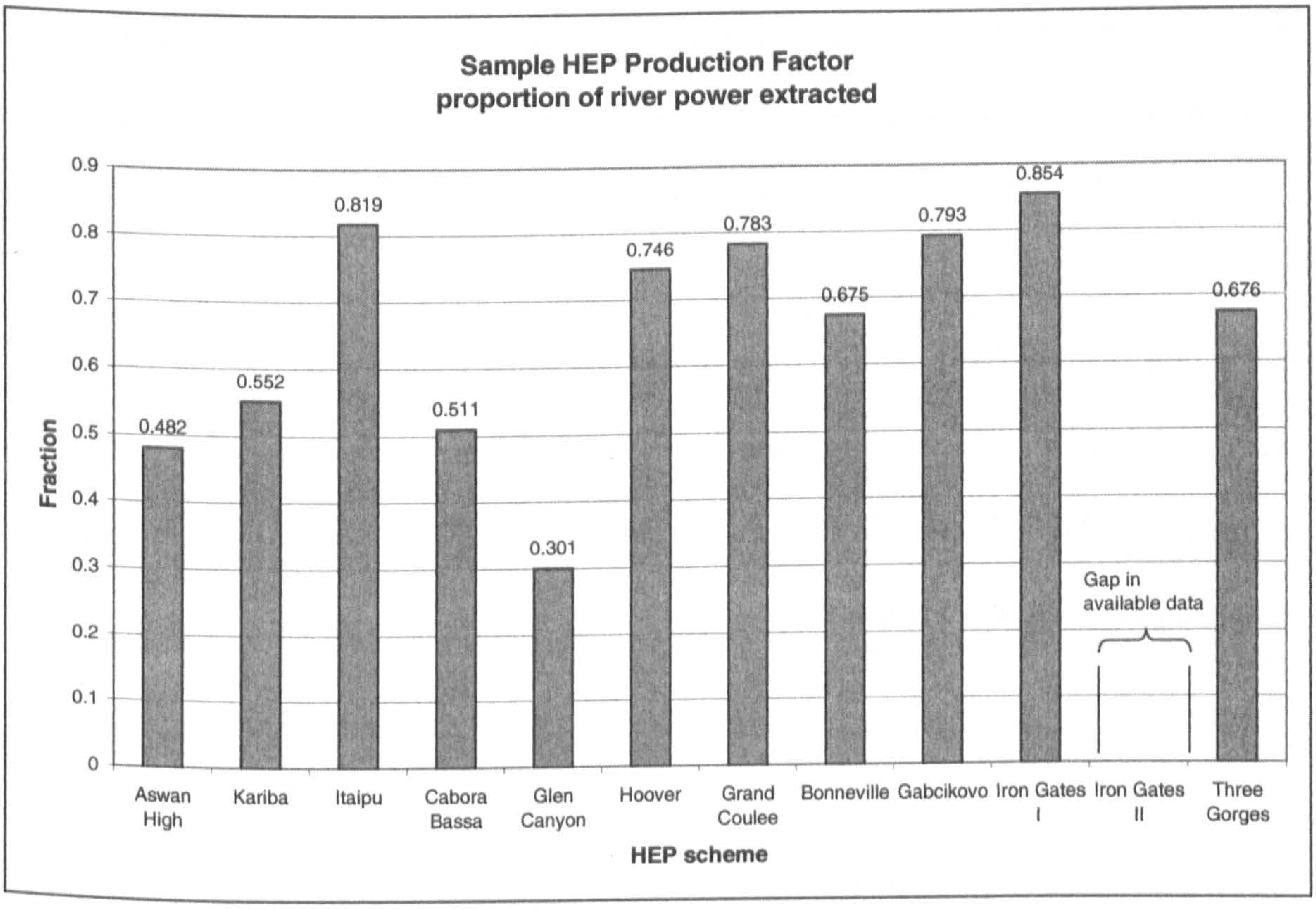


Fig 6.4 Chart representing the production factor of sample HEP schemes.

6.1.4 Land Use: average energy production per square metre of land use.

This is a measure of energy actually generated per land area used. There is a wide range in the sample of approximately by a factor of fifty, in this measure and the sample shows two distinct groups one of relatively high energy production per square metre and one low group. The Three Gorges scheme has the highest value at 0.0089 kW per square metre, or 8.9W per square metre, average energy generated, while the lowest value in this sample is the Kariba at 0.000166 kW per square metre or just 0.166 W per m^2, while not far from this value is the Aswan Dam at 0.00022kW per square metre, or 0.22 W / m^2. Then in ascending order, comes the Cabora Bassa at 0.00039 kW/m^2. After the Three Gorges scheme, the next highest value is the 0.0073 kW per square metre of the Grand Coulee scheme, or 7.3 W per square metre. This is followed by the Itaipu scheme at 0.0063 kW per square metre or 6.3 W/m^2. Then the Bonneville dam follows at 0.0061 kW per square metre, or 6.1 W/m^2. Next in this sample is the Gabcikovo scheme at 0.0057 kW per square metre or 5.7 W/m^2. Considerably lower in this sample is the Hoover scheme, at 0.00071 kW/m^2, or 0.71W/m^2, and then Glen Canyon at 0.00061 kW / m^2, or 0.61W/m^2. This data is shown in the figure 6.5 below.

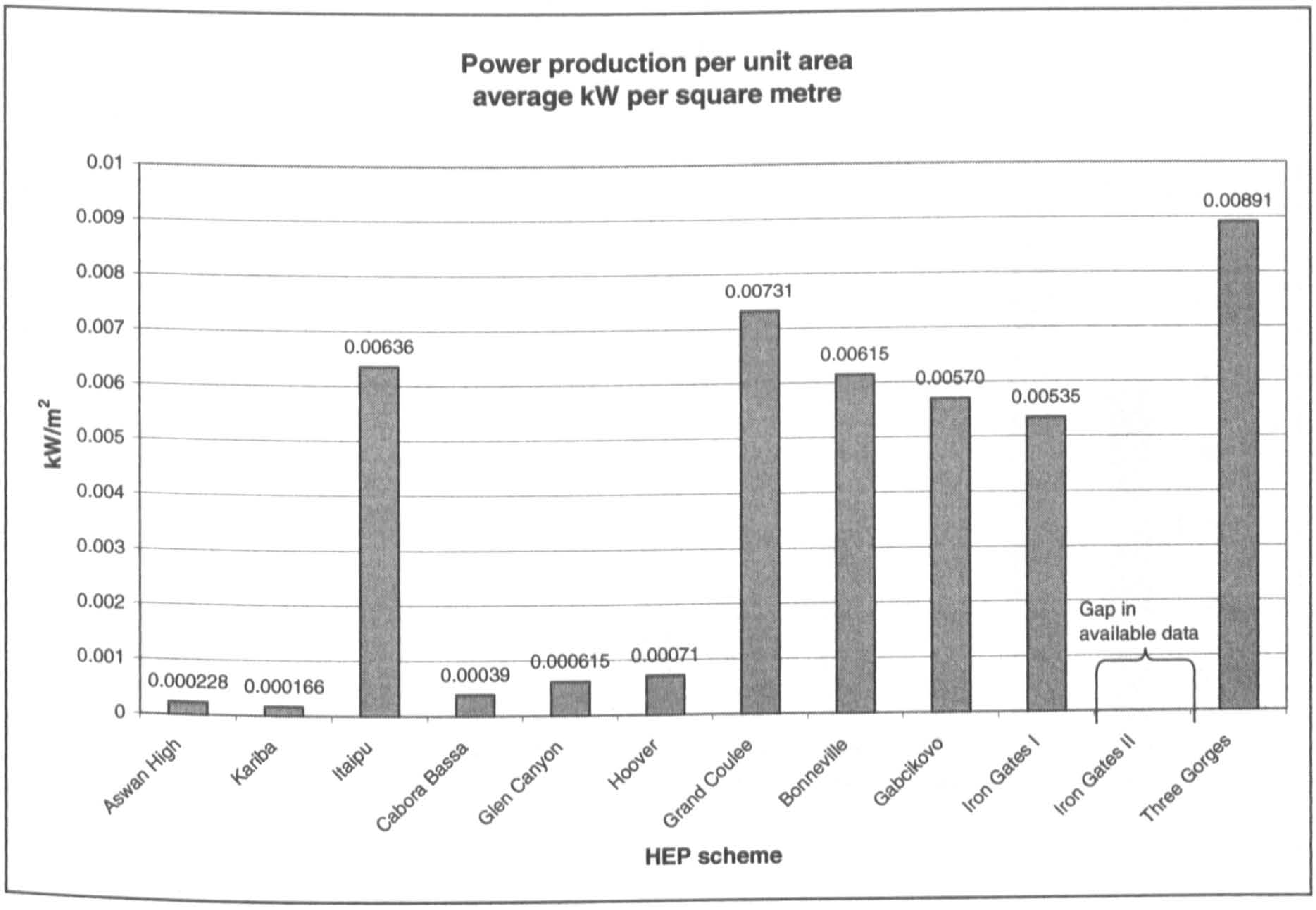


Fig 6.5 Average power production per m^2 of reservoir area.

As shown above in figure 6.5, the data of the sample of HEP schemes falls distinctly into two groups, those schemes with relatively high energy capture per unit of reservoir area, and those with relatively low energy capture. The group with relatively high energy capture per unit area is characterised by relatively short water residence time, contrasted with the relatively long water residence time of the low energy capture per m^2, which might be expected, the reservoir area and volume being large relative to the average flow rate. Alternatively the data can be expressed as km2 / TWh per annum see figure 6.6 below, as for example Gagnon (2002) appears to have done, allowing comparison with his figures, cited in Chapter 3 figure 3.5 page 90.

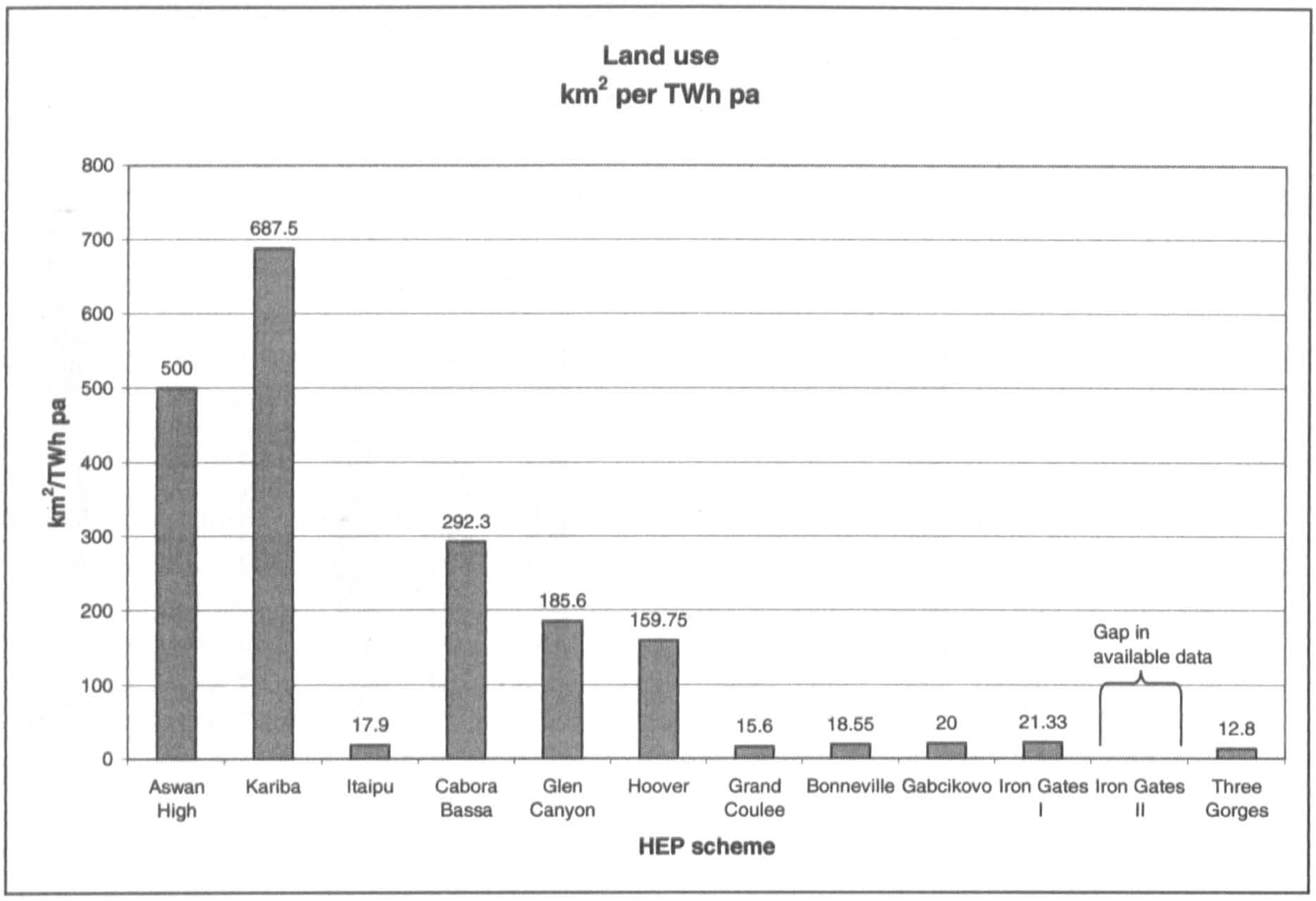


Fig 6.6 HEP scheme land use square kilometres per terawatt-hour per annum.

6.1.5 Former River Mean Gradient

This parameter could relate to the change in power flux density, as well as the land area used to achieve the head height. The mean gradients of the former river course now inundated by the reservoir, for the sample schemes can be compared, as seen in figure 6.7 below. The Hoover dam scheme at 0.13% or 1 in 777 has the steepest former river course gradient, followed by the Gabcikovo scheme at 0.08% or 1 in 1209. Next is the Itaipu scheme with a former river course gradient of 0.0696 %, or 1 in 1436, followed by the Glen Canyon scheme with a gradient of 0.0519% or one in 1926. The lowest gradient in this sample, of the former river course is that of the Iron Gates II at 0.00875%, then the High Aswan dam scheme follows, at 0.014% or 1 in 7142, followed by the Three Gorges scheme at 0.017% or 1 in 5882. Following this, comes the Bonneville scheme at 0.0212% or 1 in 4724. In the middle range in this sample come the Grand Coulee, the Cabora Bassa and the Kariba with, respectively, 0.0481% or 1 in 2079, 0.0446% or 1 in 2240, and 0.038% or 1 in 2632.

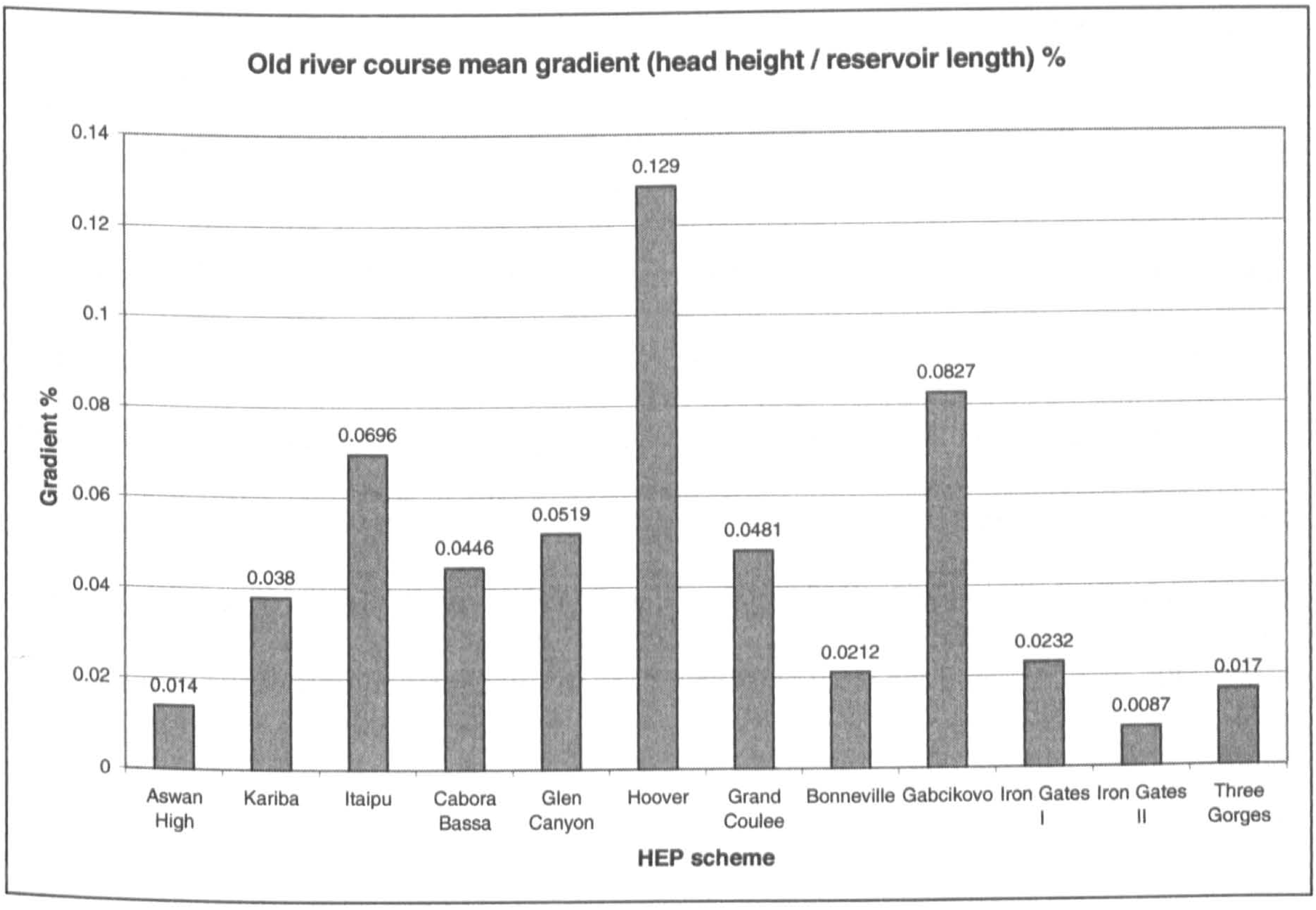


Fig 6.7. HEP scheme mean former river gradient.

Some of the HEP schemes that have steeper gradients in this sample, appear to occupy less land area per unit of energy generated. So the Gabcikovo and the Hoover, schemes with the steepest gradients have relatively efficient use of land area per TWh, the Gabcikovo scheme at 20 km^2 / TWh and the Hoover scheme at 159.75 km^2 / TWh. Conversely those schemes with the lowest gradients show to some extent the greatest use of land per unit of energy output, e.g. in the case of the Aswan dam at 500 km^2 / TWh. However, the second lowest gradient is exhibited by the Three Gorges scheme, which in fact shows the least land use per unit electricity generated, at 12.8 km^2 / TWh. This can be accounted for by the relatively small volume of the reservoir compared to the installed capacity, i.e. the storage capacity is small, at 2.159 x 10^6 m^3 per MW of installed capacity and also the high flow rates of the Yangzte River at the Three Gorges site.

6.1.6 Reservoir Volume

Reservoir volume data was collected for the sample, as shown in figure 6.8 below. The Kariba and Aswan High schemes have the greatest volumes at ~180600 x 10^6 m^3 and 168900 x 10^6 m^3 respectively. This is followed by the Cabora Bassa at 6300 x 10^6 m^3 and the Three Gorges at 39300 x 10^6 m^3. The smallest reservoir volumes are Gabcikovo at 243 x 10^6 m^3 and the Bonneville at 662 x 10^6 m^3 followed by the Iron Gates I at 2500 x 10^6 m^3. The Grande Coulee at 11790 x 10^6 m^3, the Glen Canyon with 27000 x 10^6 m^3, the Itaipu with 29000 x 10^6 m^3, and the Hoover 34850 x 10^6 m^3, occupy a middle range in the sample.

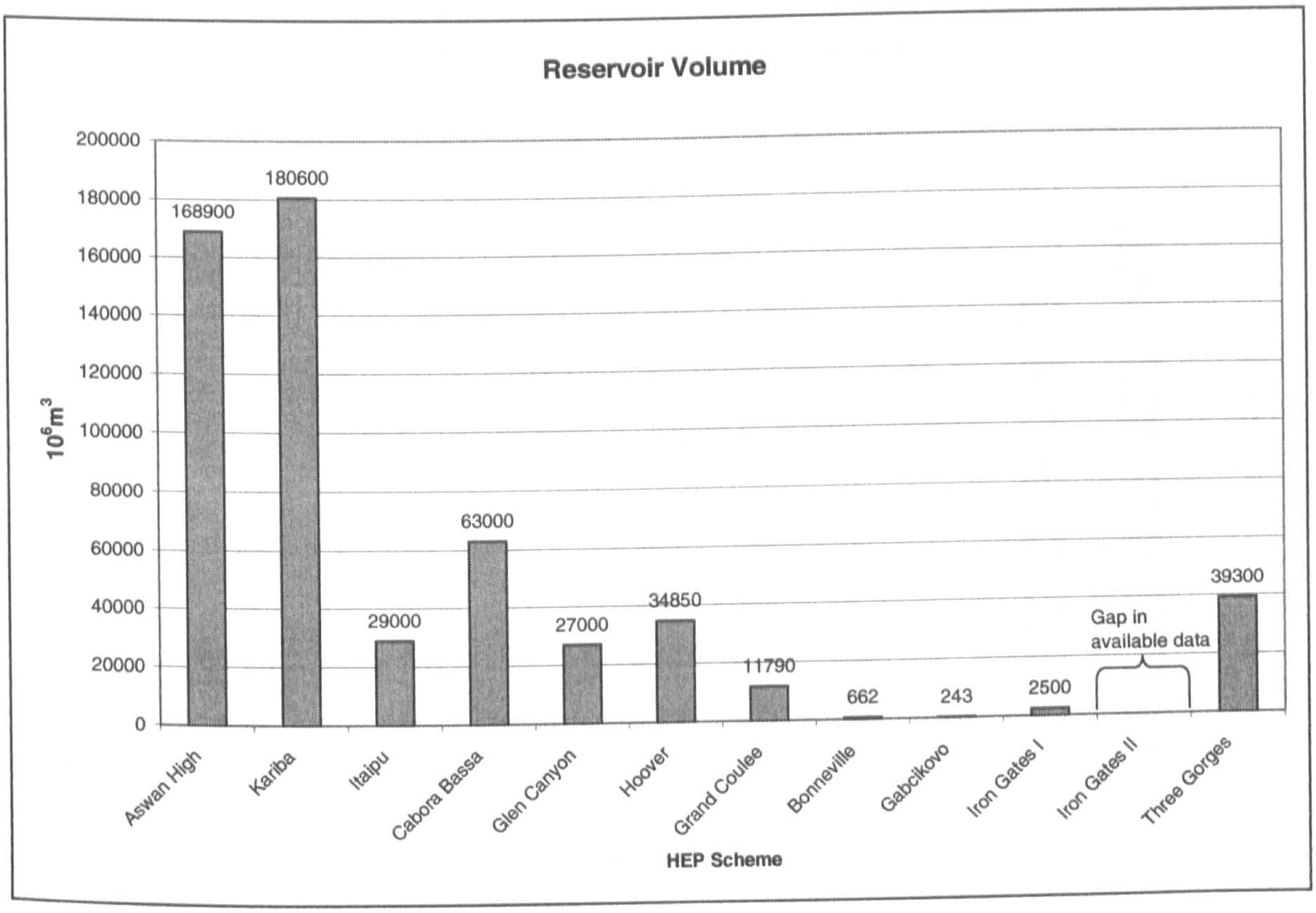


Fig 6.8 Reservoir basin volume in cubic metres for sample. (International Water Power & Dam Construction 1996)

Reservoir Volume per GWh per annum generated

The reservoir volume per annual electricity generated shows that in the sample, the Kariba and the Aswan schemes have the greatest volumes per unit of electricity generation, at 22.575 and 21.113 × 10^6 m^3 per GWh pa. The Gabcikovo has the lowest volume at 0.081 × 10^6 m^3 per GWh pa, other low values being those of Bonneville and then the Iron Gates. Somewhat greater volumes are found in the Three Gorges, Itaipu and Grand Coulee schemes, at 0.464, 0.387, 0.561 × 10^6 m^3 per GWh pa respectively. The Hoover, Glen Canyon and Cabora Bassa, have respectively, 8.712, 7.675 and 4.846 × 10^6 m^3 per GWh pa, as seen in figure 6.9 below.

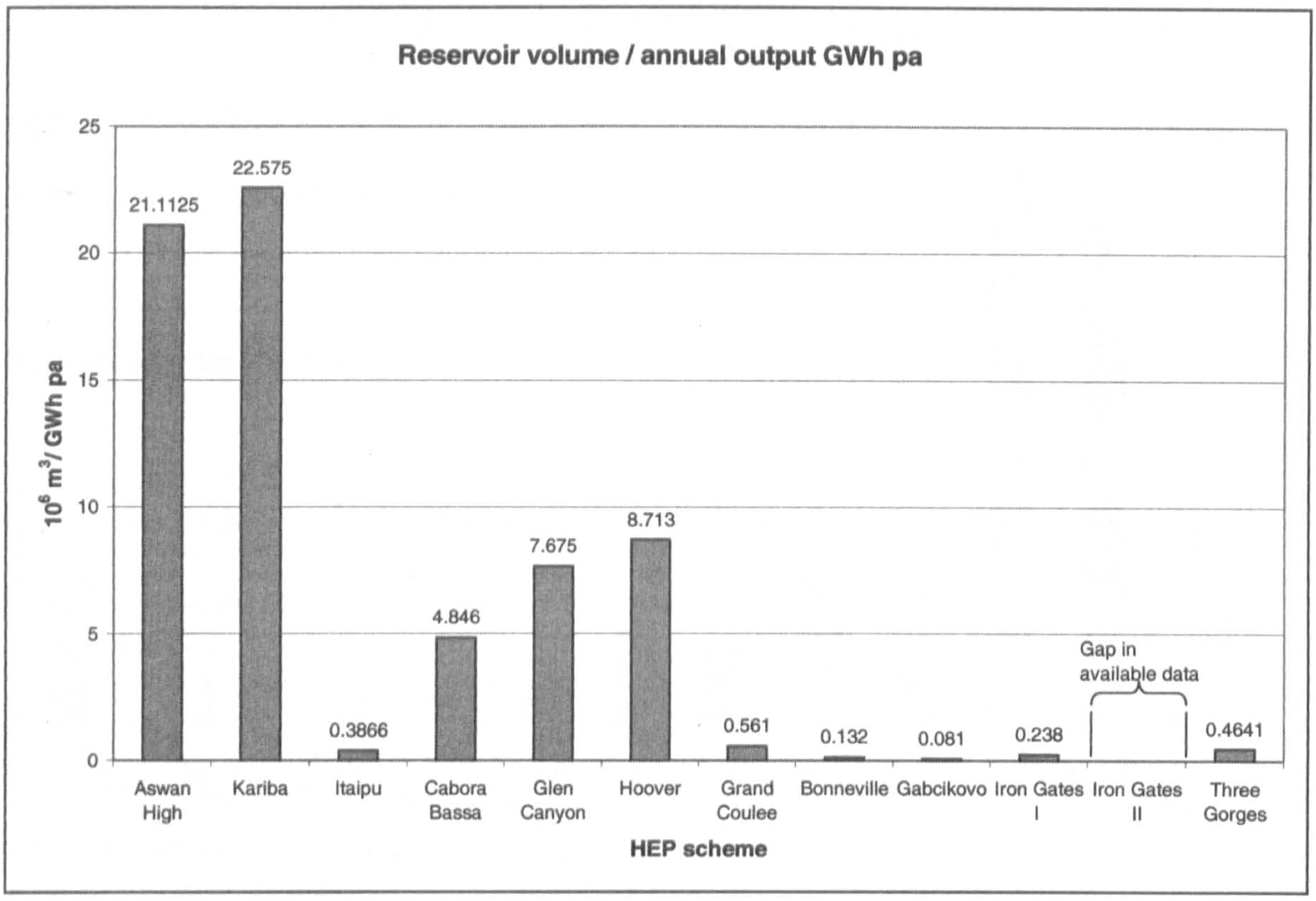


Fig 6.9 Reservoir volume per annual output in million cubic metres per gigawatt-hours per year.

6.1.7 Average Water Residence Time

The reservoir volume divided by the average river flow gives the water residence time. There appear to be three groups in the sample; long, short and intermediate residence times. It can be seen that the Kariba scheme has the greatest average residence time at 1177.5 days or 3.226 years, followed by the Hoover scheme with 1024.5 days or 2.807 years residence time, and then the Aswan High scheme at 708 days or 1.94 years. The lowest residence times are those of the Bonneville scheme at 1.35 days, (0.0037 years) followed closely by the Gabcikovo scheme at 1.37 days (0.00376 years), then the Iron Gates scheme at 5 days (0.0138 yrs), and then the Three Gorges scheme with 31.8 days

(0.0871 years) residence time. This is followed by the Itaipu scheme with 37.3 days (0.1021 years) average residence time.

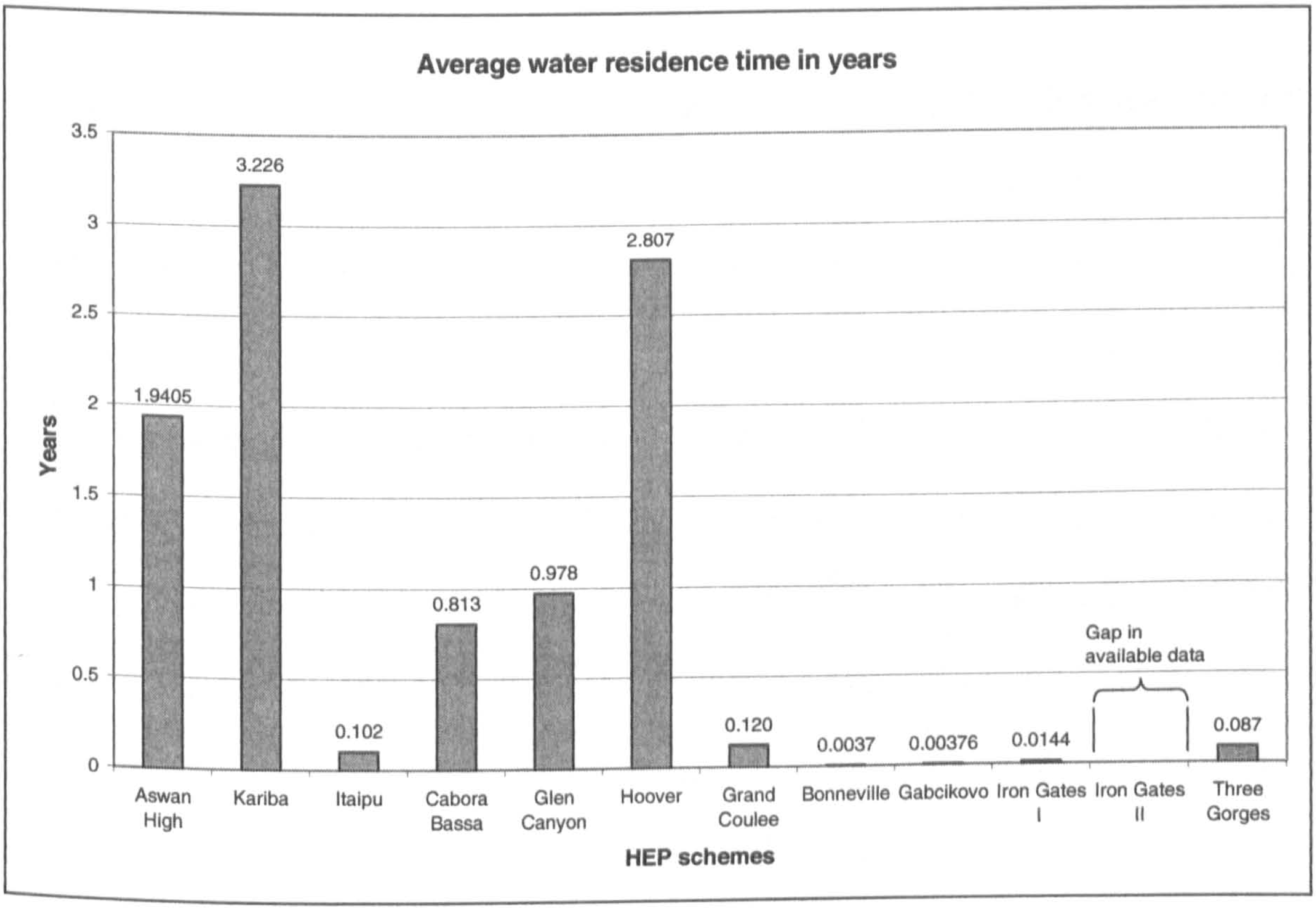


Fig 6.10. Average water residence time in years.

The Grande Coulee scheme has 72.9 days (0.1998 years) average residence time, followed by the Cabora Bassa at 295.8 days (0.8103 years), and the Glen Canyon scheme at 356.97 days (0.978 years). See figure 6.10 above.

Water residence time is linked to water flow rates, (i.e. m^3s^{-1}) and water velocity (i.e. ms^{-1}), and so to silting, due to decrease of water flow velocity and also linked to water quality. The long water residence times belong, in this sample, to rivers in arid or desert regions with relatively low flows apart from a flood period. These schemes are multi-use ones, used for irrigation and water supply purposes as well as energy and so large storage capacity has been a design feature.

6.1.8 Average Reservoir Fluid Velocity

The inflow rate divided by the cross-sectional area gives the average fluid velocity. An assumption here is that the flow is evenly distributed across the cross sectional area. The highest mean velocity rates are those of the Iron Gates 1 scheme and the Bonneville, at 0.62 ms^{-1} and 0.62 ms^{-1} respectively. The Chief Joseph scheme reservoir flow rate is the next highest at 0.34 ms^{-1}, followed by the Gabcikovo scheme and the Three Gorges schemes, at 0.22 ms^{-1} and 0.22 ms^{-1} respectively. The Iron Gates scheme has a relatively high flow rate and relatively small cross-sectional area. Following this, the next highest velocity is that of the Itaipu scheme at 0.052 ms^{-1} with the Grand Coulee scheme following at a velocity of 0.033 ms^{-1}. The lowest reservoir velocity is that of the Hoover scheme at only 0.0013 ms^{-1} while the Kariba scheme has a reservoir velocity of 0.002 ms^{-1}. In ascending order the Aswan High scheme comes next with 0.008 ms^{-1} mean velocity and then the Glen Canyon scheme with 0.0097 ms^{-1} and the Cabora Bassa with 0.010 ms^{-1}.

The Bonneville scheme is a run of the river type and thus high velocity rate might be expected. The Iron Gates scheme has a relatively high flow rate and relatively low reservoir capacity. The Chief Joseph scheme, although an impoundment type dam of 50m head height, contains a reservoir with relatively low volume, only 731 x 10^6 m^3. This graph of average reservoir fluid velocity, see figure 6.11 below, is largely a reversed image of the mean water residence time chart above, as might be expected. The lowest water velocity rates are those once again of the desert reservoir dam schemes which incorporate inter seasonal storage. These schemes are likely to be associated with the greatest sedimentation rates.

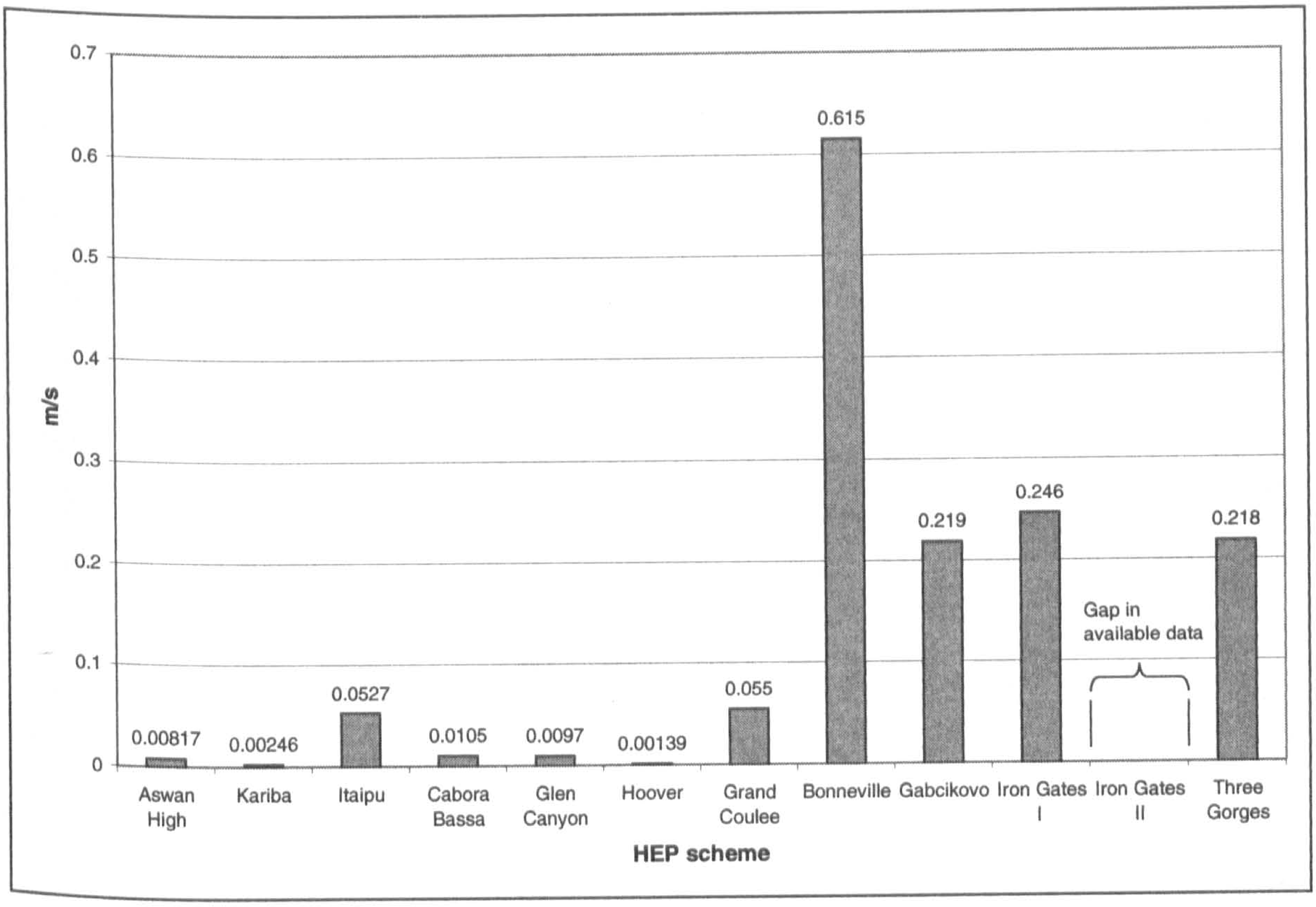


Fig 6.11 Average reservoir fluid velocity in metres per second.

6.1.9 Stream Power

Total Stream Power expresses the energy available to the river from the acceleration due to gravity, the flow rate, and the drop in height over the river reach in question. This has been calculated for the former river bed of the reservoir reach of each of the HEP schemes, in kW as shown below in figure 6.12. The assumption is made here that the river bed has an even gradient over the length of the reservoir since detailed information about the former bed is not available.

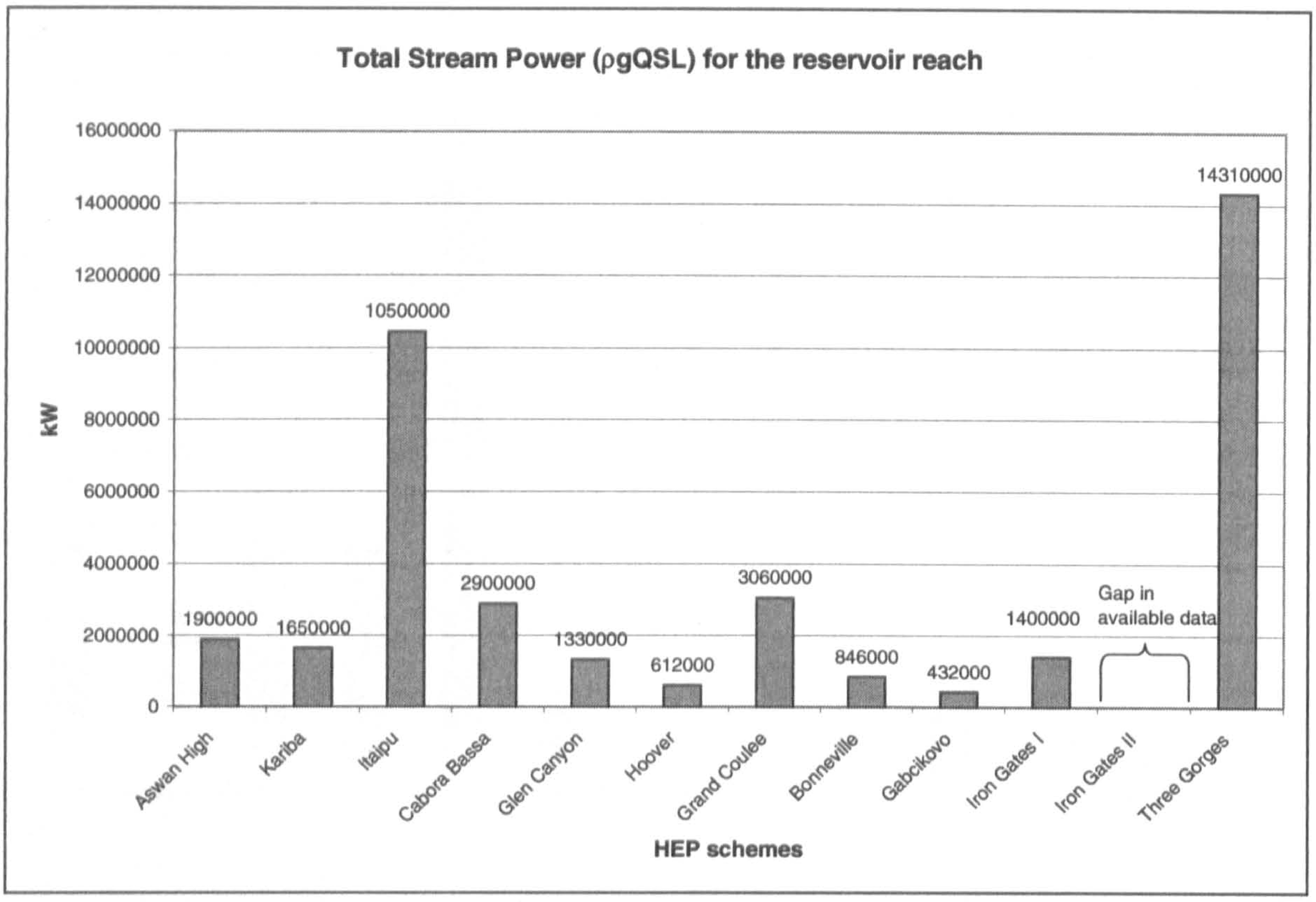


Fig 6.12 Total Stream Power for the former river reservoir reach in kW.

What the Total Stream Power (TSP) represents is the mean power available to the river reach for overcoming friction, both internal and with the bed, for transporting sediment load, and for degrading or eroding the river bed (Rhoads 1987). For this calculation, average flow rates have been used, so the TSP here is an average value. As such it should correlate roughly with the average power output from the HEP schemes, taking into account turbine and generator losses, as well as compensation flows by-passing the turbines. It can be seen that this is roughly the case, with the Three Gorges scheme having a TSP of 14.3×10^6 kW, followed by the Itaipu scheme with a TSP of 10.4×10^6 kW, as the two largest HEP schemes in the sample, followed by the Cabora Bassa at 2.9×10^6 kW, then the Aswan High Dam scheme at 1.89×10^6 kW, and then Grand Coulee with a TSP of 1.84×10^6 kW, closely followed by the Iron Gates scheme with a TSP of 1.83×10^6 kW. This is followed by the Kariba scheme with a TSP of 1.6×10^6 kW, and then Chief Joseph with a TSP of 1.6×10^6 kW. The Dalles follows with a TSP of 1.4×10^6 kW followed by Glen Canyon with a TSP of 1.3×10^6 kW. The smaller schemes in the sample are the Bonneville scheme at 0.84×10^6 kW, then the Hoover scheme at TSP of 0.61×10^6 kW, and then Gabcikovo with a TSP of 0.43×10^6 kW.

Stream Power can also be expressed in terms of the power per unit length of a defined reach. Using the equation (4) $\Omega = \gamma Qs$ for Cross-sectional Stream Power (CSP), see Ch 5 p152 (Rhoads 1987 p194), this was calculated for the sample rivers and Hydro Electric schemes, over the old river course now occupied by the reservoir, to give an average Wm^{-1} value. The results are shown in figure 6.13 below.

From this chart it can be seen that while most of the sample lie within the range $\sim 4 \times 10^3$ - 24×10^3 Wm^{-1} (4000 - 24000), one scheme, the Itaipu has a value of over 66×10^3 Wm^{-1} (66000), while another the Dalles has 37.9×10^3 (or 37900) Wm^{-1}. The lowest value is that of the High Aswan dam, at 3.79×10^3 (3790) Wm^{-1}, with the Glen Canyon and Iron Gates II followed by Hoover schemes having the next lowest values at 4.46×10^3 (4460) Wm^{-1}, and 4.97×10^3 (4970) Wm^{-1}. In ascending order the Kariba scheme follows with 6.61×10^3 (6610) Wm^{-1}, and then the Grand Coulee with 8.8×10^3 (8825) Wm^{-1}, and the Cabora Bassa with 10.7×10^3 (10700) Wm^{-1}, and then Bonneville with 11.8×10^3 (11800) Wm^{-1}. The Gabcikovo and the Three Gorges dam have respectively 16.6×10^3 (16600) Wm^{-1}, and 23.8 × 10^3 (23800) Wm^{-1}. In this sample the Itaipu scheme stands in a class of its own with 66.1 × 10^3 (or 66100) Wm^{-1}.

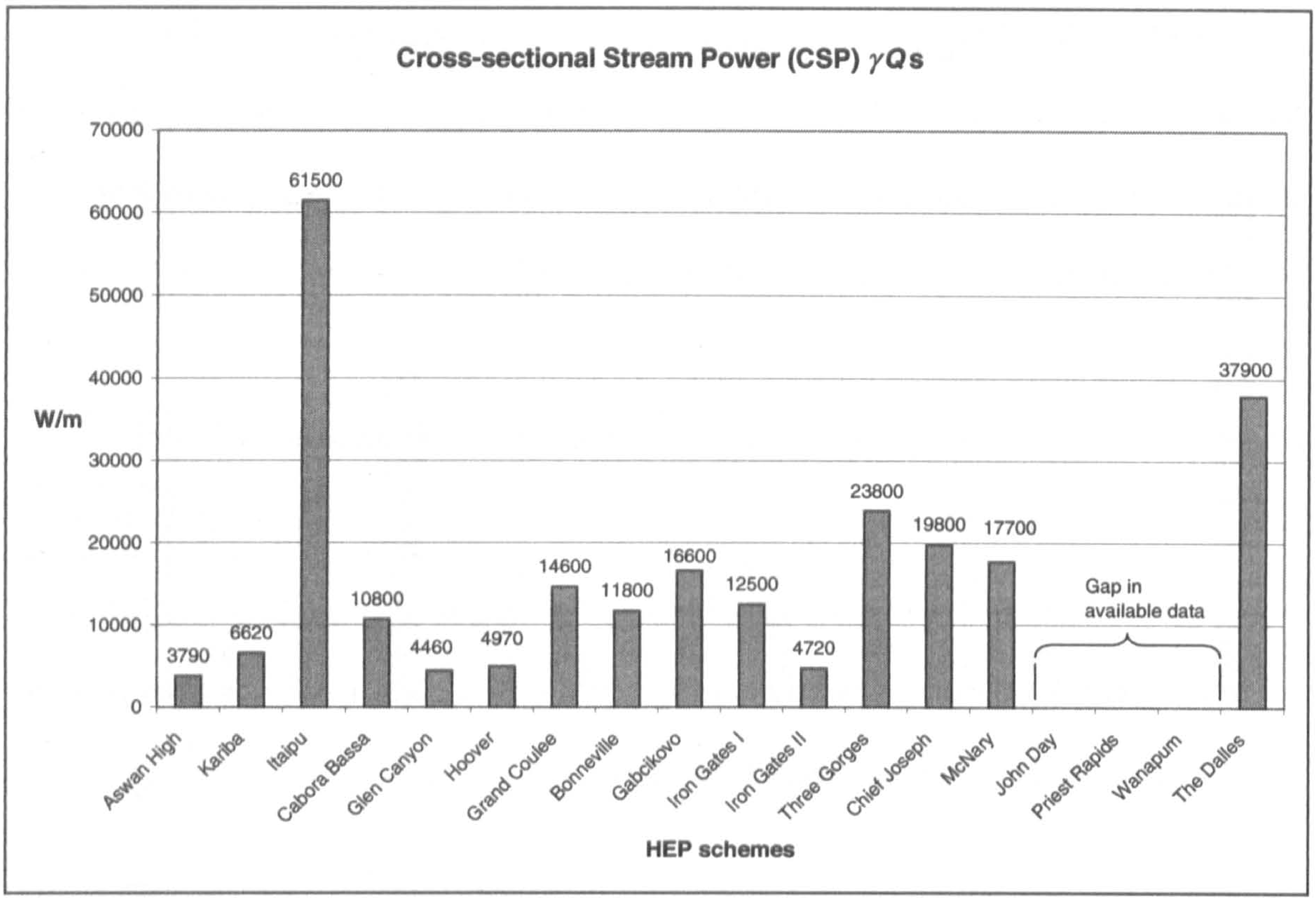


Fig 6.13 Average Cross-sectional Stream Power (CSP) $\gamma Q s$ in watts per metre of cross section of the former river reservoir reach of the sample HEP schemes.

Inundation of the former river bed, with a resulting level reservoir, will reduce the Cross-sectional Stream Power to effectively zero since there is no slope. In terms of Total Stream Power for the whole reservoir reach, the absence of any slope again reduces this to zero until the dam. Since Stream Power represents the available potential power in the stream for overcoming friction, and with the remaining energy eroding the bed and transporting sediment, it might be initially concluded that in the sample it is the Itaipu scheme that has the most surplus energy to perform these 'functions', while the Aswan, Glen Canyon and

Hoover schemes have the least surplus energy. However, the resolution available is coarse, and varies for each sample, since the former river gradient has been averaged over the reservoir length and this may hide considerable variation in the former river bed, affecting the calculation of Stream Power. Some studies show that a smoothed coarser resolution level results in underestimates of calculated Stream Power values (Worthy 2005).

A summary of the main impacts from the sample is shown below in Table 6.1 below.

HEP Scheme	River	Impact
Aswan High	Nile	Silting, loss of silt fertiliser downstream; erosion of delta, fishery loss, water loss evaporation from reservoir surface, salinity at delta, land use, population displacement.
Kariba	Zambesi	Population Displacement, flow fluctuation, Water Evaporation Loss, Wildlife Effects, disease
Cabora Bassa	Zambesi	Flow fluctuation, downstream wetlands loss and silt loss, downstream terrain drying out, population displacement.
Itaipu	Parana	Drowned vegetation -CO_2 emissions
Hoover Dam	Colorado	Flow fluctuations, water abstraction, flood attenuation, silting
Glen Canyon	Colorado	Water abstraction, flow fluctuations, silting
Bonneville Dam	Columbia	Migratory fish barrier, upstream river changes
Grand Coulee	Columbia	Supersaturation / (TDG) Anadromous fish barrier
Gabickovo	Danube	Land Drainage, Groundwater changes, channel changes, eco system damage
Iron Gates	Danube	Sediment trap, land inundation
Three Gorges	Yangste (Changjiang)	Population displacement, loss of habitat, sedimentation fears / predictions, Flow changes, Silting

6.1.10 Sedimentation / Silting

This is one of the most important impacts of hydro electric power plants and dams, after use of land area. As well as trapping sediment, in the reservoir reach, *transport* of sediment below the dam can be affected by HEP schemes. As described in Chapter 5, the sediment trap efficiency of reservoirs has been estimated using the equation to describe Brune's trap efficiency curves, and incorporated in the spreadsheet. A 90% trap efficiency indicates that 90% of the sediment transported would be trapped by the reservoir, rather than carried downstream by the river.

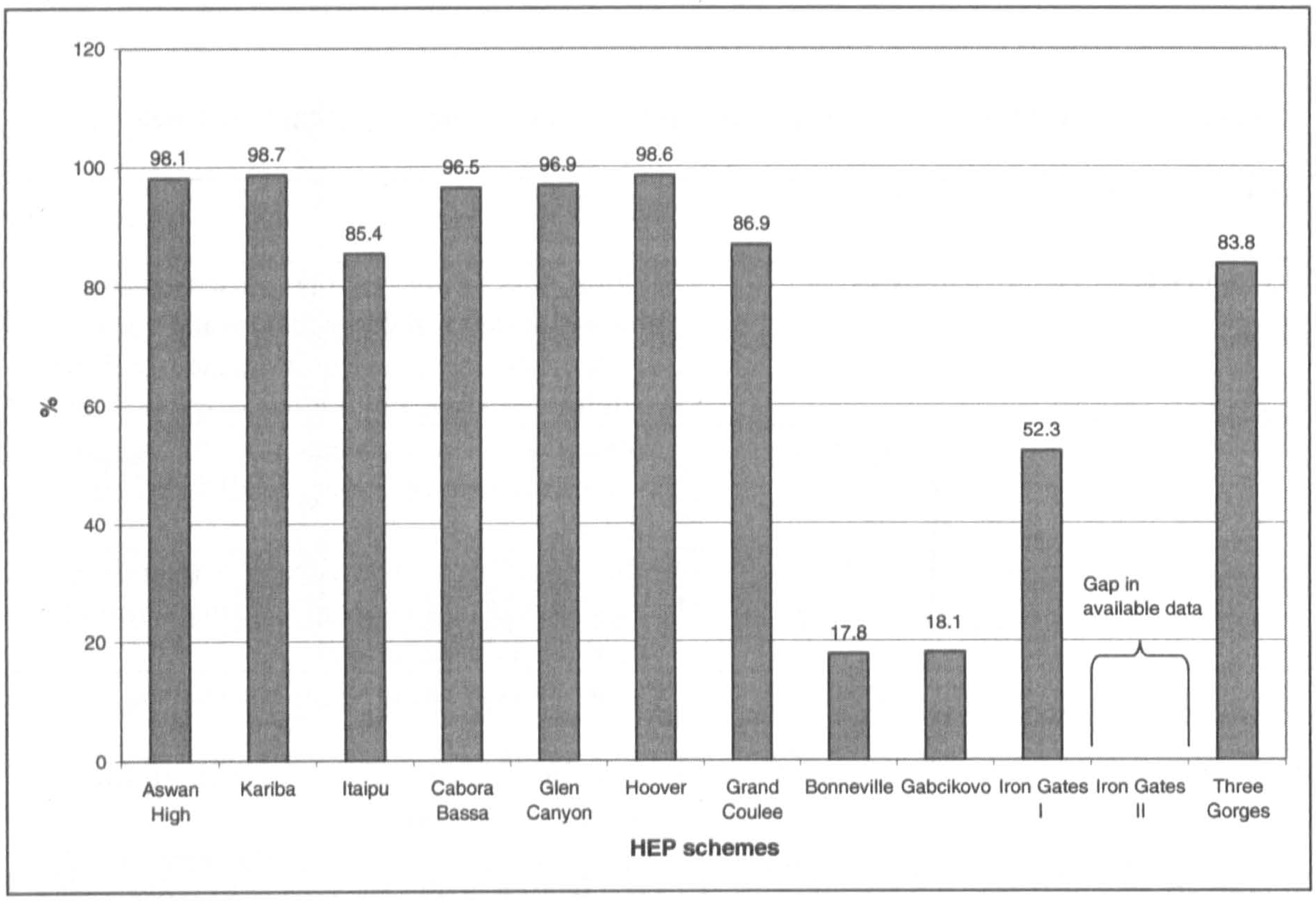


Fig 6.14 Sediment trap efficiency, Brune curve prediction.

The results are shown in Figure 6.14 above, 'Sediment trap efficiency'. This shows that the trap efficiency of most of the sample predicted, is above 80%, with several in the 90% plus range, while the two examples that are below 20% are both "run of the river", type schemes, i.e. with small reservoirs and very low water residence periods. The highest trap efficiency predicted by this method is that of the Kariba dam, with 98.7% sediment trap efficiency, followed by the Hoover dam with 98.6%, and then the Aswan High dam with 98.1% trap efficiency. Also above 90% is the 96.9% of the Glen Canyon scheme, and the

96.5% of the Caborra Bassa scheme, and the 90.7 % of the Grande Coulee scheme. In the sample the Itaipu scheme follows, with 85.4% trap efficiency, and then the Three Gorges scheme with 83.8% trap efficiency. The lowest trap efficiencies are those of the "run of the river" schemes, the Bonneville at 17.8% and the Gabcikovo at 18.1%, followed by the Chief Joseph scheme has a predicted trap efficiency of 35.7%. The Iron Gates I scheme has a predicted 52.3% trap efficiency.

These values reflect the differences in reservoir capacity and flow rates, with this ratio being the most significant in the calculation. Where the reservoir is large in volume in proportion to the river flow rate, the flow rate in the reservoir will be reduced proportionately, thus causing the transported sediment load to be deposited. So the greater the reservoir capacity in proportion to the inflow rate, the greater the trap efficiency. This applies with the proviso that the majority of the reservoir's volume is contained in the main submerged river valley, rather than in side valleys, and also that the inflow is largely from the main river system. As Petts (1984) and others have pointed out, the shape of the submerged valley is significant, i.e. the cross sectional area. However, as a rule of thumb guide, Brune curves have been found to be a reasonable indicator of trap efficiency (US ACE 1989 pF4).

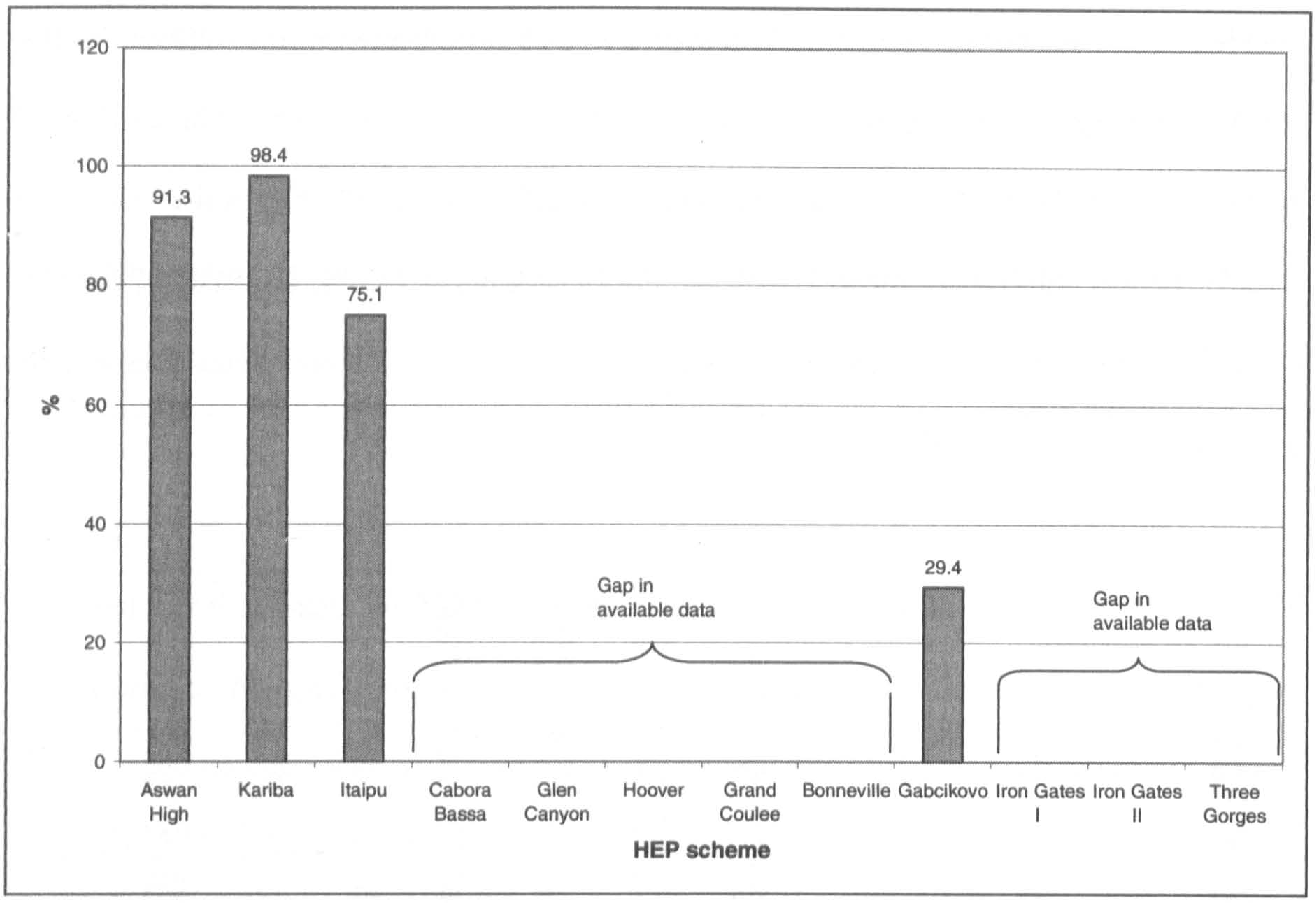


Fig 6.15. Sediment trap efficiency according to Brown.

A chart showing the trap efficiency (where data was available) using Brown's curves is shown above in figure 6.15. The results, where available, differ quite considerably from those of Brune since both a different formula and different parameters, e.g. watershed area are used (US ACE 1989).

Sedimentation at Lake Nasser and Aswan on the Nile

Before the Aswan High dam was constructed, the Nile River carried an estimated 125 million tons of sediment per year, mostly as suspended load, 98% of which was brought down during the flood season, i.e. August to November, (Marndouh 1985, p459). Suspended load was measured regularly, from 1928 to 1963 and beyond, at a number of locations, e.g. Wadi Halfa and Gaafra. The average percentages of clay silt and sand proportions in the suspended load are Clay < 0.002mm : 30-35%, silt 0.002-0.02mm :35-45 %, and sand 0.02-0.2 mm 20-30%, depending on the month. Since 1964 the operation of the Aswan High dam, the flood reaching Lake Nasser experiences a drop in velocity from over 1m/s to about 0.02m/s (Marndou 1985 p460), which results in 98% of the sediment load being deposited. The average sediment load passing through Aswan is now about 2.5 million tons or a fiftieth of the former load. (Shalesh S. 1974, cit in Marndouh 1985). Marndouh states that "The Nile is a silt bearing river and the delta and valley in Egypt are made up of its sediments. The rate of sedimentation in the pre-storage period was estimated at 6 to 15 cm/ century, with an average of 0.8mm/yr, used to cover the surface of agricultural soil in Egypt. Since 1964 this amount no longer reached the soil, with the following consequences:

i) loss of a unique source of natural nourishment to the soil and

ii) loss of a supply of fresh soil, thereby eliminating any chance of natural improvement of depth to water table" . (Marndouh 1985 p461).

The Aswan High Dam has been designed to have a "dead volume" of 30 x 10^9 m^3 in order to store the silt for an estimated 400 years. However, sediment has been accumulating faster than originally estimated, at an average rate of 109 × 10^6 m^3 per year, in the upper 250km of the reservoir. (Sutcliffe & Parks 1999 p156) This will still provide for 275 years of silt storage at present rates. Since the sediment is now trapped in the reservoir, and the flood discharge eliminated, scouring below the dam occurred at a rate of 0.02-0.03 m per year after 1966 (Sutcliffe & Parks 1999), though was stabilized by controlling flows.

The effects of the High Aswan Dam can be seen in the loss of Total Stream Power of 1932000 kW, or 1.932 GW of mean river power flux and the loss of the flood discharge below Aswan, results in a loss of 5293000.0 kW or ~5.3 GW during the peak flood month of September when a mean 7707m^3 of flow occurs (based on mean September flows at Aswan 1869-1984).

However, the High Aswan Dam has allowed a more stable flow downstream to be maintained and the over year storage of water, (~1.8 years mean storage) has enabled irrigation to be provided reliably, even in times of drought upstream, e.g. on the Blue Nile. The absence of peak flooding has enabled more agricultural development on the banks too. Moreover, a considerable portion of Egypt's electricity supply has been derived from the hydro electric power scheme (Sutcliffe & Parks 1999).

6.1.11 Sub Conclusion

Run of river schemes have much lower trap efficiencies than impoundment dams. Impoundment schemes reduce the water velocity more than run of the river schemes. This appears to accord with the hypothesis that the greater the reduction in the velocity rate, i.e. power flux density, the greater the impact from sedimentation. The reduction in velocity rate might be linked to head height -in part, and in part to the extent of change to the mean former river gradient. E.g. the Hoover (second highest trap efficiency) scheme has the highest head height in the sample, and the Glen Canyon scheme, second highest head height, comes fourth in trap efficiency (using Brune's method), at ~96%. The lower head heights of the run of river schemes fit this linking. However, the highest trap efficiencies appear to be linked largely to those desert dam schemes that have very large storage capacity, which can in turn be linked to low former river gradients, for the impoundment schemes.

6.2 Test First Results: Calculations for Stream Power over river reach below Dam

6.2.1 Cross-sectional Stream Power for the Danube

The Cross-sectional Stream Power (CSP) for the Danube below Bratislava, and the Gabcikovo dam was calculated at a coarse resolution scale, for the seven reaches of the Joint Danube Survey JDS, using flow stations from the GRDC network. Figure 6.16 below shows that whereas the steeper gradients provide greater Cross-sectional Stream Power of 8000 Wm^{-1} in reach 3-4, at Passau, declining ~3800 Wm^{-1} by Bratislava, and to a low of ~920 Wm^{-1} by Budapest, thereafter the effect of the increasing flow rate, despite fairly constant gradients, increases the Cross-sectional Stream Power to over 2000 Wm^{-1} and to ~ 2400 Wm^{-1} by Ruse, JDS reach 8 at about km 400, declining thereafter due to just 75 Wm^{-1}, as the slope flattens out to the mouth.

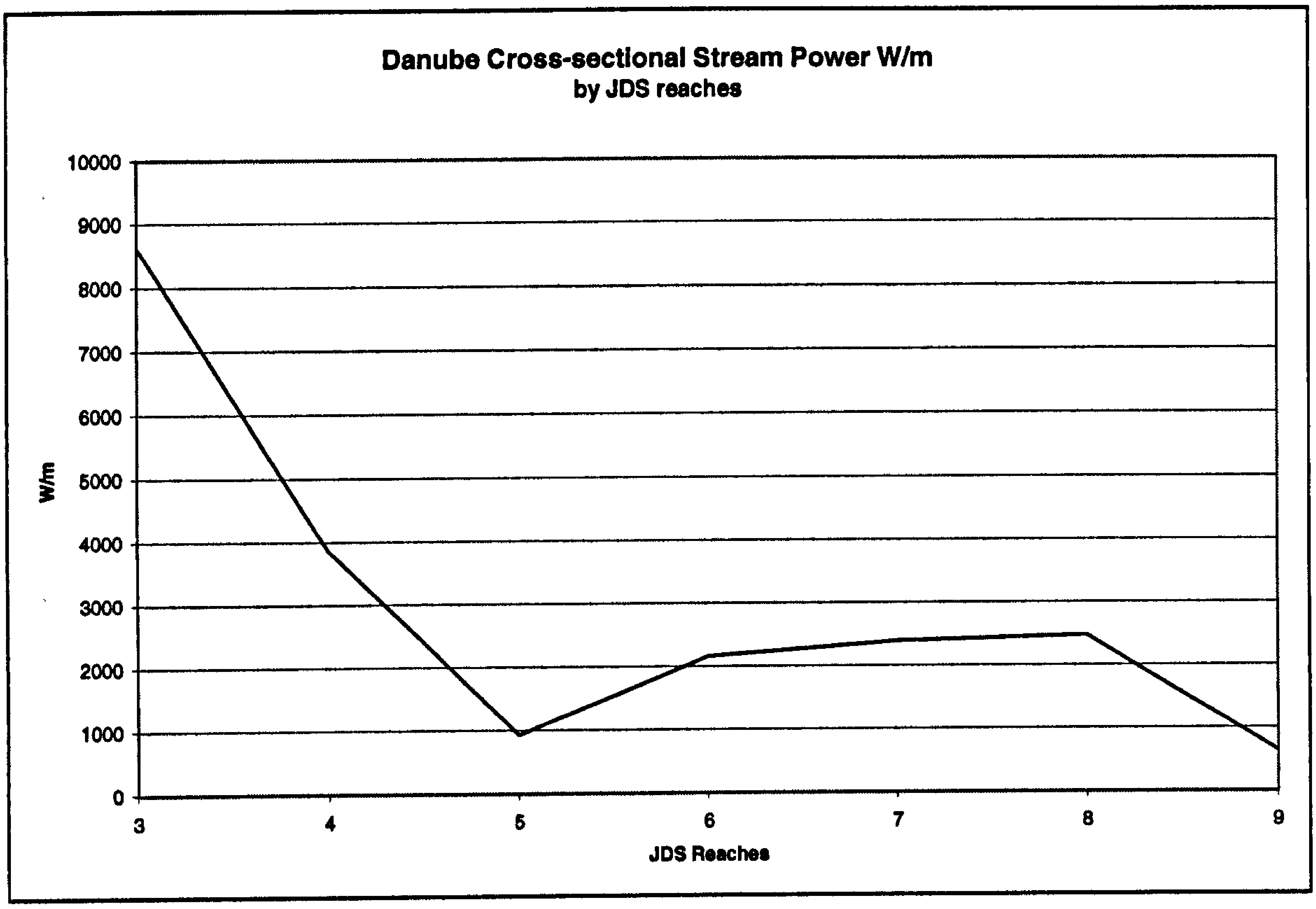


Fig 6.16 Cross-sectional Stream Power watts per m by JDS reaches below Bratislava

Another version of the Cross-sectional Stream Power per metre of river is shown per river km in figure 6.17 below.

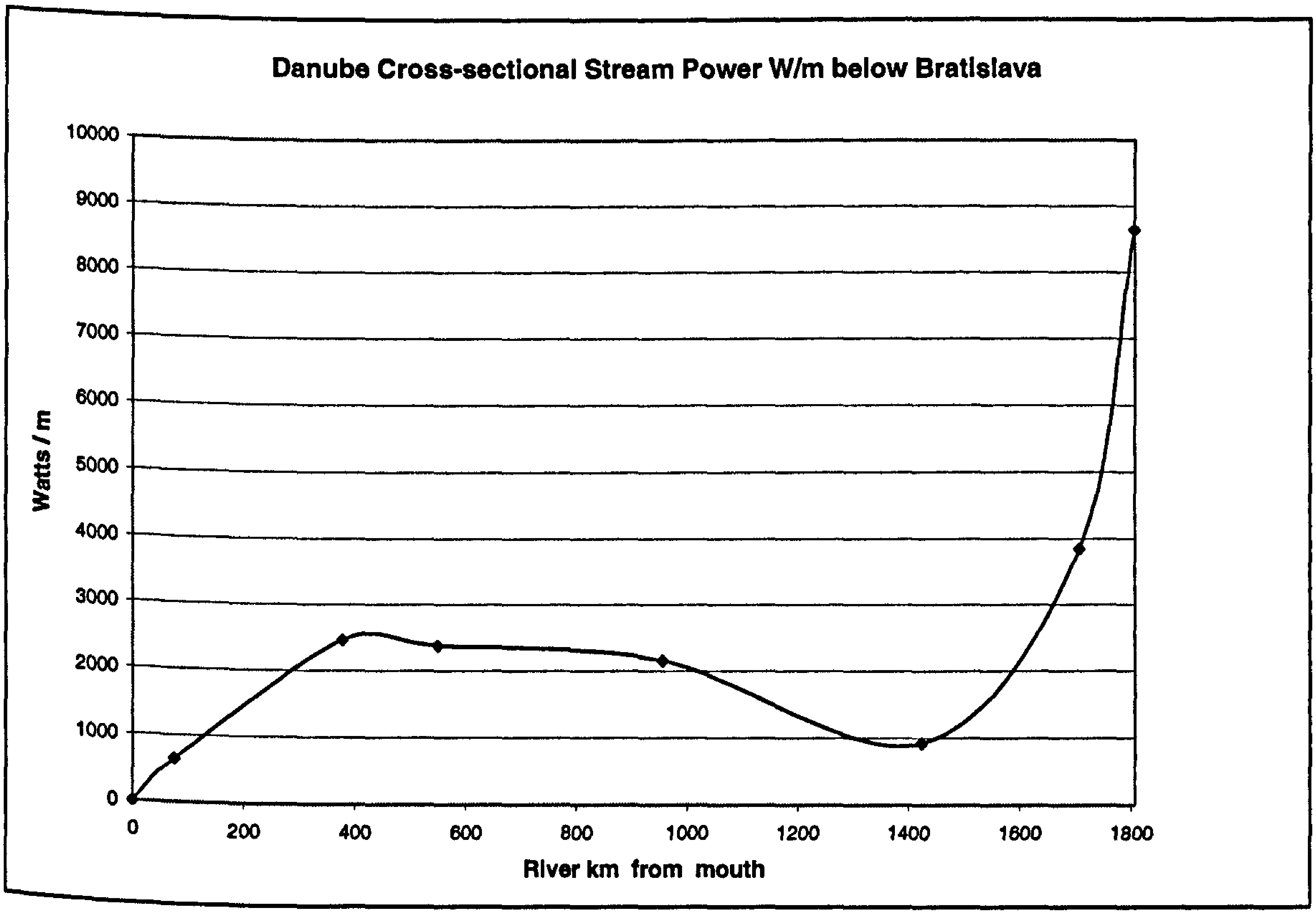


Fig 6.17. Danube Cross-sectional Stream Power per m, by km from river mouth. (Measuring stations: Ceatal Izmail, Silistra, Svistov, Iron Gates, Mohacs, Nagymaros, Bratislava respectively}

6.2.1 Total Stream Power for the four sample rivers Nile, Danube, Columbia and Colorado.

River Gradient Profiles

The longitudinal river gradient profiles for four of the selection of rivers was plotted using data from a variety of sources, (GRDC 2008, Rzoska 1978, Mamdouh 1985, Google Earth 2008 elevation), so that the Stream Power before and after dam construction could be modelled. The mean gradient of the Nile between Khartoum and Cairo, is 0.0126 %, as the Nile falls from 375m to 12m, in 2873 km. However, this hides variations in gradient of

0.098 % at the Cataracts IV, to 0.0042% below the Cataracts III. The zero gradient of Lake Nasser, the Aswan Dam reservoir can be observed, from figure 6.18 below. This reservoir has inundated the Cataracts I and II and therefore masks further gradient variations. The decline in gradient after Cairo, which comprises the delta region, can be discerned.

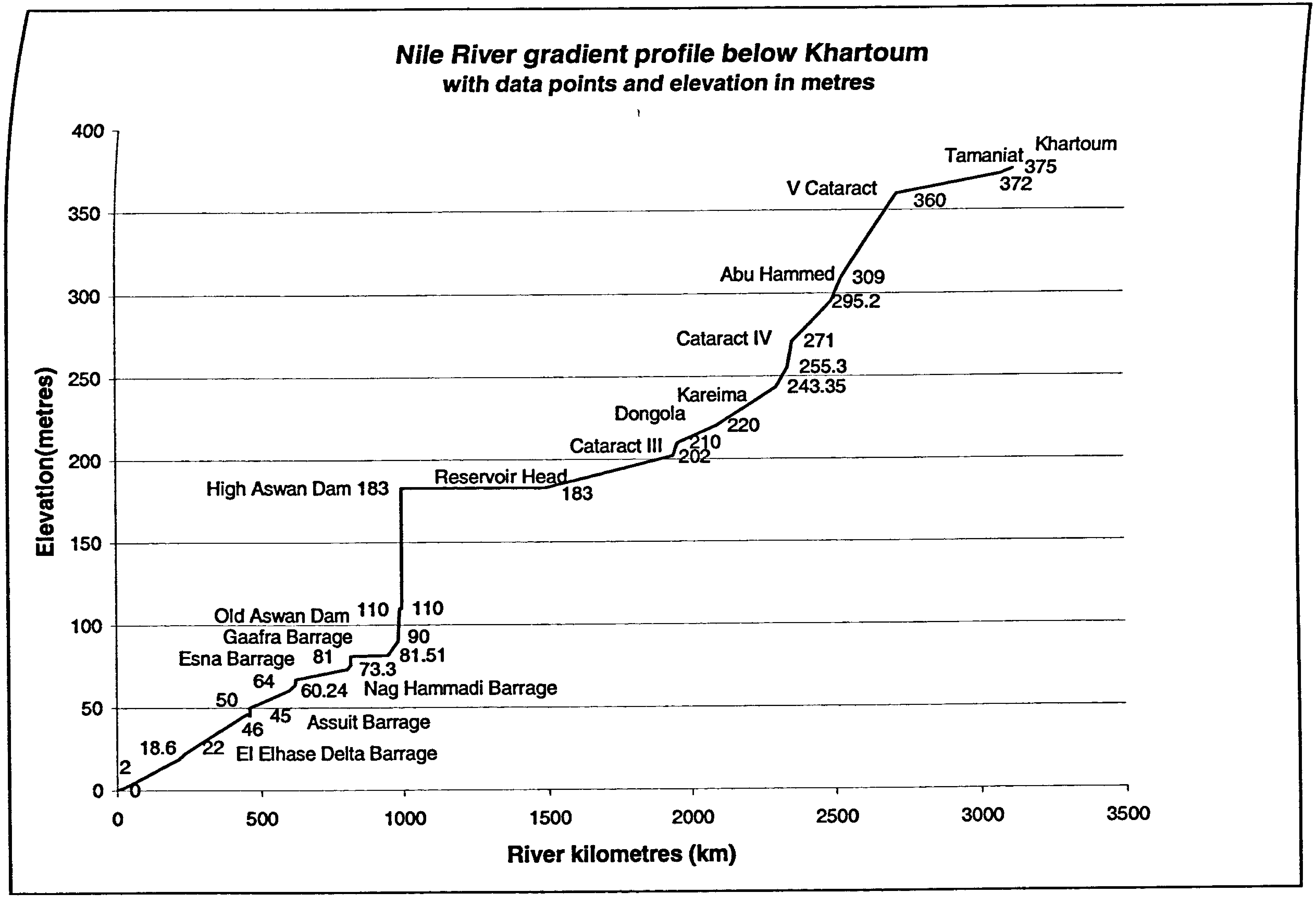


Fig 6.18 River Nile surface gradient profile below Khartoum.

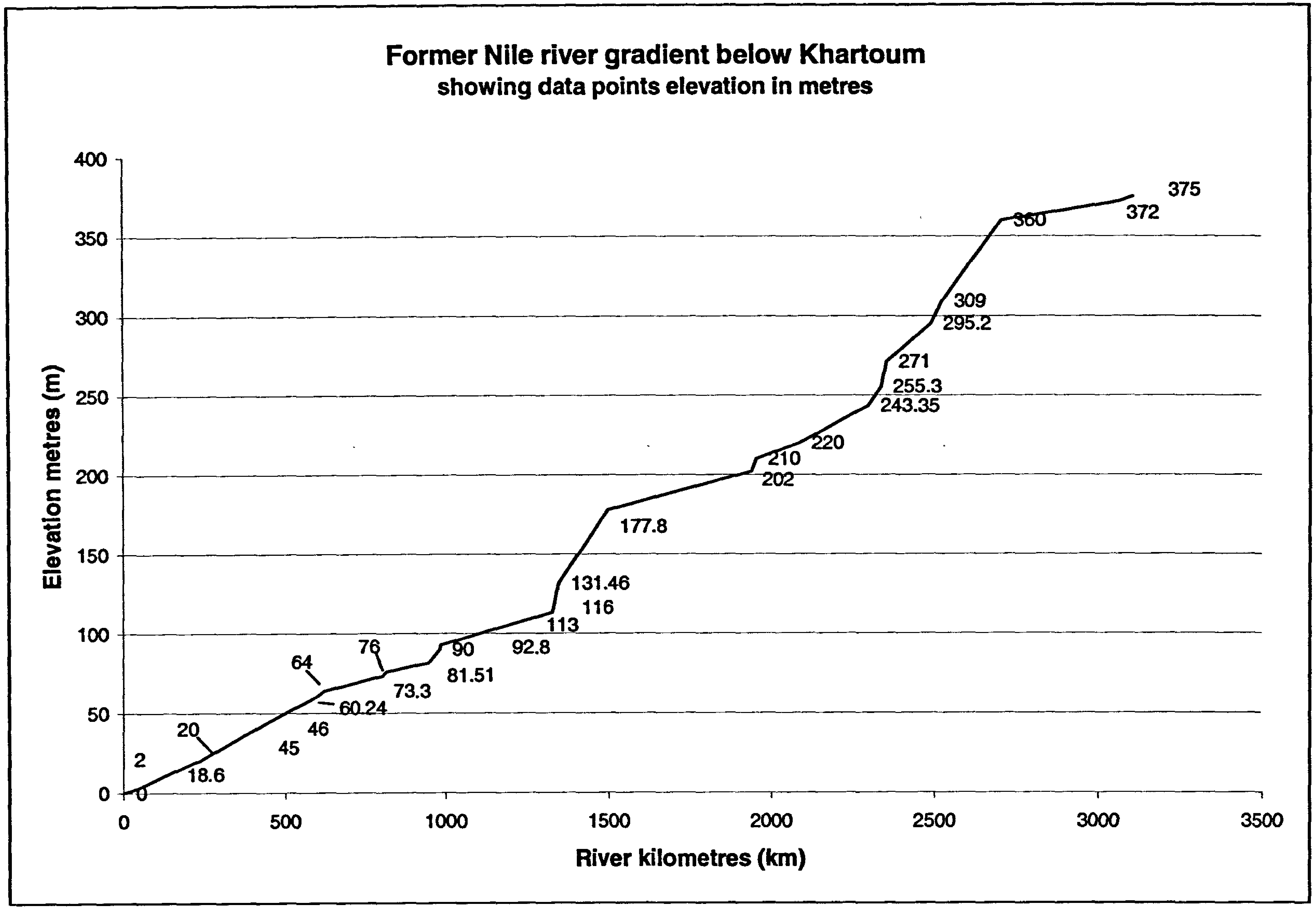


Fig 6.19 Former Nile River surface gradient profile

Former Nile River gradient profile

The approximate former river gradient was plotted for the rivers, before construction of the Aswan Dam and the High Aswan Dam as well as the impoundments lower down the river, for the section below Khartoum and is shown in figure 6.19 above. This shows the change in the profile, in broad terms, though no detailed profile data for the series of rapids now inundated by Lake Nubia and Lake Nasser was found. The same exercise was carried out for the Danube, Columbia, and Colorado Rivers.

Danube gradient profile

The mean gradient of the Danube below Bratislava is 0.0073% as the Danube falls from 139m to sea level. However, the gradient profile displays a gradual lessening in slope to the delta region. The two hydro electric scheme dams below Bratislava are both in relatively steeper reaches. The Gabcikovo scheme is at the end of the steeper Austrian / Slovakian section with a gradient of 0.043%, where the river flattens out in the Hungarian plain section to a gradient of 0.017-0.007% and then to 0.004% (JDS 2005). The Iron Gates section is steeper where the river cuts through the Carpathian Mountains in a narrow gorge with a gradient of 0.027%, as shown in figure 6.20 below.

Former Danube river gradient

The former Danube river gradient profile below Vienna, see figure 6.21 below, shows that this river gradient profile has been altered less by the two major HEP schemes constructed, the Iron Gates in 1970 and the Gabcikovo in 1992, than the other rivers in the sample. This is due to the "run of river" nature of these two schemes, with relatively small reservoir volumes and lengths, as well as the fact that the head heights in each case, 26m and 7 m for Iron Gates I & II, and 21 m for the Gabcikovo scheme are relatively modest compared to much of the sample.

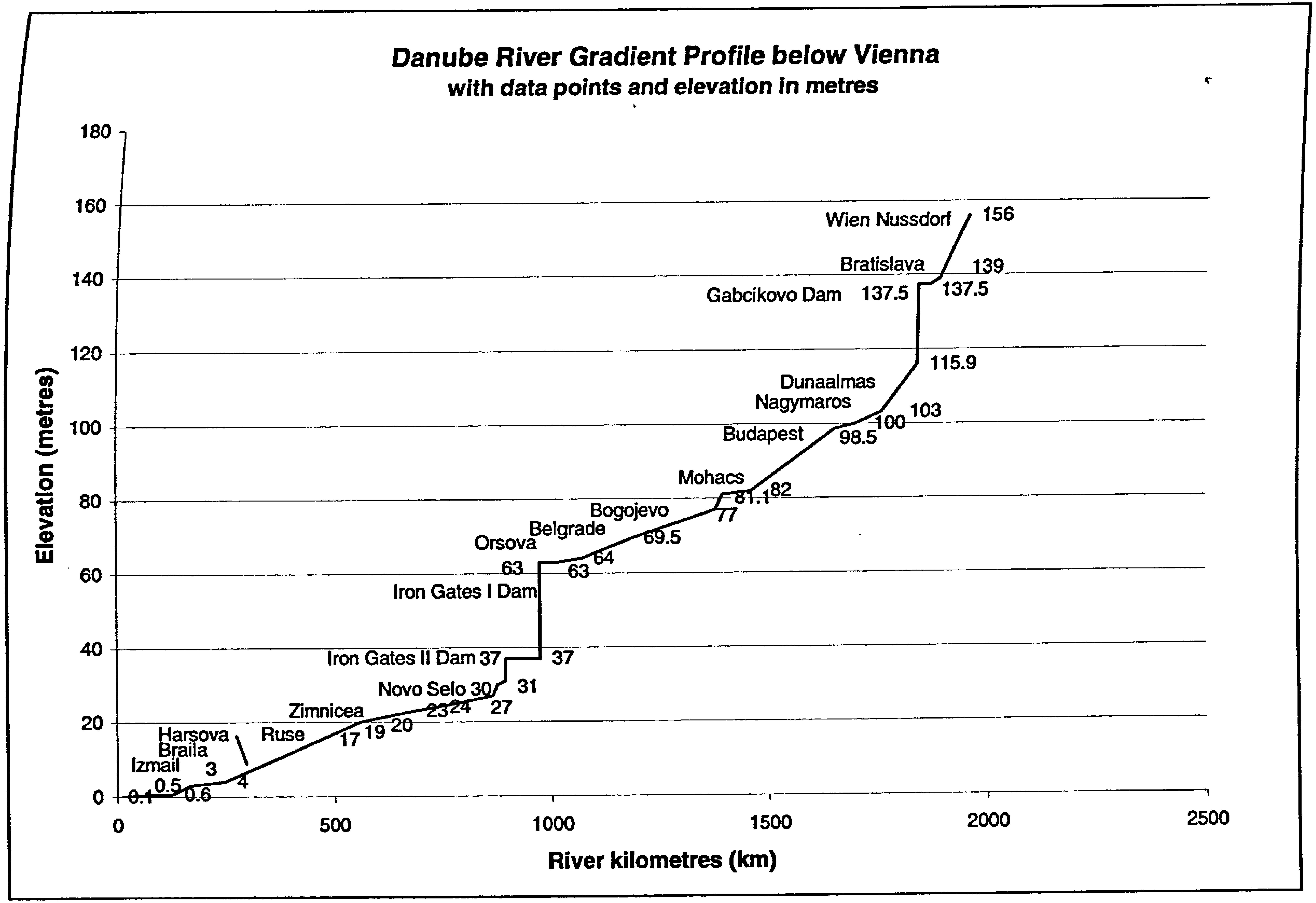


Figure 6.20. Danube longitudinal surface river gradient profile below Vienna

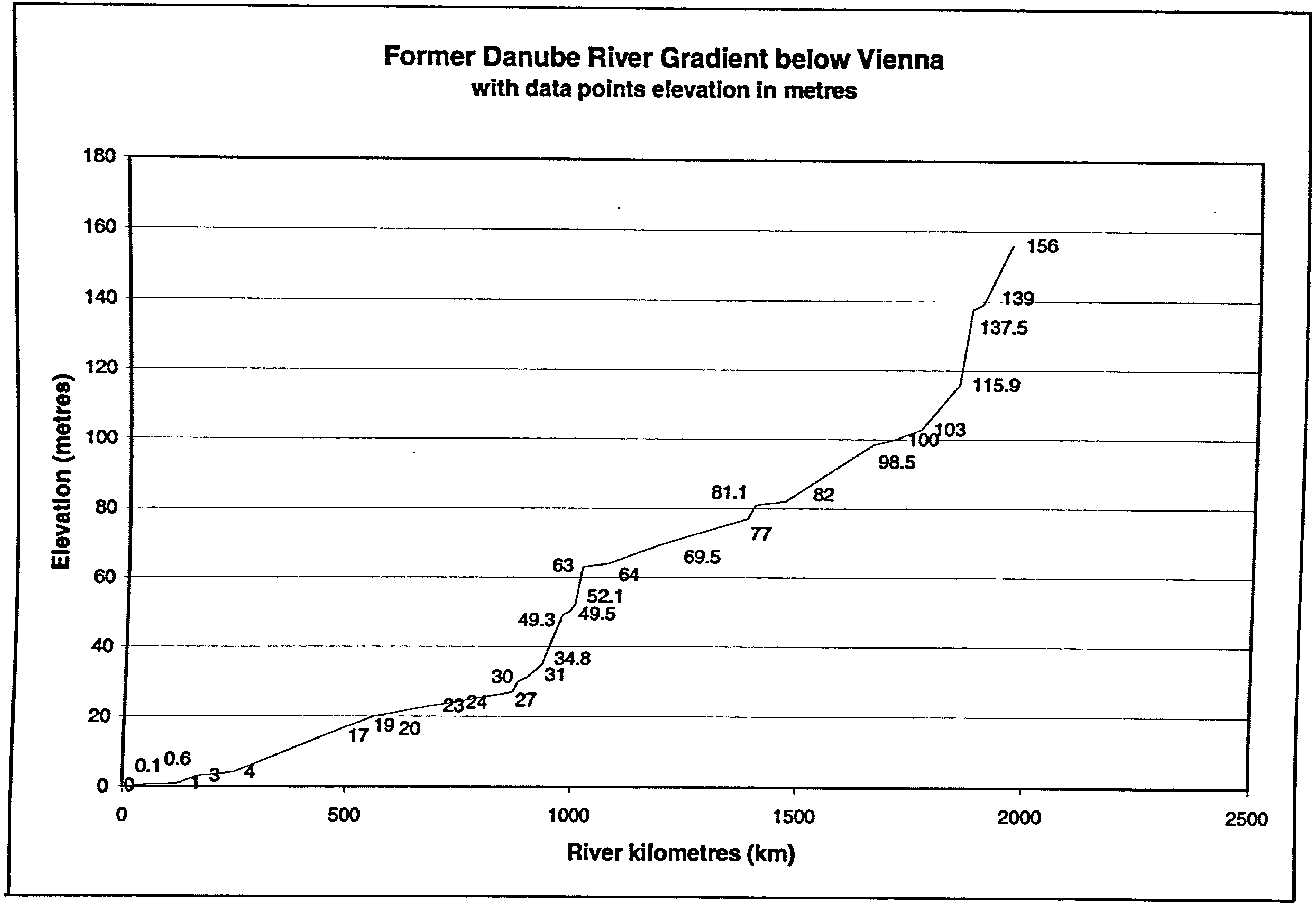


Figure 6.21 Former River Danube surface gradient profile below Vienna

River Columbia gradient profile from McNary reservoir.

The first 1200 kilometres of the Columbia River can be seen, from figure 6.22, below, to be almost entirely converted into a cascade of dams and reservoirs. The average gradient from the upstream end of the McNary Dam to the sea is 0.019% as the river falls from 104m to sea level in 540km. However, the average gradient between the top of the McNary reservoir and just downstream of the Bonneville dam is 0.032%, while the gradient of the last 233.7km to sea level is just 0.0021%. Some sections are steeper, for example from the upper end of the Bonneville reservoir to the upper end of the Dalles reservoir, at 0.066%. The reservoirs have inundated rapids sections at several points.

Former River Columbia Gradient Profile

It can be seen from the gradient profiles above and below in figure 6.23 that the Columbia River has been changed very considerably by the construction of a series of eleven dams over the ~1200 km course through the USA, to the extent that only two reaches, the Hanford reach and the last tidal reach to the sea, are in their natural state. The size of the large HEP scheme, the Grand Coulee, at the upper section, with its 105m dam head height and 233 km long Rufus Wood Lake reservoir, with its 1.179 $\times 10^{10}$ m cubic capacity is striking.

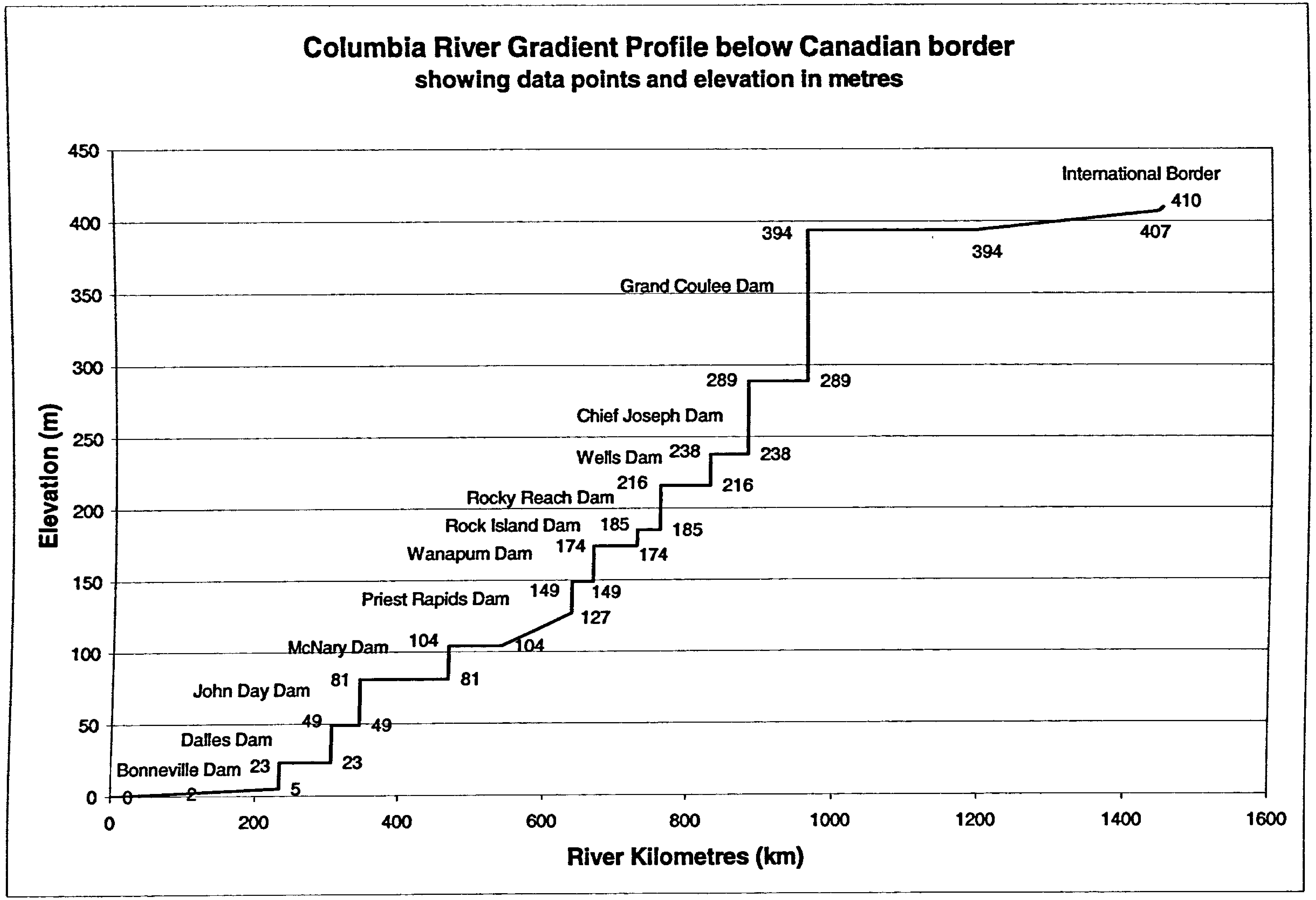


Figure 6.22 Columbia River longitudinal surface gradient profile below Canadian border.

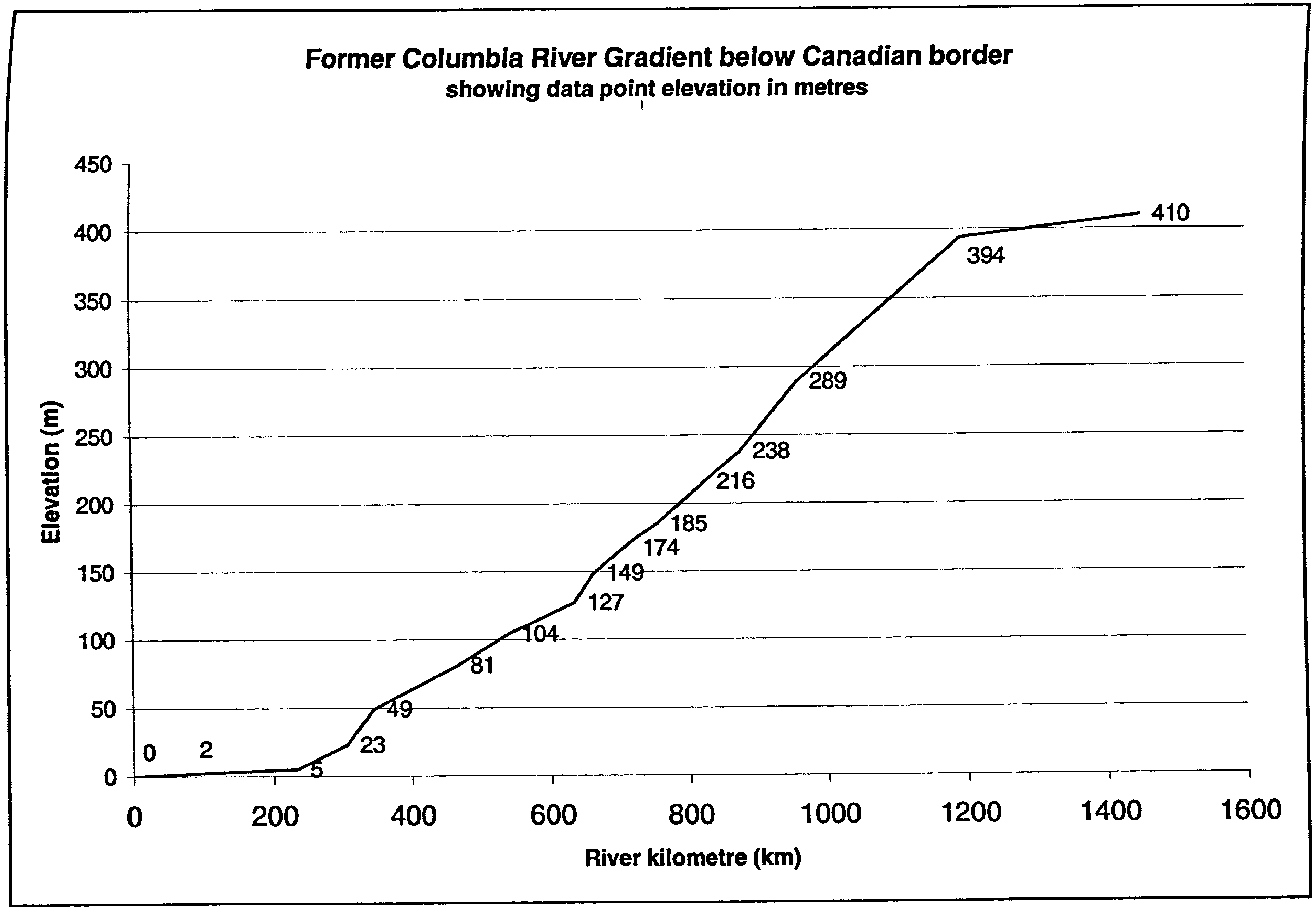


Figure 6.23 Former Columbia River surface gradient profile below the Canadian border

River Colorado gradient profile.

The Colorado River gradient profile below Lake Powell is shown below in figure 6.24. The average gradient in this section is 0.077%. However, the river gradient shows four or five different sections, the first 545 km from the Mexican border has an average gradient of 0.032 %, the next 423 km is steeper with an average gradient of 0.127%, following which the next section of 41 km steepens to an average gradient of 0.22%. The next 98.4km has a gradient of 0.117%, and after this the 323 km to the upper end of Lake Powell at km 1431 (from the Mexican border) is less steep with an average gradient of 0.059%.

Although the Colorado River has two large HEP schemes, in this lower 1400 km section, the Glen Canyon scheme (built in 1964 with 155m head height) and the Hoover Dam (built 1933 and now with 158m head height), as well as three smaller dams, the Davis Dam, the Parker dam and the Headgate Rock dam, the gradient profile is less changed than that of the Columbia. Between the Glen Canyon Dam and the top of Lake Mohave, (the reservoir for the Hoover scheme) there is 461 km of natural river gradient, flowing through the Grand Canyon, with series of rapids.

Below the Headgate Rock dam at kilometre 286 (from the US border), the gradient profile is natural. For the pre existing gradient profile for the river in this section see figure 6.25 below.

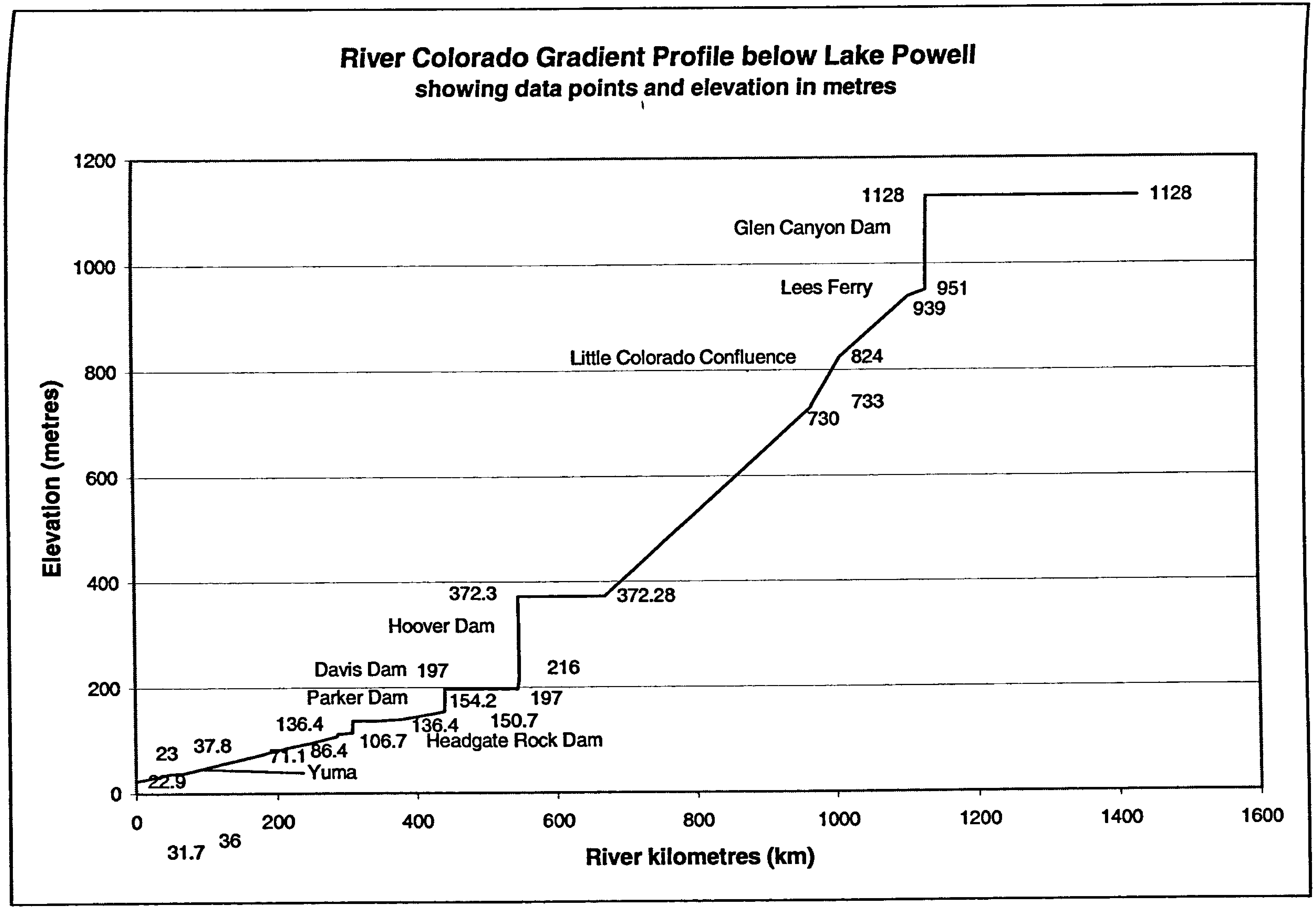


Figure 6.24 River Colorado surface gradient profile below Lake Powell.

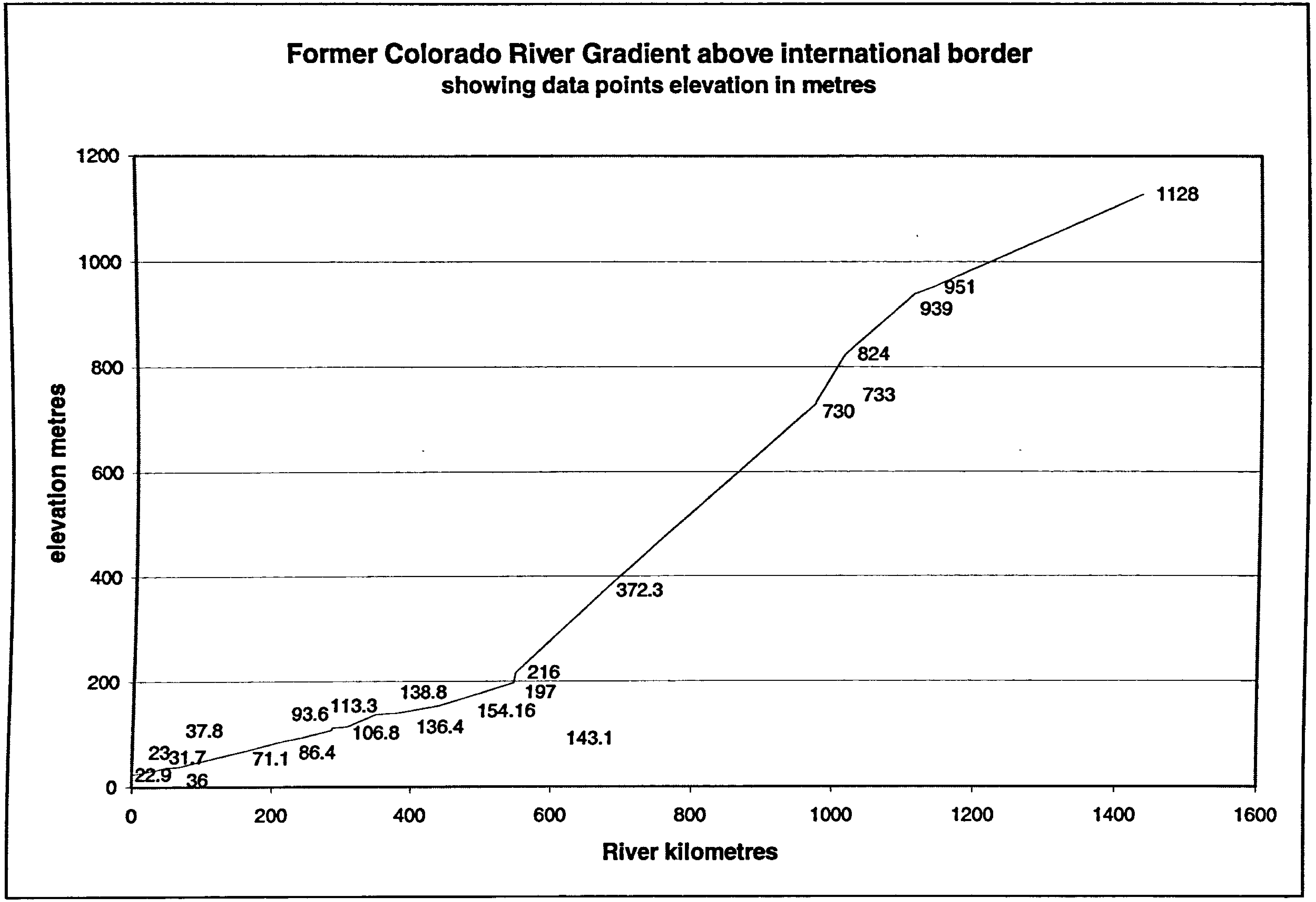


Figure 6.25 Approximate former River Colorado surface gradient profile.

6. 2.2 The Effect of the Dams & Reservoirs on Flow Rates downstream

It can be assumed that the effect of the reservoirs downstream of the dam would be to attenuate the variations between peak and minimum flows. Reduction of the peak flood flows will have great significance for the river's transport of sediment, since this is when most sediment transport occurs. The degree of attenuation will depend on the volume of the reservoir in relation to the river flow rate and on how the reservoir releases are managed, whether for electricity generation, water supply, navigation or flood control.

The attenuation of the variation between peak and minimum flows can be observed in figure 6.26 below, showing the graph of the mean monthly flow rates on the River Nile at the old Aswan dam, just below the High Aswan Dam, pre 1963 and post 1963. The flood flows from August to October, peaking in September have been reduced from an average of ~8700 m^3/s to less than 2000 m^3/s, as can be seen in figure 6.27 below. The mean peak flow has now been moved to July. This is of course to be expected, since the purpose of the High Aswan Dam, was to store up to about two years of river flow and to be able to provide a constant water supply downstream for irrigation, domestic and industrial water and electricity generation. The High Aswan Dam has been successful in these respects.

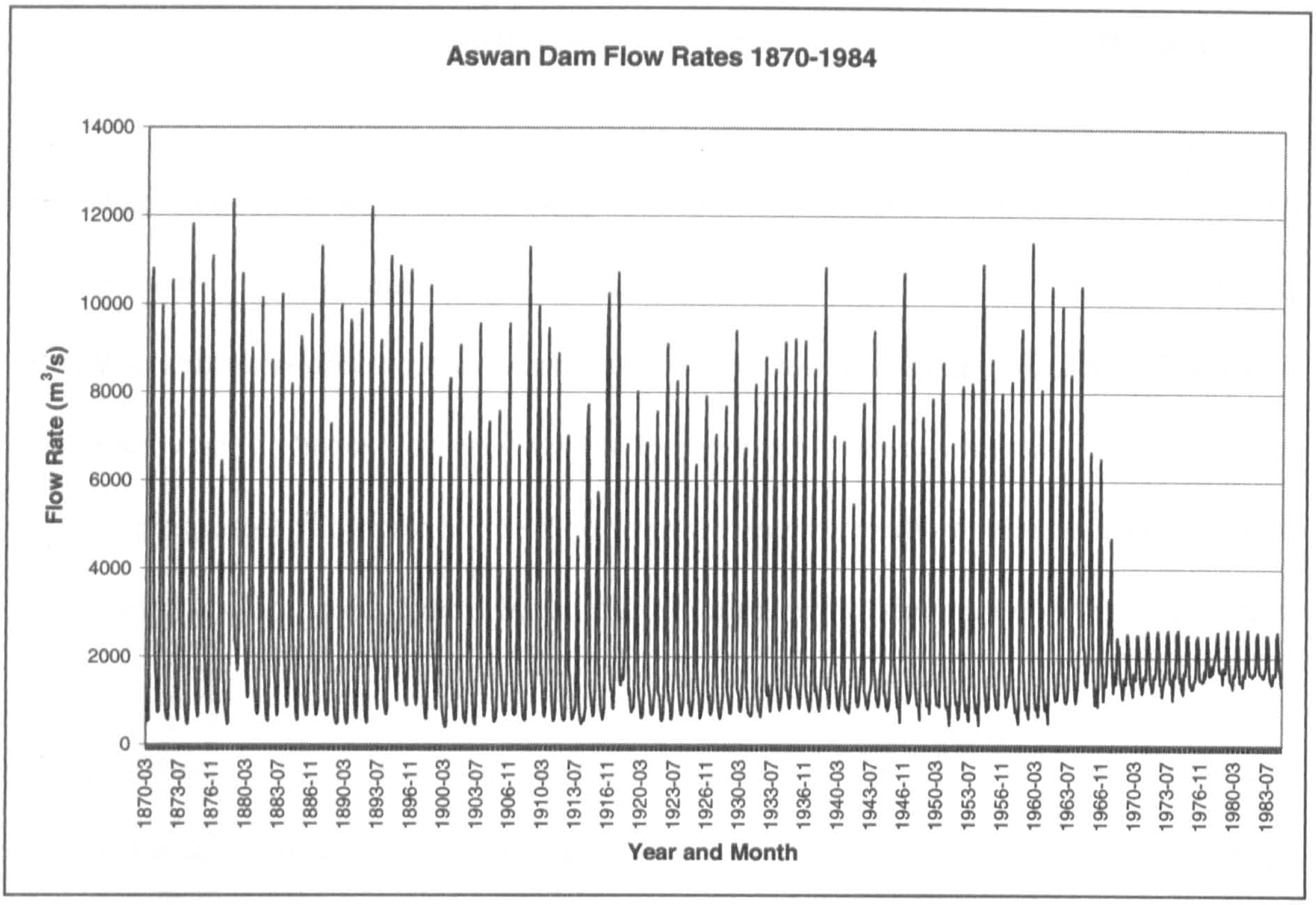


Figure 6.26 Aswan dam flow rates, 1870-1984, pre and post the Aswan High Dam. (Flow Data from GRDC 2007/8)

However, the loss of the flood flows, and the energy they represent, means that little sediment ~2% is transported below the High Aswan Dam (Marndouh 1985, p459).

6.2.3 The loss of power through attenuation of the flood flows

Since the instantaneous power of the river ultimately determines the extent of sediment 'pick up' and transport (Bagnold 1966), the difference in Total Stream Power in the peak flow period before construction of the dam and after can be estimated as a measure of the overall loss of Stream Power. The flow rates at Aswan, just below the Old Aswan Dam and a little downstream from the High Aswan Dam before the filling of the reservoir from 1967 to 1970 show how great the change is; see figure 6.27 below.

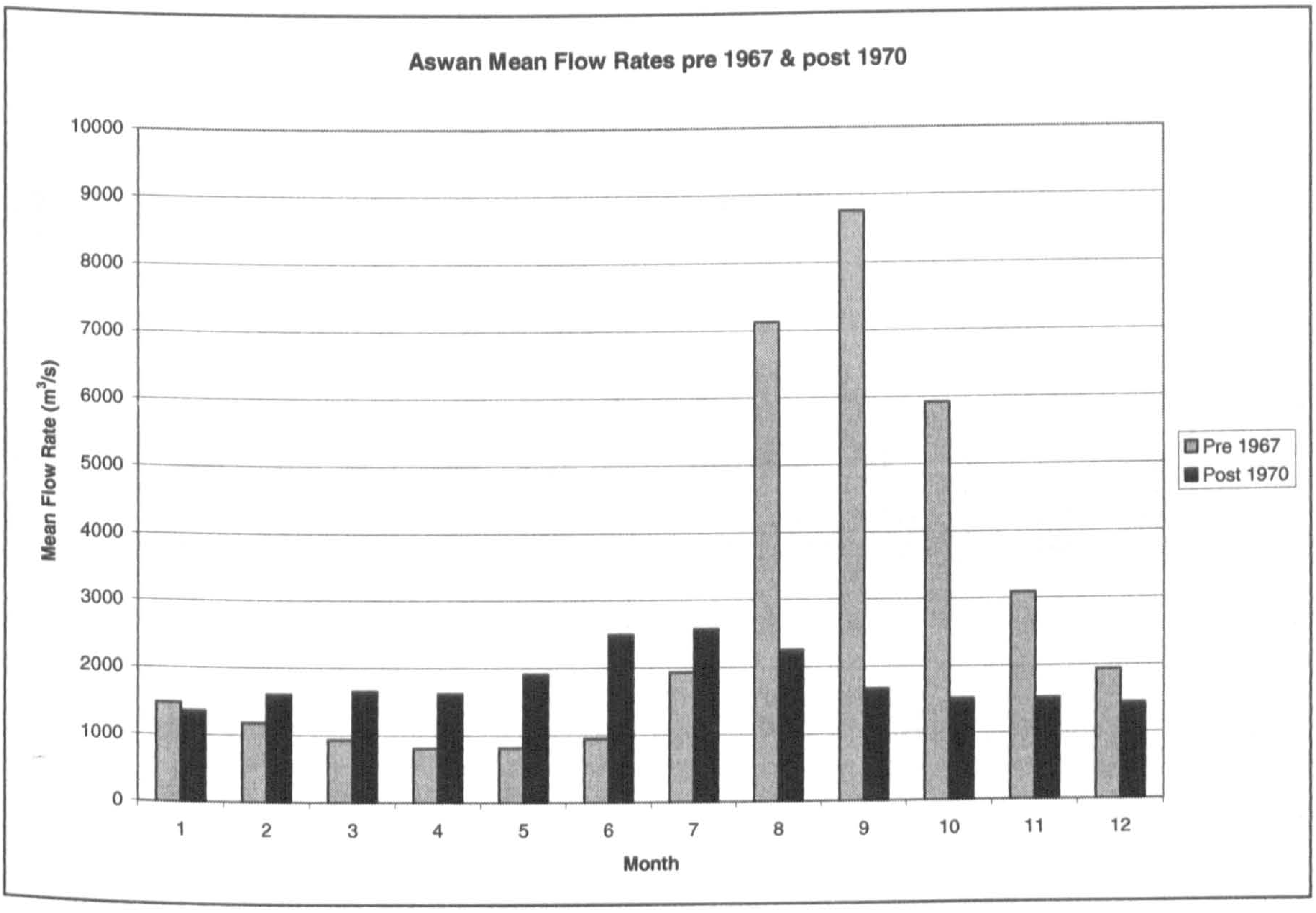


Fig 6.27 Aswan mean monthly flow rates pre 1967 and post 1970.

The peak mean monthly flow of 8763 m^3s^{-1} in September, pre filling of the reservoir from 1967, has been reduced to a peak mean monthly flow of 2573 m^3s^{-1} in July, a reduction of the peak flow by over 70%. The former minimum mean monthly flow of 812 m^3s^{-1} in April, pre 1967, has increased to a new minimum mean monthly flow of 1365 m^3s^{-1} in January. A maximum September mean flow of 12345 m^3s^{-1} for the period 1871 to 1967, has been reduced to 2554 m^3s^{-1} in June for the period 1970-1984. The hydrograph for the flow station has changed markedly as a result of the flow regulation. This change can be represented in Total Stream Power, for the reach, i.e. in kilowatts.

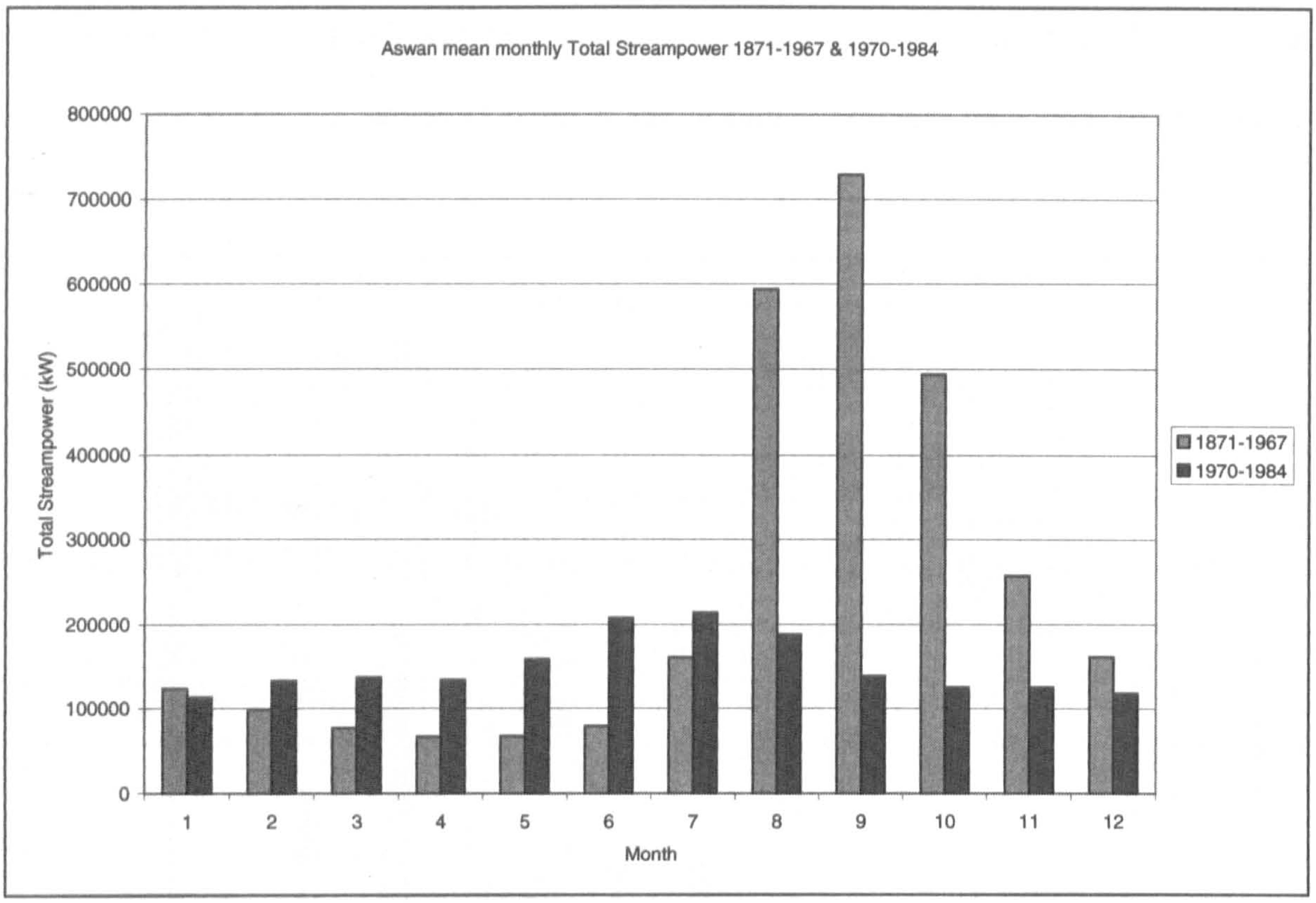


Figure 6.28. Aswan mean monthly Total Stream Power1871-1967 and 1970-1984.

It can be seen from figure 6.28 above that the Total Stream Power for the 35.7 km river reach Aswan to Gaafra has been reduced for the peak flow months of August to October and increased for the minimum flow months, in concert with the mean flow rate changes. From a peak value of 730000 kW in September in the period 1871-1967, the Total Stream Power peak is 214000 kW in July for the period 1970-1984, since the dam construction. This is just 29% of the previous peak Total Stream Power, a drop of 71%.
This diminution of Total Stream Power is that for the reach *below* Aswan of 35.7 km, with a mean gradient of 0.0237%, and is distinct from the TSP lost to the High Aswan Dam and Old Aswan dam over the reservoir reach.

Data for the pre dam period for points further down the river was not available, only post 1973, so it was not possible to estimate the Total Stream Power reduction for all the reaches below Aswan. However, the flow regime in figure 6.27 above could be expected to be reflected at points downstream, to the delta and sea mouth. This loss of TSP available for the picking up and transport of sediment is evident.

Danube mean flow rates post large dam construction.

A certain amount of attenuation of the peak and minimum flows can be discerned on the two Danube HEP schemes studied here post 1970, below the Iron Gates scheme and below the Gabcikovo scheme post 1991. See the graphs below in figures 6.29 and 6.30 of the mean monthly flow rates at Zimnicea measuring station some 336km below the Lower Iron Gates dam, and at Dunaalmas station 83 km below the Gabcikovo HEP scheme.

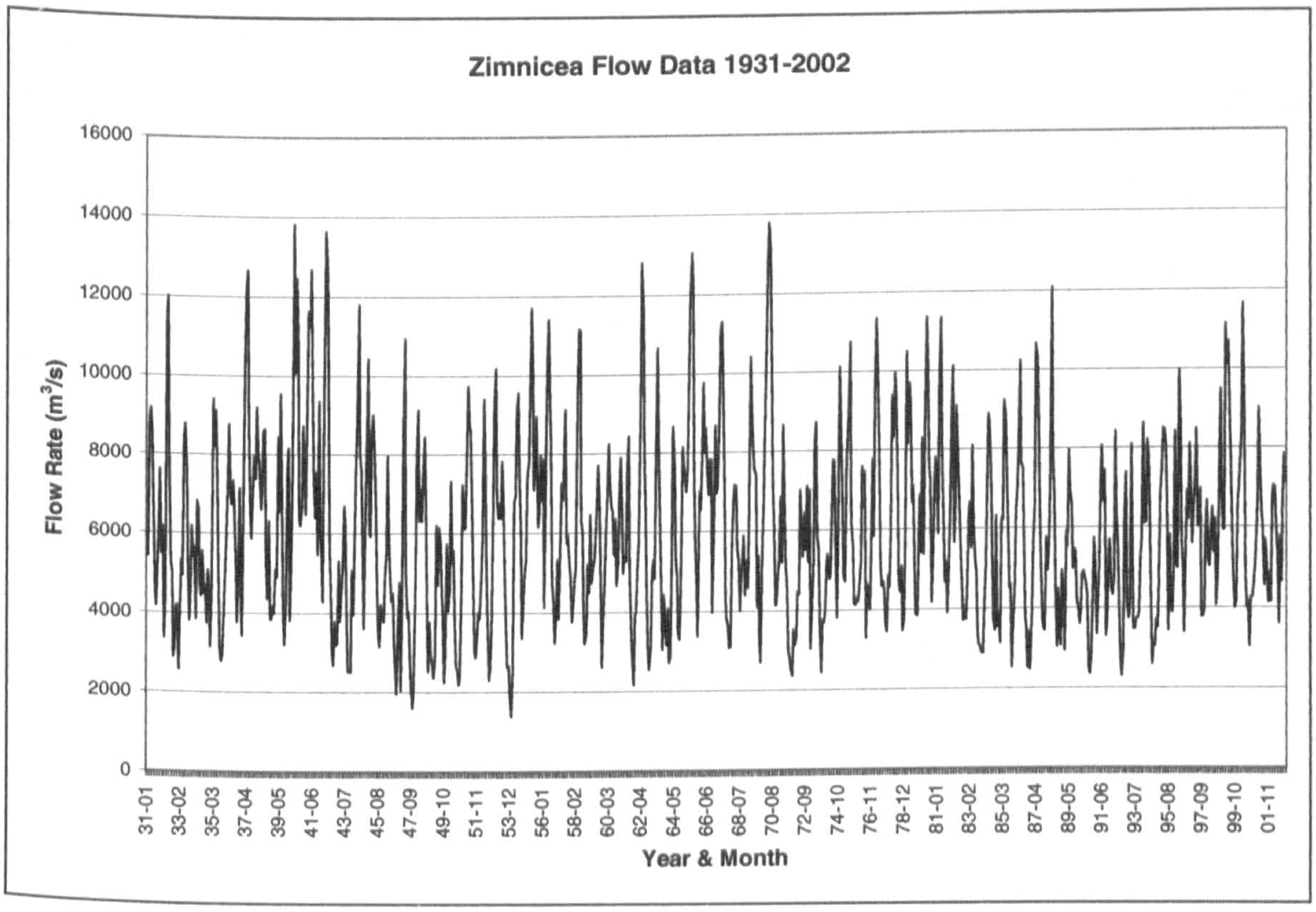


Figure 6.29. Zimnicea Flow Rates River Danube 1931-2002, 336 km below the Iron Gates dam.

However, as can be seen the effect on flow rates is slight, reflected in a diminution of maximum rates of flow from 14000 m^3/s to ~12000 m^3/s, and with the frequency of such maxima reduced. This effect can be seen in the reduction in standard deviation of flow rates pre 1970 and post year 1970, in the peak months of April and May, the peak flow months, from 2554 m^3/s to 1988 m^3/s (in April), and from 2594 to 1486 m^3/s (in May). The significance of this can be estimated in terms of reduction in Stream Power. The reduction in Stream Power for the two peak months of April and May, after the dam construction, has been estimated for the reaches between the flow measuring stations of Novo Selo, 21km below the Lower Iron Gates Dam and for Lom (157.6 km below the Lower Iron Gates Dam) and then for the Lom - Jiul reach, on the Danube. For the 128.5 km Novo Selo to Lom reach, the reduction in Total Stream Power for the peak months of April was from 24200 kW to 227000 kW or 6.9 % and for May from 230000 kW to 206000 kW or 10.4%. Total Stream Power for the 51 km reach from Lom to Jiul has been calculated as 81100 kW for April before dam construction, and 76100 kW after dam construction, a reduction of 6.14%. For May a reduction from 76000 kW to 69800 kW equates to a reduction of 8.14%. The reduction in Stream Power is not great and unlikely to be significant given the variation in flow.

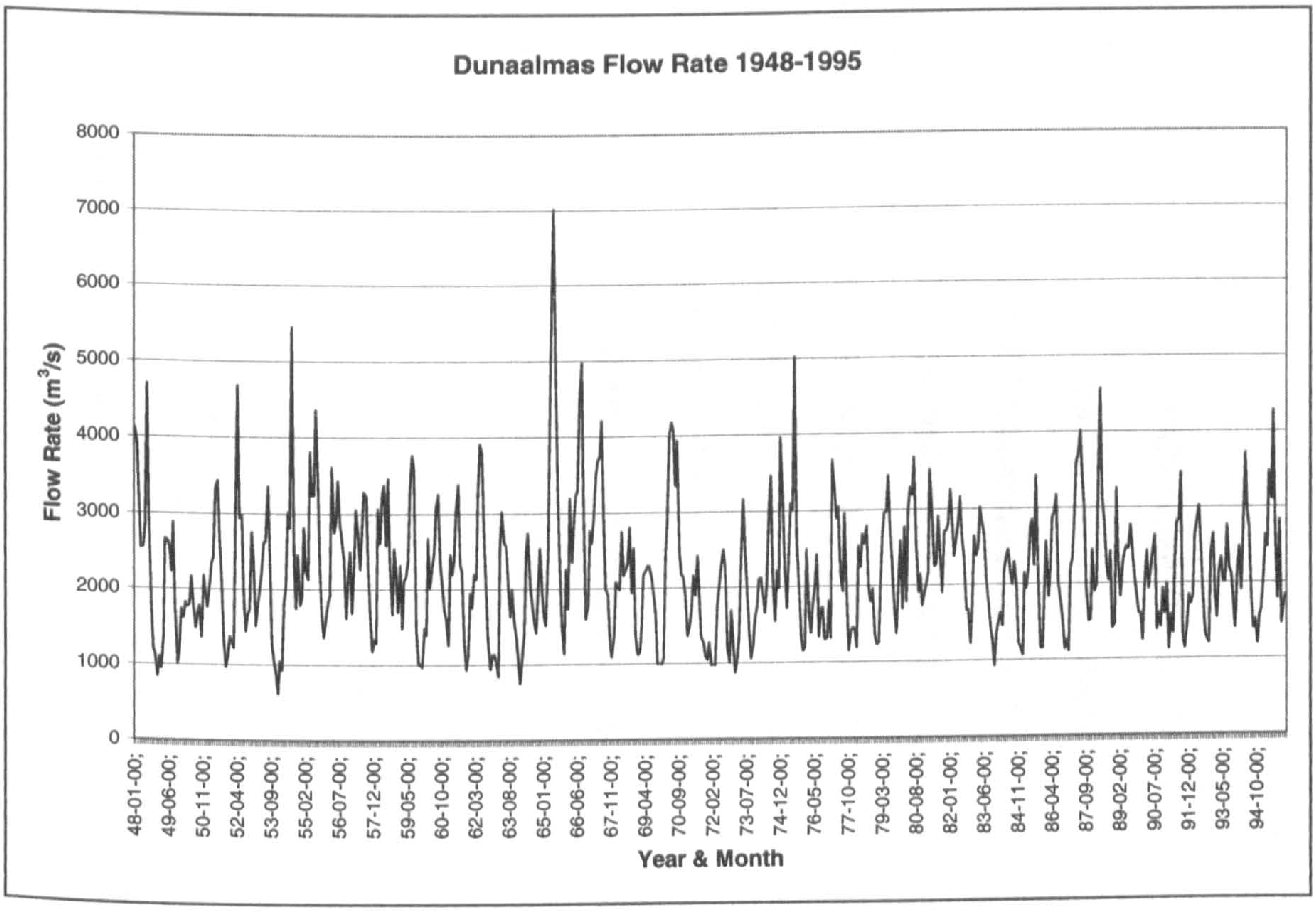


Figure 6.30 Dunaalmas Flow Rates 1948-1995 River Danube 83 km below the Gabcikovo HEP scheme.

At Dunaalmas, 83 km below the dam, attenuation of flood flows is also relatively slight, and the effect of the Gabcikovo dam, in 1992 is not apparent, see fig 6.30 above. However, the data set here runs only until 1995, some three years after the Gabcikovo scheme was operating, and therefore cannot be a representative sample. The gradual diminution of the peak flows between 1948 and 1995 may be the result of the cumulative damming of the river upstream, where numbers of dams have been constructed since 1960s (Schwarz 2008).

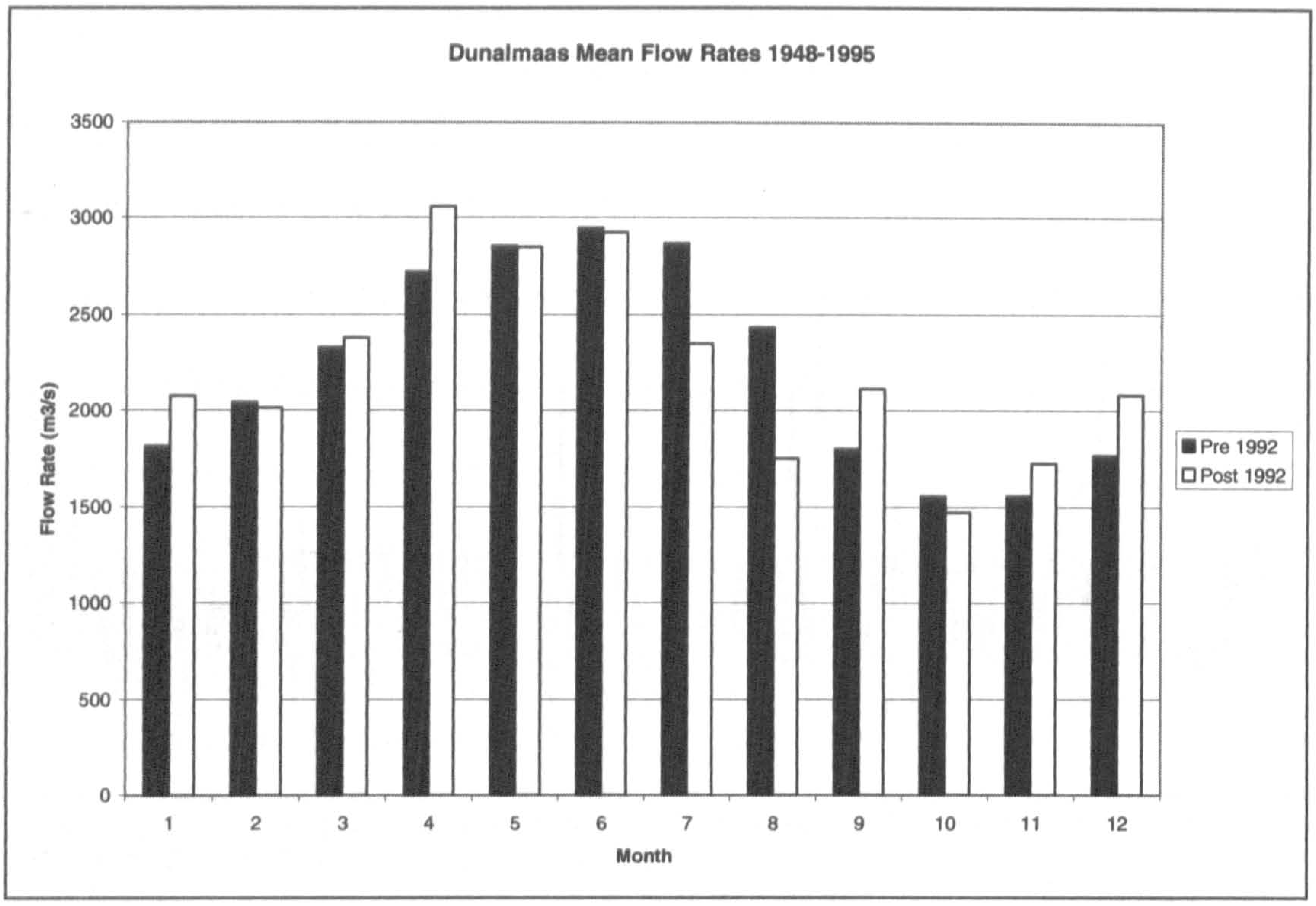


Figure 6.31. Dunaalmas mean monthly flow rates 1948-1995, pre 1992 and post 1992.

Little or no discernible effect can be seen from figure 6.31, in the mean monthly hydrograph flow rates for Dunaalmas 87 km below the Gabcikovo HEP scheme, allowing for the small amount of data available, just three years post dam completion.

River Columbia flow rate changes since dam construction.

The River Columbia has, as stated before, been extensively impounded by large dams in the upper and middle reaches, as have its tributaries, for example the Snake River. In particular the large Canadian Mica Dam of 1976 and the Grand Coulee dam of 1941 have attenuated the flood and low flows.

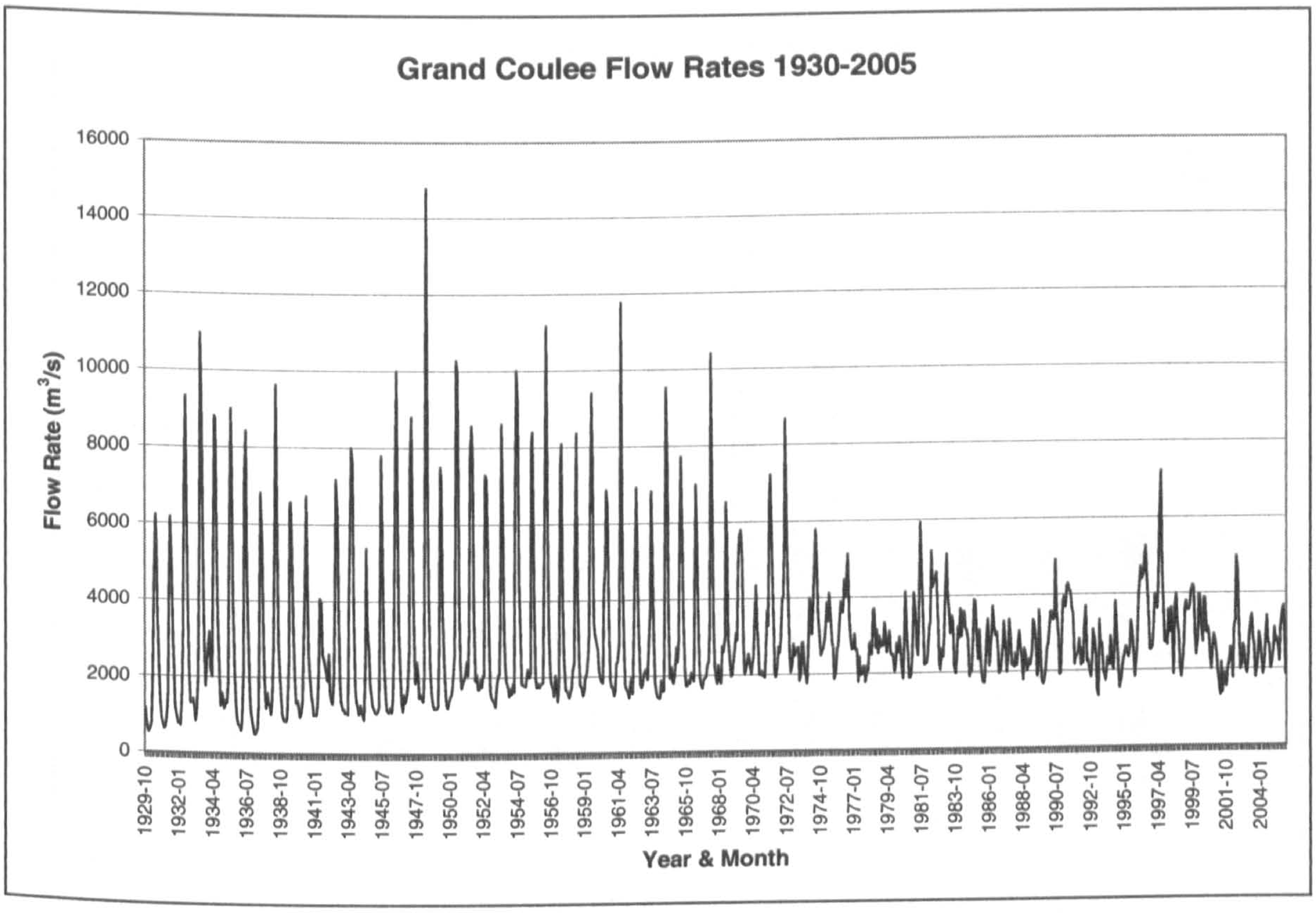


Figure 6.32 Grand Coulee flow rates 1930-2005. (GRDC data 2008).

The effect of the storage dams upstream of the Grand Coulee dam on the river Columbia, on the flow rates can be seen in figure 6.32 above, on the diminution of the variation in flow rates. This is especially marked post 1973, after the building of the Mica Dam in Canada, in 1973.

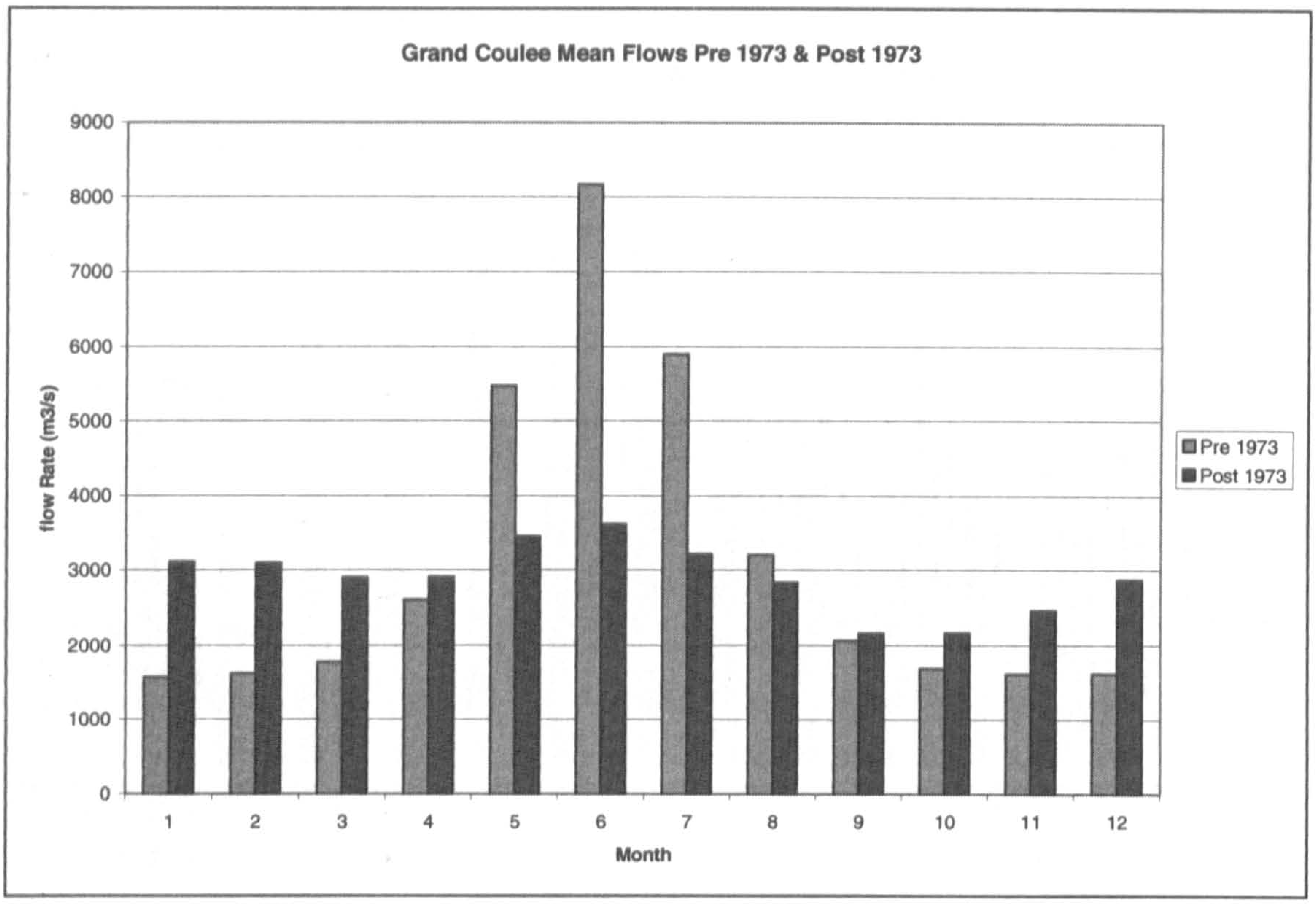


Figure 6.33 Monthly mean flow rates Grand Coulee, pre 1973 and post 1973. (GRDC data 2008)

The effect of the three Canadian storage dams on the Columbia river flow can be seen in figure 6.33 showing the flow rates pre 1973 and post 1973, from the monthly mean flow rates chart above of Grand Coulee HEP scheme. Prior to the Canadian storage dams, the flood flows were very pronounced from May to July exceeding 5000 $m^3 s^{-1}$, with a peak of over 8000 $m^3 s^{-1}$ in June itself, compared to the mean flow of 3100 $m^3 s^{-1}$ (GRDC data 2008). Subsequently there is only a minor peak in June and a second slight peak in January, formerly the lowest flow month.

This attenuation of the summer flood flow continues downstream throughout the river, and can be calculated in Total Stream Power terms to provide before and after dam Total Stream Power value changes.

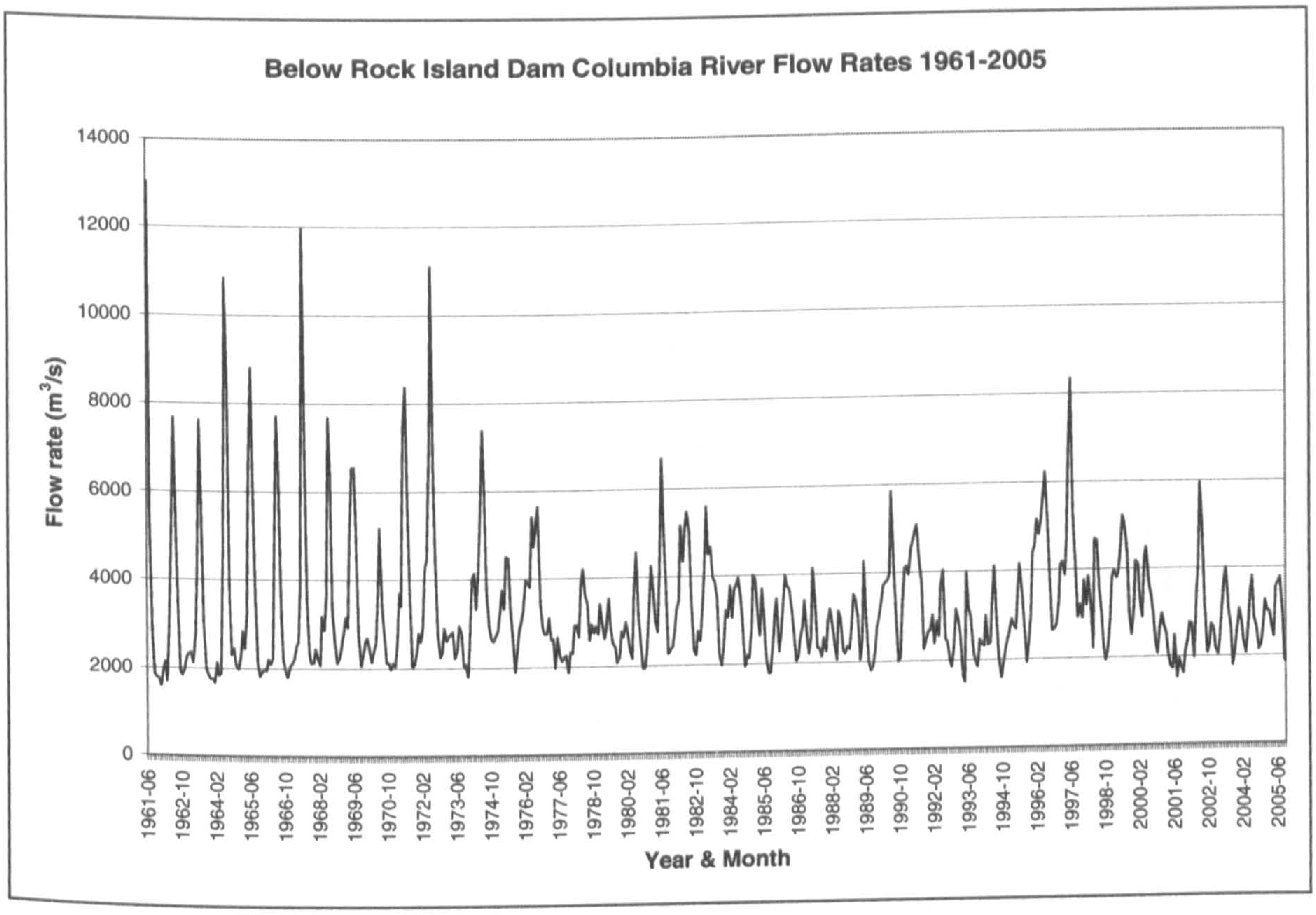


Figure 6.34 Flow rates for below Rock Island dam Columbia River 1961-2005 (GRDC 2008)

In figure 6.34 above, the diminution of flood flows after 1973, can be seen at the flow measuring station below Rock Island dam, 209km below Grand Coulee dam.

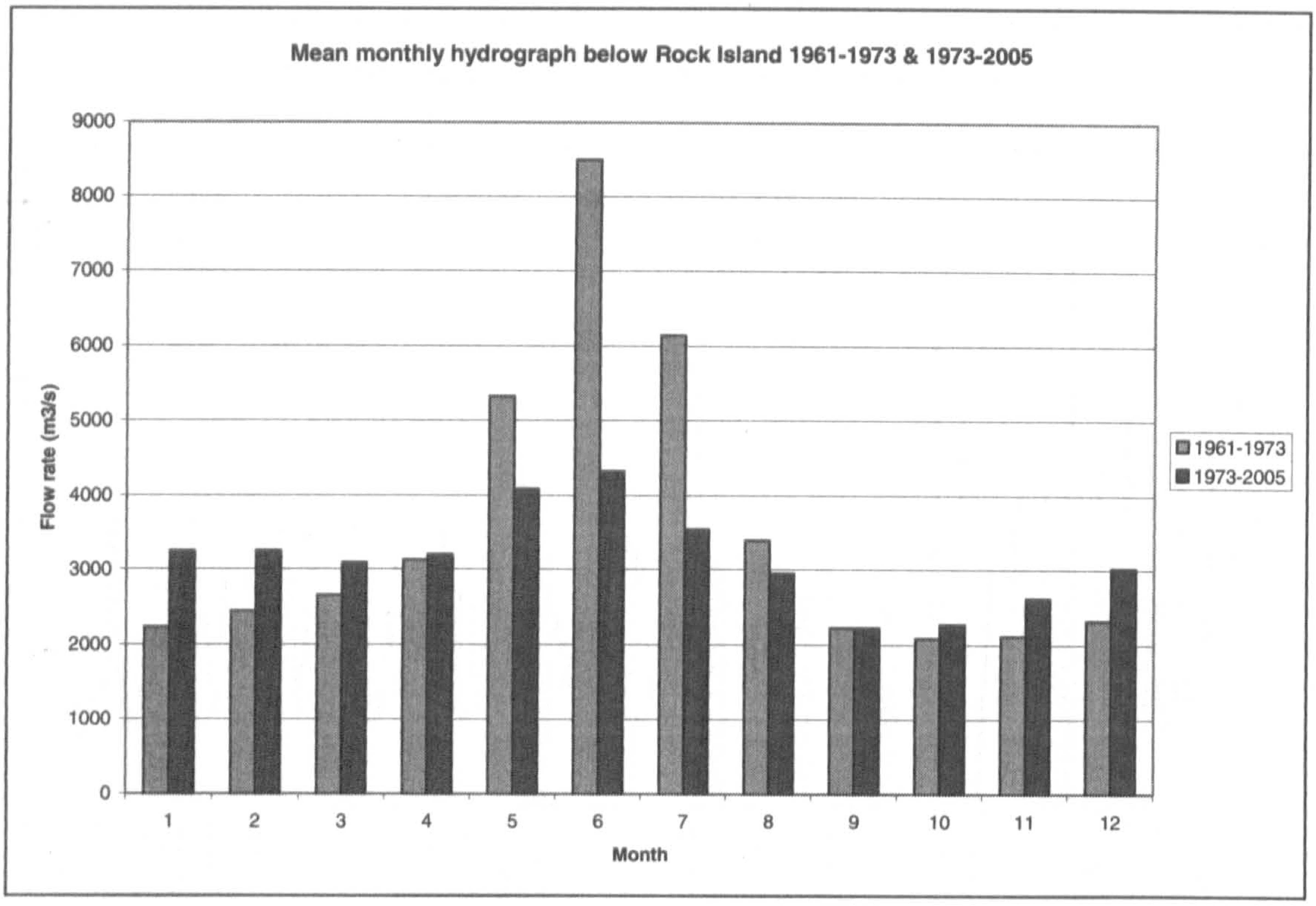


Figure 6.35 Mean monthly hydrograph below Rock Island 1961-1973 & 1973-2005. (GRDC 2008)

The peak flow rate has diminished by approximately half, and the minimum flows in October are slightly increased, as shown in figure 6.35. Further down the river 323 km below the Grand Coulee dam, the effects of the Mica dam impoundment can be observed. See below figure 6.36 for the Total Stream Power at the measuring station, Below Priest Rapids for the years 1917-1973, and then 1973 to 2006. The flood flow TSP has diminished by half in June from 2050000 kW to 1014000 kW, while the low flows have increased by one and half time from 368000 kW in January to 514000 kW in November, for the 95 km reach from below Priest Rapids to the upstream end of the McNary reservoir. The diminution in variation can be expressed as a reduction in maximum mean monthly flows from 16539 $m^3 s^{-1}$ in June between 1917 and 1973, to 9031 $m^3 s^{-1}$ between 1973 and

2006, and an increase in the minimum mean monthly flows of 607 $m^3 s^{-1}$ in January to 1621 $m^3 s^{-1}$ in April.

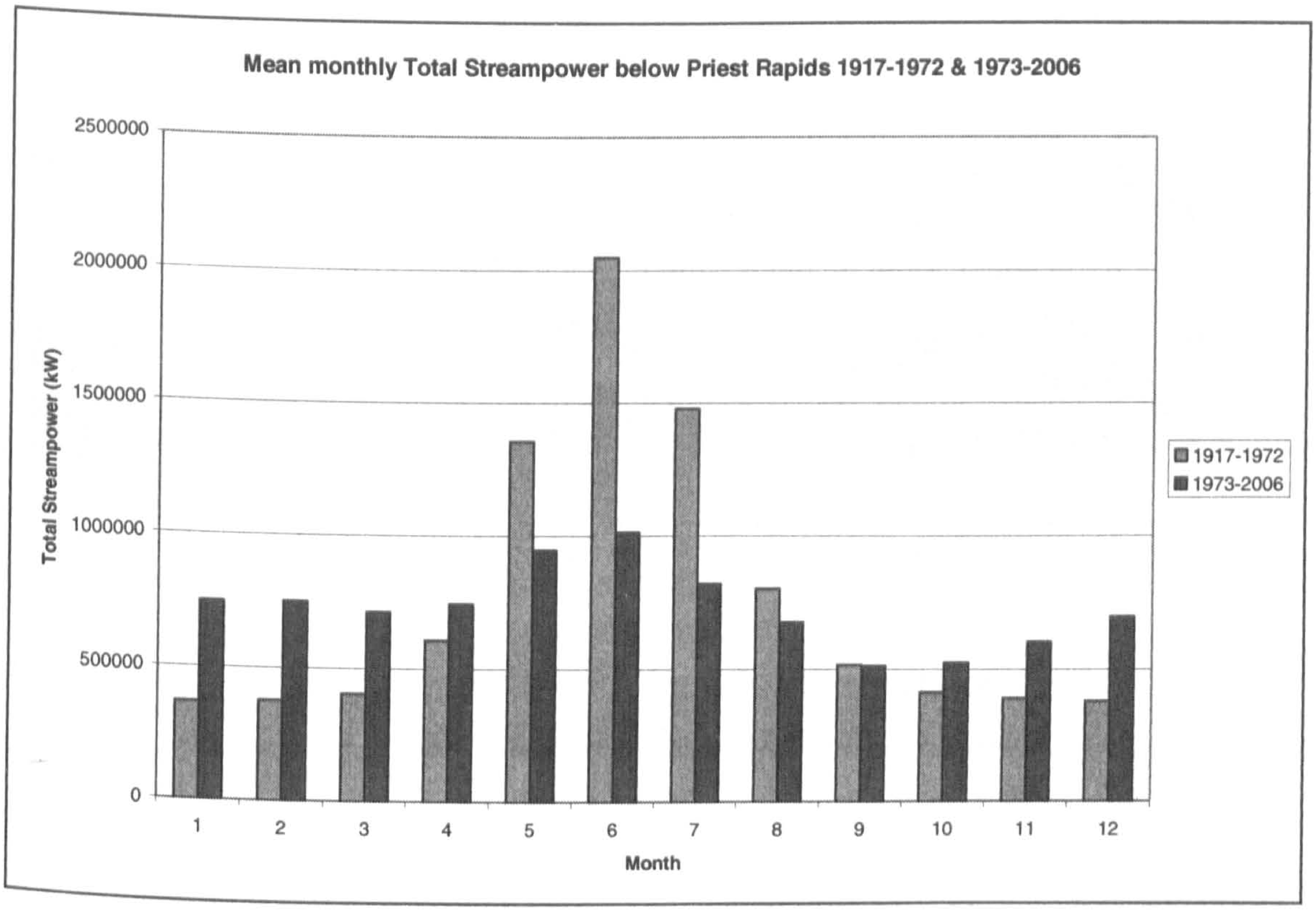


Fig 6.36 Mean monthly Total Stream Power below Priest Rapids 1917-1972 & 1973-2006.

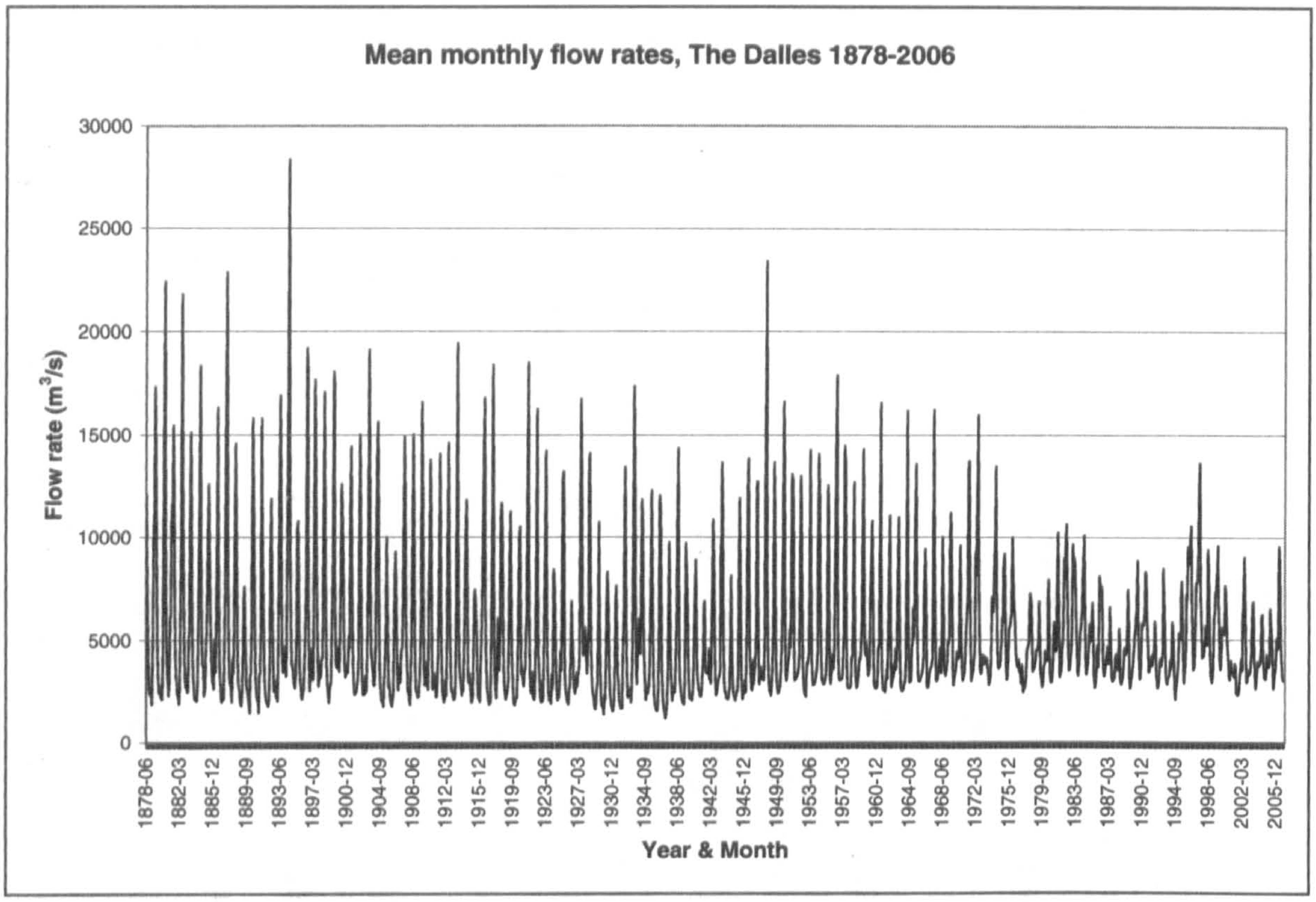


Figure 6.37. Mean monthly flow rates The Dalles 1878 to 2006.

At The Dalles flow station at 847 km below the Grand Coulee, complete flow rate data from 1878 to 2006, shown in figure 6.37, shows the diminution of variation both since 1940 and, more pronounced, since 1973. The Dalles is situated at 306 km from the river mouth, 656 km below the Grand Coulee dam, and it is approximately 194 km below the confluence with the largest tributary the Snake River, which has also been subject to impoundment.

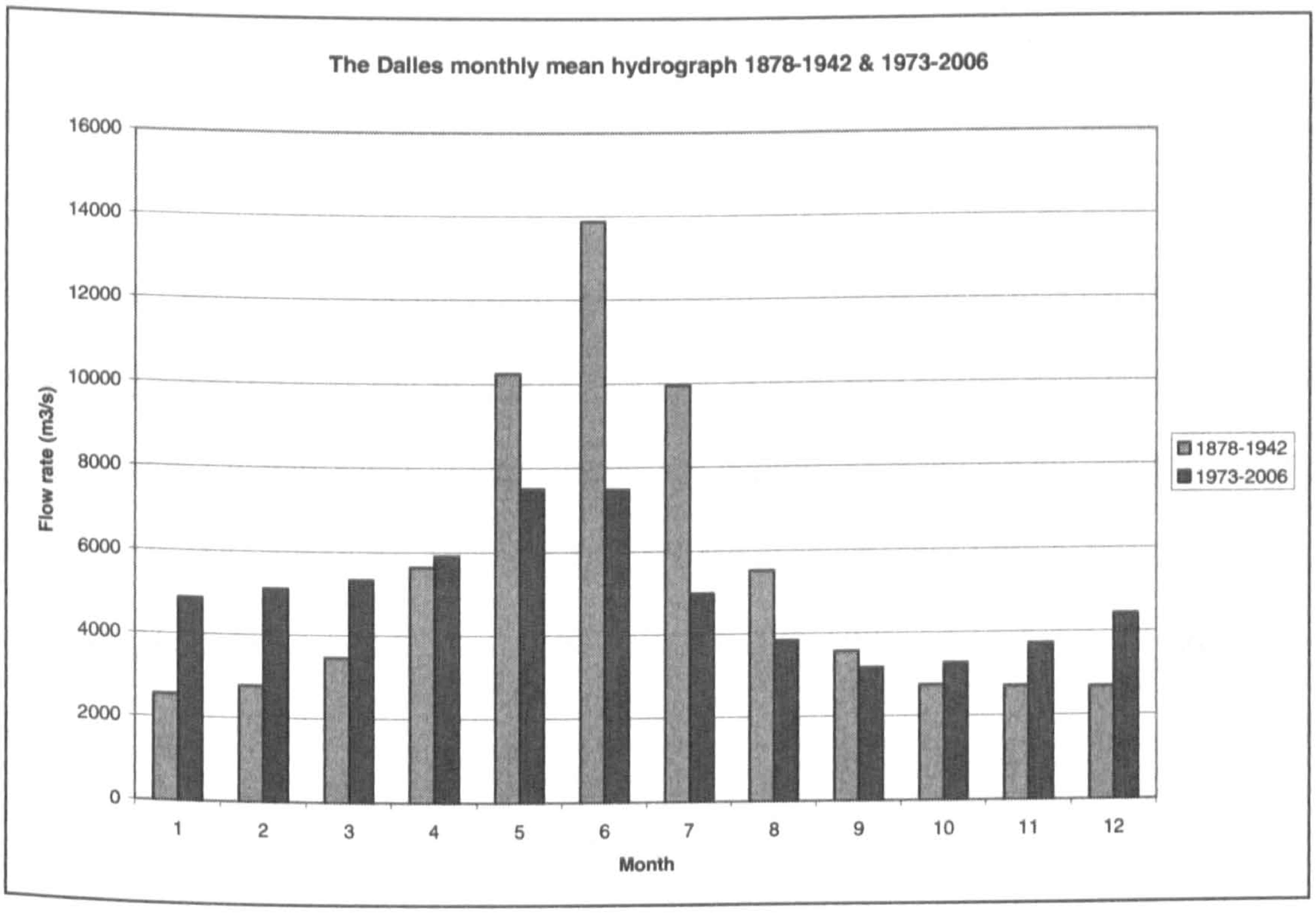


Figure 6.38 Mean monthly hydrograph for The Dalles, Columbia River 1878-1942 & 1973-2006. (GRDC 2008)

Once again a diminution of the peak flow by approximately half from 13879 $m^3 s^{-1}$ to 7520 $m^3 s^{-1}$ is seen from figure 6.38, together with a shift in the peak from June to May, and with low flows increased by about a from 2814 $m^3 s^{-1}$ in January to 3174 $m^3 s^{-1}$ in September. The maximum flow has been reduced from 28377$m^3 s^{-1}$ in the period 1878-1972, to 13636$m^3 s^{-1}$ for the period 1973-2006. Minima are increased from 1187 $m^3 s^{-1}$ to 2121 $m^3 s^{-1}$ in these periods. While the maximum flows still occurred in the same month, i.e. the former peak flow month of June, the minima are transferred from January to September. The standard deviation was calculated and for the peak flow period it had decreased from 3941 $m^3 s^{-1}$ to 2581 $m^3 s^{-1}$ in the 1973-2006 period, i.e. the variability had decreased. For the former minimum flow period in January, the standard deviation increased from 961 $m^3 s^{-1}$ to 1060 $m^3 s^{-1}$, i.e. the variability had increased.

River Colorado flow rate changes and effects of impoundment and water abstraction on Total Stream Power.

Although the River Colorado has been less impounded than the Columbia River, it flows with great seasonal flow variations, through an arid region with few major tributaries and much of the water is abstracted for irrigation and water supply. The effect of the large dams on the flow rates has been very pronounced as they have been designed to store about one year's river flow in the case of the Glen Canyon scheme and 2.8 years in the Hoover Dam scheme.

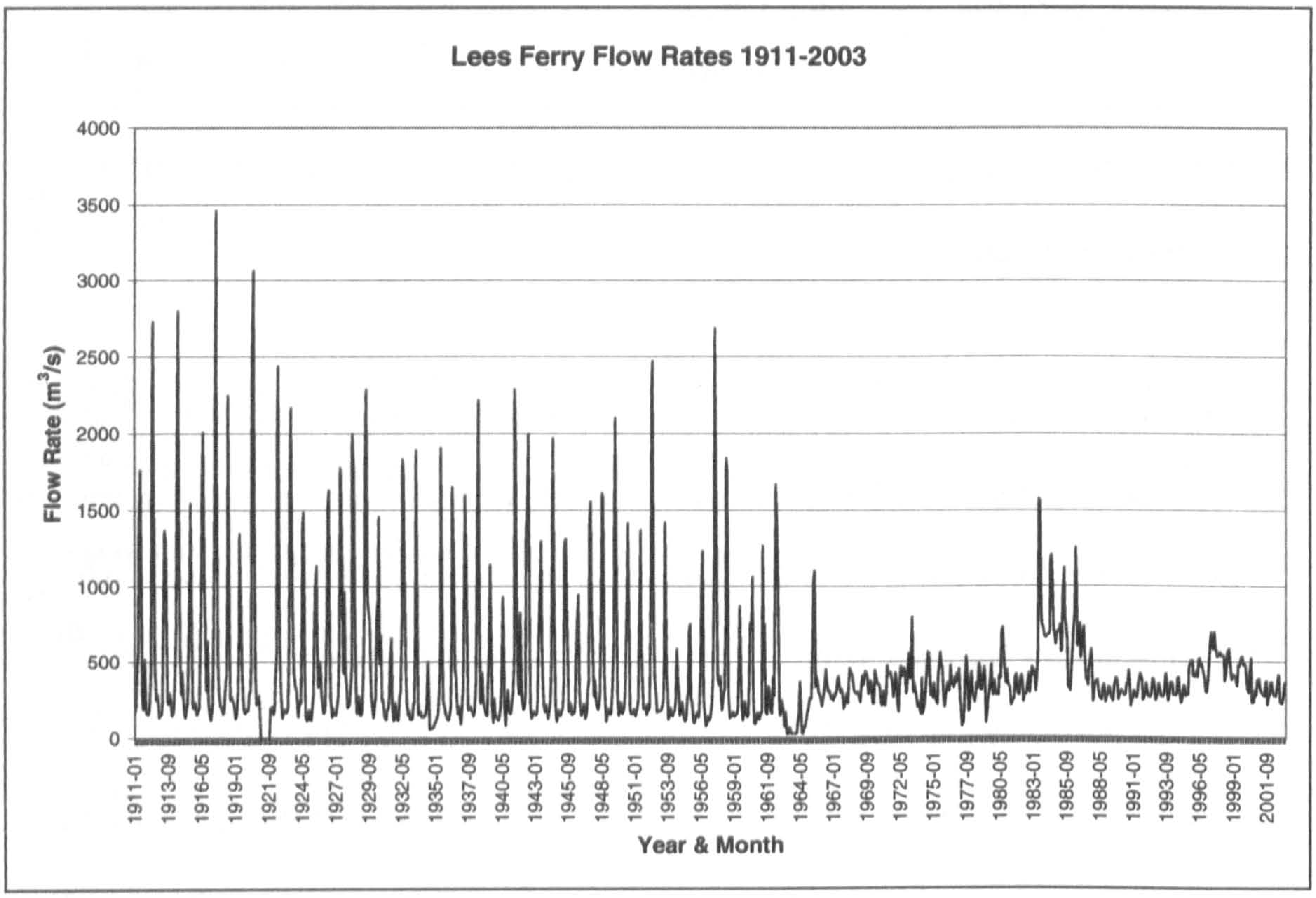


Figure 6.39 Lees Ferry flow rates 1911-2003, below Glen Canyon dam, River Colorado. (data from GRDC 2008)

The changes in flow rates from 1911 to 2003 can be seen in figure 6.39 above, for Lees Ferry 24km below Glen Canyon dam, on the Colorado after the construction and filling of the dam in 1963-4. Very low flows of mostly between 28 and 32 $m^3\ s^{-1}$ can be observed in early 1963 to early 1964 while the reservoir was filling.

As is clear from the flow rate graph above and the mean monthly hydrograph in figure 6.40 below, the flow regime has been considerably altered, with a near elimination of the flood and low flows, apart from some high flows in 1983, to 1986 peaking each year at over 1000 $m^3\ s^{-1}$, when presumably the reservoir capacity was not sufficient to contain these high flows.

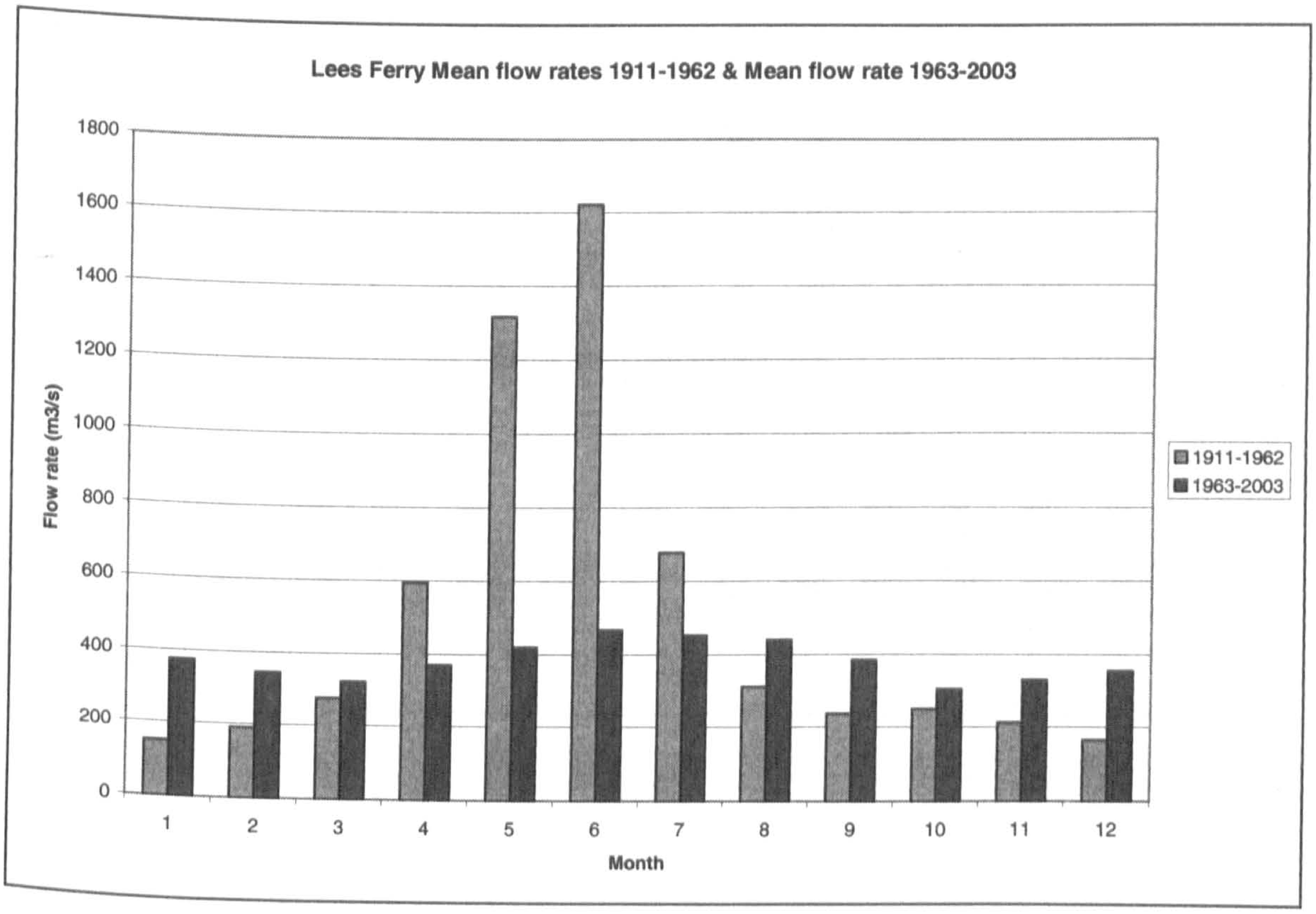


Figure 6.40. Mean flow rates at Lees Ferry, River Colorado below Glen Canyon Dam, pre and post 1963.

The loss of seasonal flow variation is pronounced below the Glen Canyon dam on the River Colorado, with maximum flows reduced by a factor of four, from 1600 m^3s^{-1} to a little over 400 m^3s^{-1}, see figure 6.40 above.

There is a reduction of Total Stream Power in proportion to the loss of peak flows and low flows after the construction of Glen Canyon dam, see figure 6.41 below.

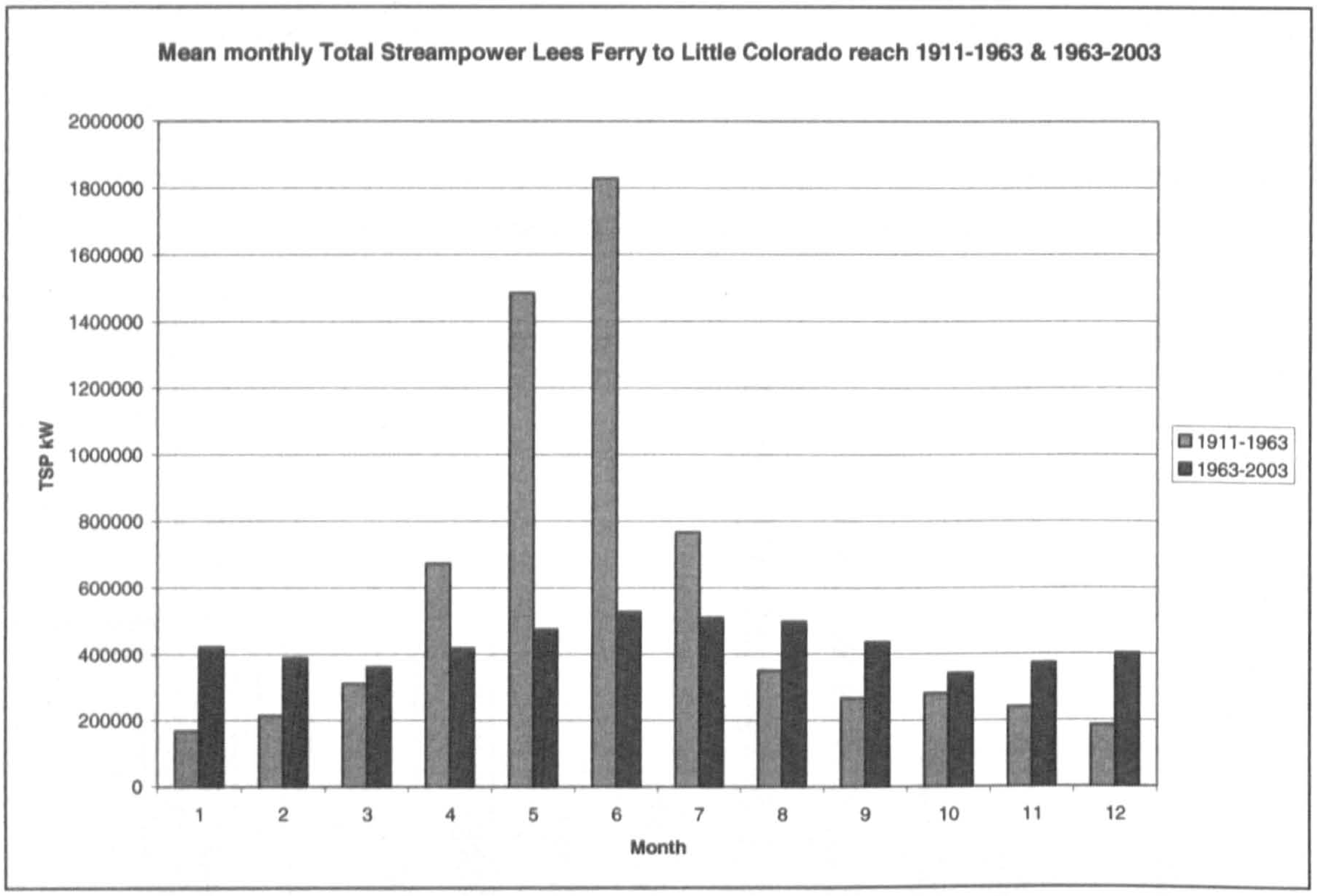


Figure 6.41 Mean monthly Total Stream Power, for the Lees Ferry to Little Colorado reach 1911-1963 and 1963-2003.

Even more outstanding are the changes in mean flow rate records at Yuma, 1038 km downstream from Glen Canyon Dam on the River Colorado in Arizona, near to the Mexican border, and 500 km downstream of the Hoover major impoundment dam, for the period 1904 to 1983. See figure 6.42 below. The river flow rates show the effect of the Hoover dam and reservoir in 1933, with associated water abstraction.

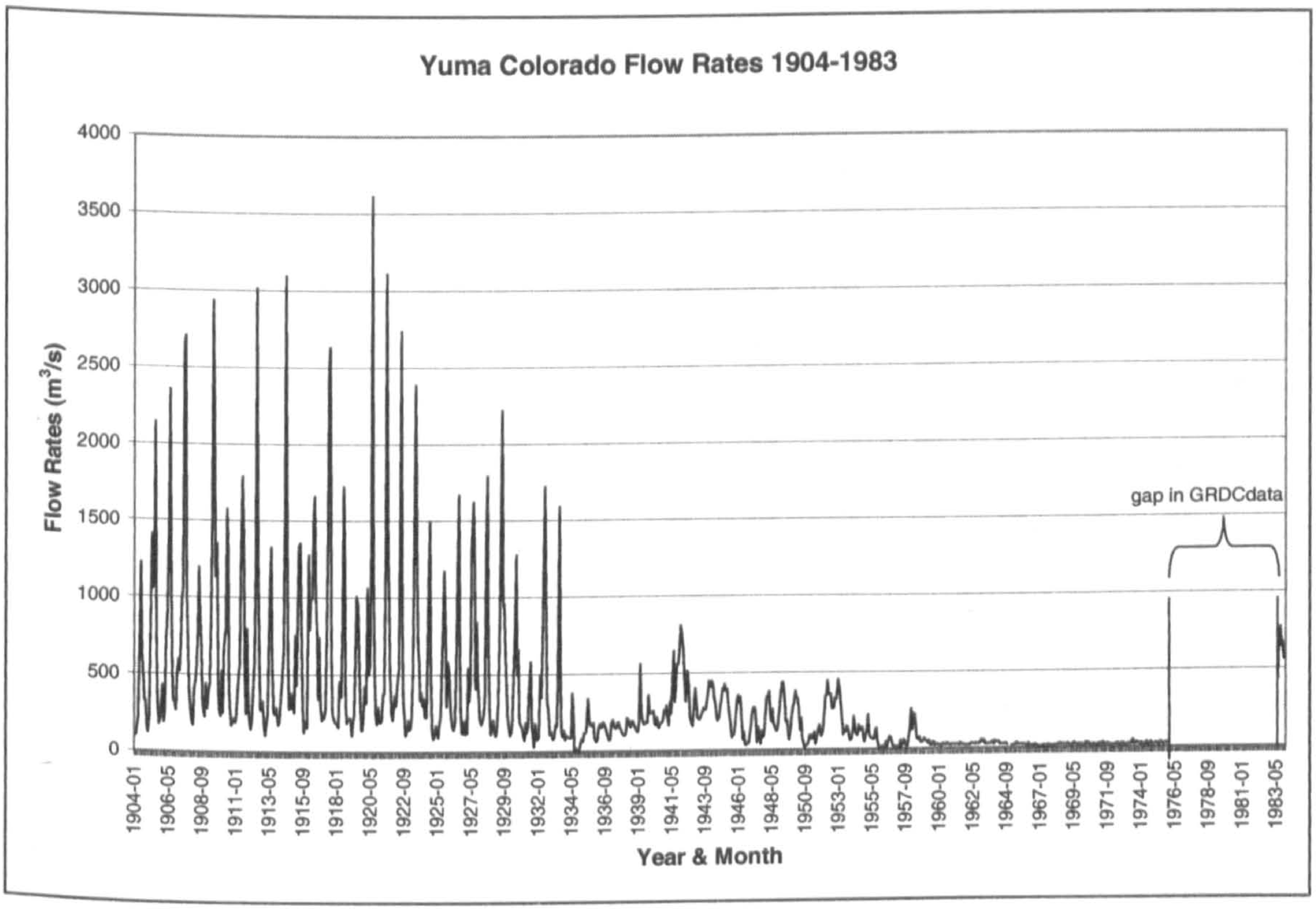


Figure 6.42 Flow rates at Yuma Colorado 1904-1983, River Colorado, (data source GRDC 2008).

Then after 1959, increased water abstraction led to a drop in mean flows from 612.96 m^3s^{-1} in the period 1904-1933, to 187.3 m^3s^{-1} between 1934 and 1959, and then just 23.4 m^3s^{-1} in the period 1960-1975. By the late 1980's flow rates were averaging about 18 m^3s^{-1} (International Boundary and Water Commission 2001), though since the 1990s slightly increased flow rates have been enabled. Not only are the flood peak flows almost entirely evened out, but some 96 % of the former flow has been abstracted. With the loss of water flow, there is of course a loss of Total Stream Power.

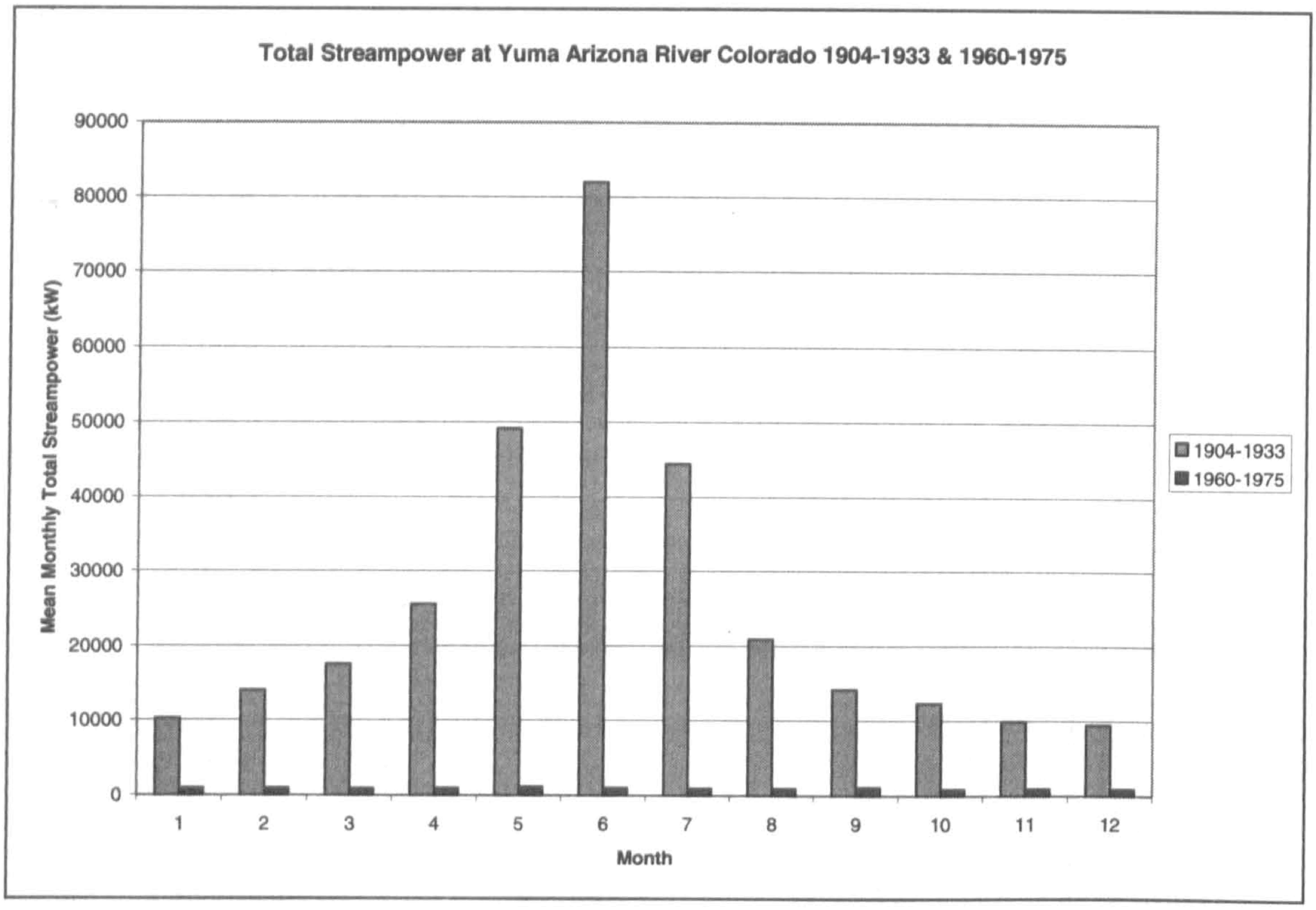


Figure 6.43 Total Stream Power at Yuma Arizona, river Colorado 1904-1933 & 1960-1975.

The loss of Total Stream Power at Yuma Arizona on the Colorado River can be seen in figure 6.43 above. From a mean Total Stream Power of 25851 kW the total available Stream Power has diminished to just 987 kW. There has been a loss of the order of 96.18% in the mean Total Stream Power. Even more important than the mean Total Stream Power values is the diminution from a peak mean monthly TSP of 82003.75 kW in June before 1934, to a peak of just 1181.12 kW in May, after 1960. This represents just 1.4% of the former flood flow TSP, and so 98.6% of Total Stream Power has been lost. The effects of this abstraction of water and hence Total Stream Power on the river Colorado are evident, in that very little sediment is transported to recharge the former delta at the mouth. This feature is now largely partly a residual one, and is just one of the environmental impacts resulting, though perhaps the most significant.

6.4 Conclusion to Initial Results

In part 1 of the test, data for the reservoir and dam parameters was obtained, which can be used to explain some of the impacts experienced. The results are summarised below in table 6.2 and 6.3. Although it had been the intention to collect data for more parameters, as described in Chapter 5, it is considered by the author that the main parameters for some of the main impacts of significance to this study, have been included above. A possible exception is that of water quality data, which should be related to residence time.

Table 6.2 Summary of reservoir and dam parameter data results

HEP Scheme	Hypothetical power flux density	Mean River Flow	Production factor	Land Use	Former mean river gradient	Average water residence time
	kW/m^2	m^3/s	ratio	km^2/TWh	%	days
High Aswan Dam	687	2760	0.48	500	0.014	708.1 (1.94 years)
Kariba	932	1775	0.55	687.5	0.038	1177.49 (3.226 years)
Cabora Bassa	1182	2457	0.51	292.3	0.0446	296.77
Itaipu	1162	9000	0.82	17.9	0.0696	37.23
Hoover	1555	395.6	0.75	159.75	0.13	1024 (2.8 years)
Glen Canyon	1525	875	0.3	185.6	0.0519	357.14
Bonneville	150	5660	0.67	18.55	0.0211	1.35
Grand Coulee	987	3100	0.78	15.6	0.129	44.02
Gabcikovo	211	2047	0.79	20	0.0827	1.37
Iron Gates 1	255	5500	0.85	21.33	0.0232	5.26
Three Gorges	1001	14300	0.68	12.8	0.017	31.81

Table 6.3 Summary of reservoir and dam parameter data results

HEP Scheme	Reservoir volume	Average reservoir fluid velocity	Total Stream Power TSP	Cross-sectional Stream Power CSP	Brune sediment trap efficiency
	$10^6 m^3$	m/s	kW	W/m	%
High Aswan	168900	0.0082	1896000	3790	98.13
Kariba	180600	0.00246	1654000	6620	98.7
Cabora Bassa	63000	0.011	2904000	10800	85.4
Itaipu	29000	0.0528	10454000	61500	96.53
Hoover	34850	0.0014	612000	4970	98.56
Glen Canyon	27000	0.0097	1334000	4460	96.95
Bonneville	662	0.616	846000		17.8
Grand Coulee	11790	0.0332	1846000	14600	86.93
Gabcikovo	243	0.219	432000	16600	18.14
Iron Gates I	2500	0.594	1403000	12500	52.3
Three Gorges	39300	0.218	14309000	23800	83.78

In part 2 of the test Total Stream Power (TSP) calculations were estimated for four rivers in the sample, and flow rates and TSP were compared for periods prior to the dam construction and post dam construction. Average monthly flow rate data was collected and tabulated and then monthly hydrographs drawn up. These were then incorporated into the gradient profile spreadsheets so that the TSP could be estimated. A summary of the main results is enclosed in table 6.4 below.

Table 6.4 Summary of TSP estimations downstream of HEP schemes before and after dams, for four rivers.

River & HEP scheme	Reach	Monthly Peak Total Stream Power Pre Dam,	Period	Monthly Peak TSP post dam	Period	Peak TSP Δ difference pre and post dam.
		kW		kW		ratio
Nile Aswan High	Aswan-Gaafra	729862	1871-1967	214338	1970-1984	-71%
Danube Gabcikovo	Dunaalmas-Nagymaros	86789.07	1948-1992	90055.8	1992-1995	+3%
Danube Iron Gates I	Novo Selo-Lom	244193.9	1931-1970	227442.7	1992-1999	-6.9%
Danube Iron Gates I	Zimnicea-Jantra	84620.5	1931-1970	81775.1	1970-2002	-3.36%
Columbia Grand Coulee	Grand Coulee-Chief Joseph Dam	8420658.6	1930-1973	3740111.5	1973-2005	-55%
Columbia	Below Priest Rapids-McNary dam	2050525.4	1917-1972	1013529.9	1973-2006	-50.57%
Colorado Glen Canyon	Lees Ferry-Little Colorado confluence	1829859.3	1911-1963	527974.2	1963-2003	-71.14%
Colorado Hoover	Yuma-Morelinos	82003.7	1904-1933	1012.4	1960-1975	-98.6%

There are discontinuities in both the time line and the river line data sets as a result of the availability of flow data. However, it is considered by the author that despite these discontinuities and comparisons of flow over different time periods, a fairly representative version can be obtained at a coarse resolution scale. Overall changes in climate and weather patterns are assumed by the author not to be significant over these periods, and the main changes apparent are due to the operation of the HEP schemes reservoirs and water abstraction.

The Nile and the Danube had the longest continuous flow rate data records, in some instances from 1880 to the present, depending on the flow stations, though the Columbia and Colorado also had long term flow records. The most geographically continuous set of flow station records was that of the Danube. For the Nile, the majority of the flow stations below Aswan are fairly recent and cover only a limited period. However, a good to fair set of data was also obtained for the Columbia River and some for the Colorado River. At Aswan (below the High Aswan Dam) on the Nile flow rate data from 1870-1984 was available, which covers the pre dam period before 1964-7 (dam filling period), and post dam, for a more limited duration. At flow stations below Aswan, such as Gaafra, Esna, El-Hammadi, and Nag Hammadi, only post dam flow data was available for a limited period, 1973-1984. Nevertheless despite these data inadequacies, the Aswan flow data is considered by the author to be revealing, and its flow patterns are likely to be repeated at the lower flow stations. The very considerable loss of monthly peak flow Total Stream Power of 71% post dam operation, attenuating the August-September floods of the Nile's seasonally flow variations, is evident from the data.

For the Danube, flow data was available for selected measuring stations from 1931-1999 and 2001-2, covering the periods before the two dams' construction, the Iron Gates in 1970, and the Gabcikovo in 1992. Zimnicea flow station data, at 83km below the Iron Gates scheme, covers a period of 1931-2002 providing almost forty years data pre dam construction and thirty since. At Zimnicea only a slight attenuation of peak flows can be discerned post 1970 and this appears to be within the normal bounds of variability. At

Lom and Novo Selo more limited flow data periods were available, 1941-1970, and then 1991-1999 for Lom and 1937-1971 and 1992-1999 for Novo Selo. Total Stream Power for the peak months of April was reduced by 6.9 % and for May by 10.4%, for the Novo Selo to Lom reach of 128.5km. At Ruse almost 400km below the Iron Gates dam, a reduction of 10% in TSP was shown post dam. This reduction is likely to be within or near normal variation and so is not considered significant. At Dunaamas, 82km below the Gabcikovo HEP scheme, there is again very little difference, in the pre and post dam flow rate regime (a 3% increase in TSP), although the data period is too short to be representative, as it extends to only three years post dam, (1948-1995). Any diminution in monthly flow rate variability is likely to be the cumulative result of dams upstream (Schwarz 2008).

The Columbia River flow data covers the period 1930-2005, giving good pre and post (The 1941 Grand Coulee dam, and 1973 Mica dam) dam construction periods. The Grand Coulee dam is at the head of the US river reach estimation for Total Stream Power, and clearly shows the reduction in flow rate variability, post 1973, although not very much in the period 1941-1973.

Average monthly peak flows in June have diminished by 55%, and now there are two peaks, one in June and smaller one in January-February, which was formerly the lowest flow period. The reduction in flow rate variability continues down river as seen in the monthly hydrographs for Rock Island pool, (reservoir reach), mean monthly peak flow reduced by 51%, below Priest Rapids dam, 50% reduction in peak flow from and therefore TSP, and The Dalles with a 45% decrease in peak flows and TSP, and at Beaver Army Terminal a 23% decrease in peak flows and TSP. Data for Rock Island was available 1960-2005, for below Priest Rapids, from 1917-2006, for The Dalles 1878-2006 and for

Beaver Army Terminal 1968-1970. The significant drop in peak flows and Total Stream Power is considered to be the result of attenuation of flood flows by the Mica and other Canadian dams primarily, which regulate the flow.

The Colorado River with two major impoundment dams, the Glen Canyon and the Hoover dam, exhibits great diminution of seasonal flow variation, since the dams have been designed for about one year's and 2.8 years flow storage respectively. A large proportion of the water of this river is abstracted for urban water supply and irrigation. A section of the river, the reach from the Mexican international boundary to kilometre 1431 at the top of the Lake Powell reservoir was modelled for gradient and Total Stream Power. Data was available from 1911 to 2003 for Lees Ferry flow station 24km below Glen Canyon dam, and this showed an average reduction in peak flow rates for June of 75% after the dam's construction in 1963. The only other data point for which consistent data was available was Yuma, at 47 km above the international boundary for the period 1904-1975. Data was also available for six months of 1983. The Yuma data clearly shows the great changes in flow rates, after the 1933 Hoover dam construction, and the Glen Canyon dam in 1959. The data is thus described in three periods, 1904-1933 pre Hoover, 1933-1959 pre Glen Canyon, and 1959-1975 post dams.

The effects of attenuation of flood flows, and associated water abstraction are clear; diminution of the average peak month flow rate for 1904-1933, by 87% has occurred for the period 1933-1959, with the peak now moved from June to January. A 98.6% decrease in peak monthly TSP occurs for the period 1960-1975. The effects of water abstraction and losses due to evaporation can be seen in the average monthly flow rate reducing by 69%, from the period 1904-1933 to the period 1933-1959, and then by ~97%, for the period 1959-1975 representing losses therefore also of TSP.

Although there are only two flow station data points for this river, the author considers these representative of the great changes in the flow regime, with consequent loss of Total Stream Power. The peak monthly Total Stream Power changes, i.e. losses, as shown in table 6.3 above, to the rivers below the major HEP schemes, are considered by the author to be the most significant impact of all the parameters used in this study.

Chapter 7

First Conclusions from the tests as applied to HEP.

7. Introduction

The previous chapter described the initial results of the test of the hypothesis, whether environmental impacts are related to the power flux density, as reflected by the HEP reservoir reach and downstream TSP parameters applied to the sample. This chapter includes parameter comparison analysis and discusses the first conclusions from the test.

As noted earlier in chapter 6 the test comprised two parts, firstly the changes to the flow and abstraction of energy at the dam and reservoir reach of the river and secondly the effects downstream from the dam, of the storage of potential energy and extraction of energy as well as changes in flow rate. In the reservoir reach of the river, the HEP reservoir and dam parameters such as power flux density, head heights and others for the different schemes have been contrasted and compared and examined for linkage to the impacts. At the dam itself, the energy available was calculated, based on head heights and flow rates. The highest head heights lead in theory to the greatest hypothetical power flux densities. The consequence of the dam is to concentrate almost all of the energy of the former river reach, as reflected in the gradient and flow, at the dam.

Expected results if power flux density effect on impact hypothesis holds true

Some of the expected results if the hypothesis is confirmed are that mechanical energy effects, such as erosion, deposition, sedimentation and load transport, will show a relationship to the power flux density, to changes in this parameter and to energy extraction. Land use could be expected to be related to power flux density, but also to the storage capacity designed into the scheme. Water quality could also be expected to be related to power flux densities and change in power flux density. Other effects such as biological ones e.g. to fish might be expected to be related to power flux densities, and extent and rate of change in them.

7. 1 Results.

7.1.1 Summary of Power flux density relationship to head height

The Hoover dam had the highest hypothetical power flux density at 1555 kW/m^2, as derived from head height, with the lowest being the Bonneville dam at 149.5kW/m^2 (derived from head height). The average power flux density in the sample of 11 was 876.53 kW/m^2. However, the Hoover had the lowest flow rate and therefore a long water residence time of 2.8 years (second longest in the sample), despite having the steepest bed gradient. Land use per TWh pa was seventh in the sample, at 159.7km^2/TWh pa, compared to the highest at 687 km^2/TWh pa, and the lowest at 12.8 km^2/TWh pa. Sediment trap efficiency (Brune), was second highest at 98.56%.

The Bonneville dam had the lowest hypothetical power flux density (derived from head height), of 149.5kW/m^2, but a flow rate of 5660m^3/s, third greatest and a residence time of 1.3 days, the shortest in the sample. Land use was relatively low at 18.55 km^2/TWh, fourth lowest in the sample. The Brune sediment trap efficiency was 17.8%.

For the selected impact parameters of land use and sedimentation, no obvious correlation of power flux density with head heights could be found, though indication of a correlation to flow rates and thus to this method of measuring power flux density, appeared.

7.1.2 Land Use

Land use in TWh pa /km^2 was compared to the parameters:

- hypothetical power flux density derived from head height
- reservoir reach Total Stream Power
- Cross-sectional Stream power
- average water residence time
- former mean river gradient
- reservoir volume
- reservoir average fluid velocity
- production factor
- mean river flow

The first graph shows land use in km^2 / TWh pa compared to the hypothetical power flux density derived from head height (i.e. flow of water is derived solely from acceleration due to gravity, acting upon one m^2), see figure 7.1 below. This shows no apparent relationship between land use and power flux density derived from head height, with considerable scatter of the data points. Six schemes in the sample have low land use, varying from 12.8 km^2 /TWh pa to 21 km^2 /TWh pa, but with power flux densities varying from

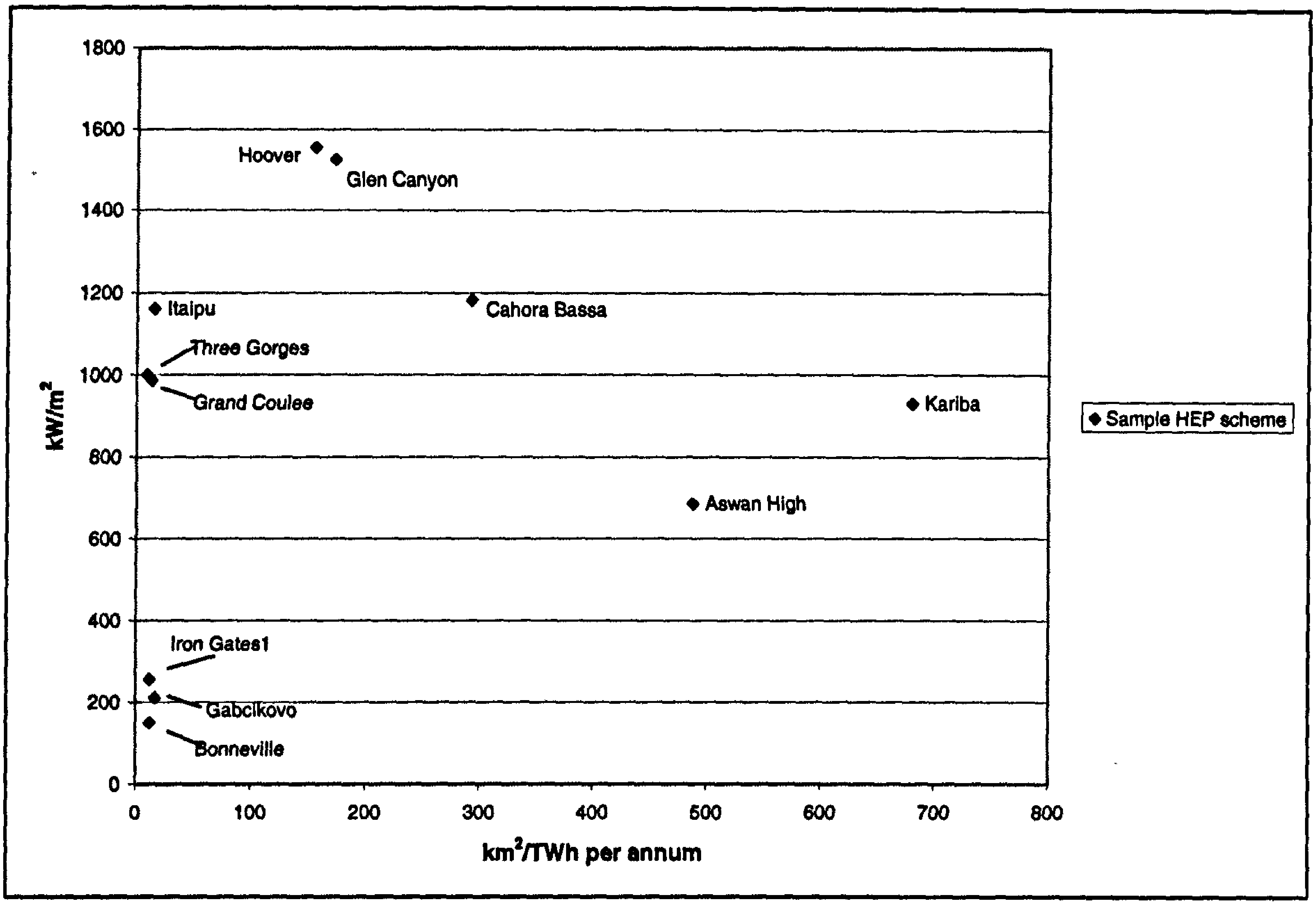


Figure 7.1 Land use compared to hypothetical power flux density derived from head height for the sample.

149.5 kW/m^2 to 1161.5 kW/m^2. The remaining five schemes with higher land use also show considerable spread with land use varying from 159 to 687 km^2 / TWh pa, and power flux density varying from 686 to 1554 kW/m^2.

The second graph shows land use in km^2/TWh pa plotted against Total Stream Power for the reservoir reach see figure 7.2 below.

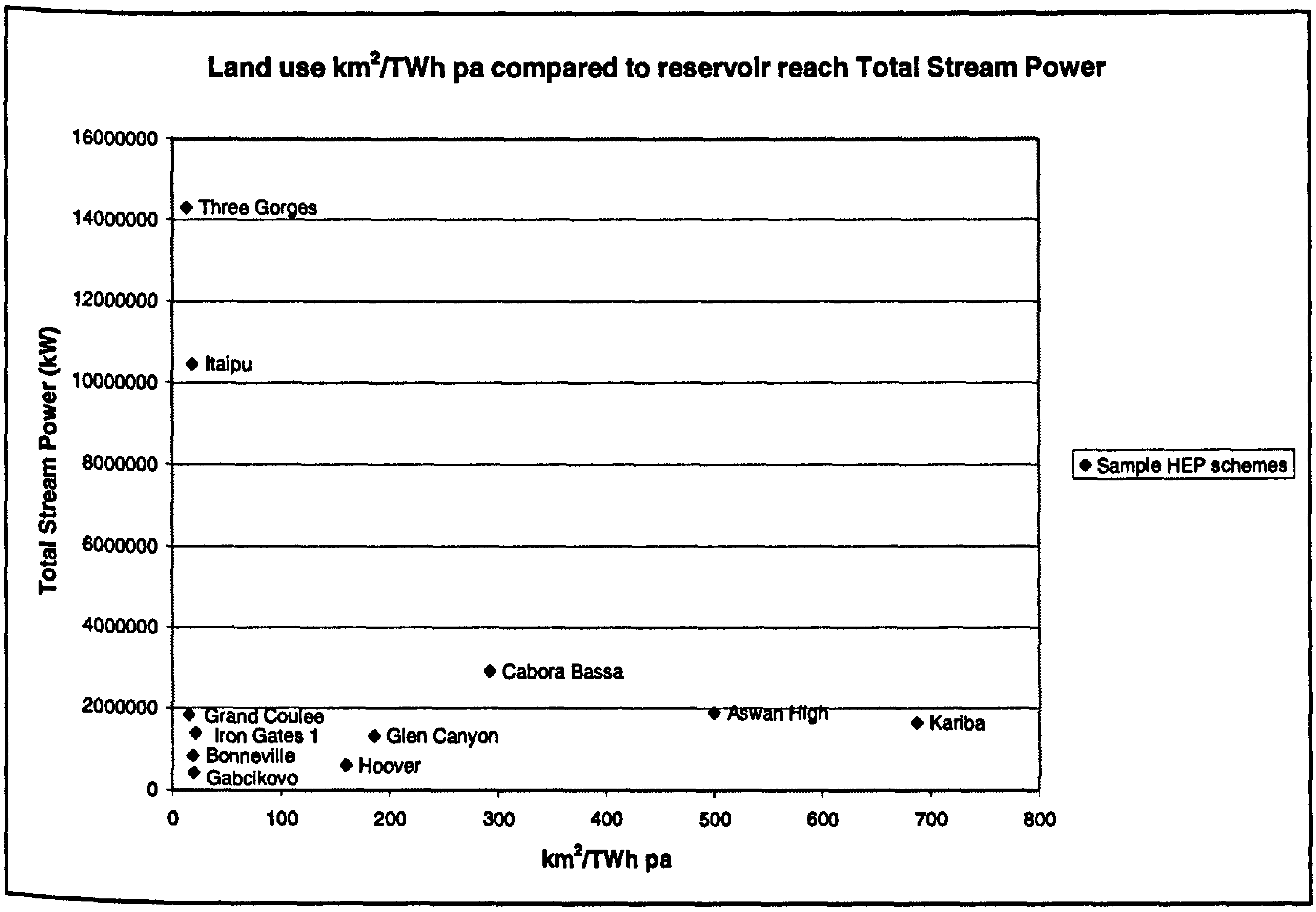


Figure 7.2 Land use compared to reservoir reach Total Stream Power.

Land use plotted against TSP for the reservoir reach shows that the sample falls into three groups with four schemes having relatively low land use and reservoir reach TSP values, and the Three Gorges and Itaipu schemes having the highest reservoir reach TSP values and the Three Gorges scheme the lowest land use. The five other schemes have relatively low but varying reservoir reach TSP values, and widely varying land use values. As a result little likelihood of a relationship is indicated.

The third graph shows land use in km^2/TWh pa plotted against Cross-sectional Stream Power, for the reservoir reach, see figure 7.3 below.

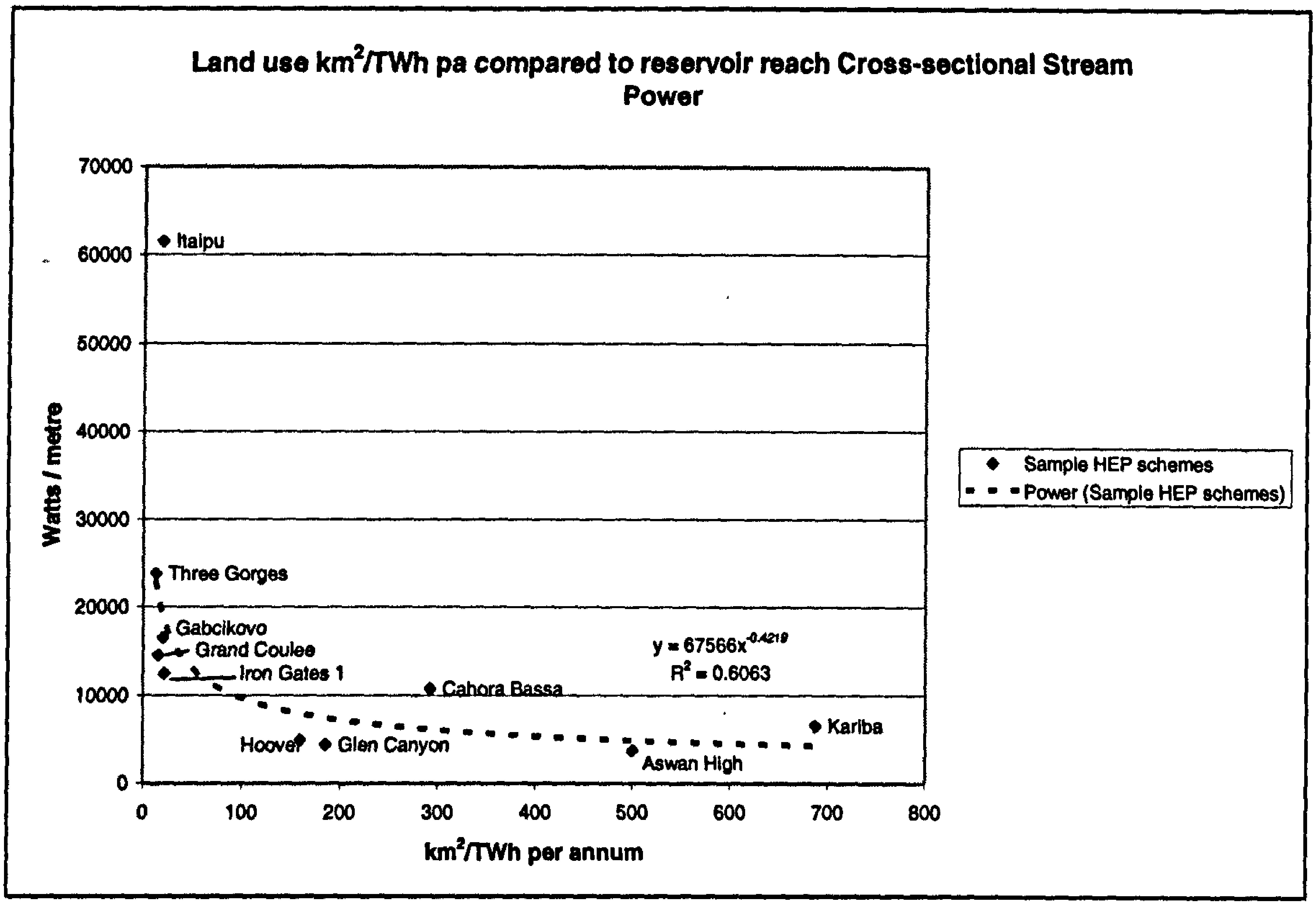


Figure 7.3 Land use per TWh pa compared to Cross-sectional Stream Power

Land use compared to CSP shows some apparent pattern in the data point scatter for the eleven schemes, with the Itaipu having low land use and the highest CSP, while the Three Gorges, Gabcikovo, Grand Coulee and Iron Gates 1 are fairly clustered together with both low land use values and medium CSP values. The remaining schemes have greater but widely varying land use with mostly low CSP values. According to the hypothesis, an inverse relationship between land use and CSP could be expected as higher CSP values, based on flow and gradient, per metre, constitute higher power flux density. The proposed formula for land used per unit of energy on page 85 in chapter 3,

Area / unit of power (e.g. TWh p.a.) = $B \times (H / H (s \times g \times Q \times \rho \times \eta))$ also suggests an inverse relationship with slope and flow rate. A linear slope of $y = -33.946x + 22461$, can be fitted with $R^2 = 0.2178$. If a curve were to be fitted to the data points, a best fit is obtained by a power equation, $y = 67566x^{-0.4219}$, with an R^2 test resulting in 0.606. This shows an indication of an inverse linear relationship, though, given the sample size it is unlikely to be significant.

The fourth graph shows land use in km^2/TWh pa plotted against average water residence time. See figure 7.4 below.

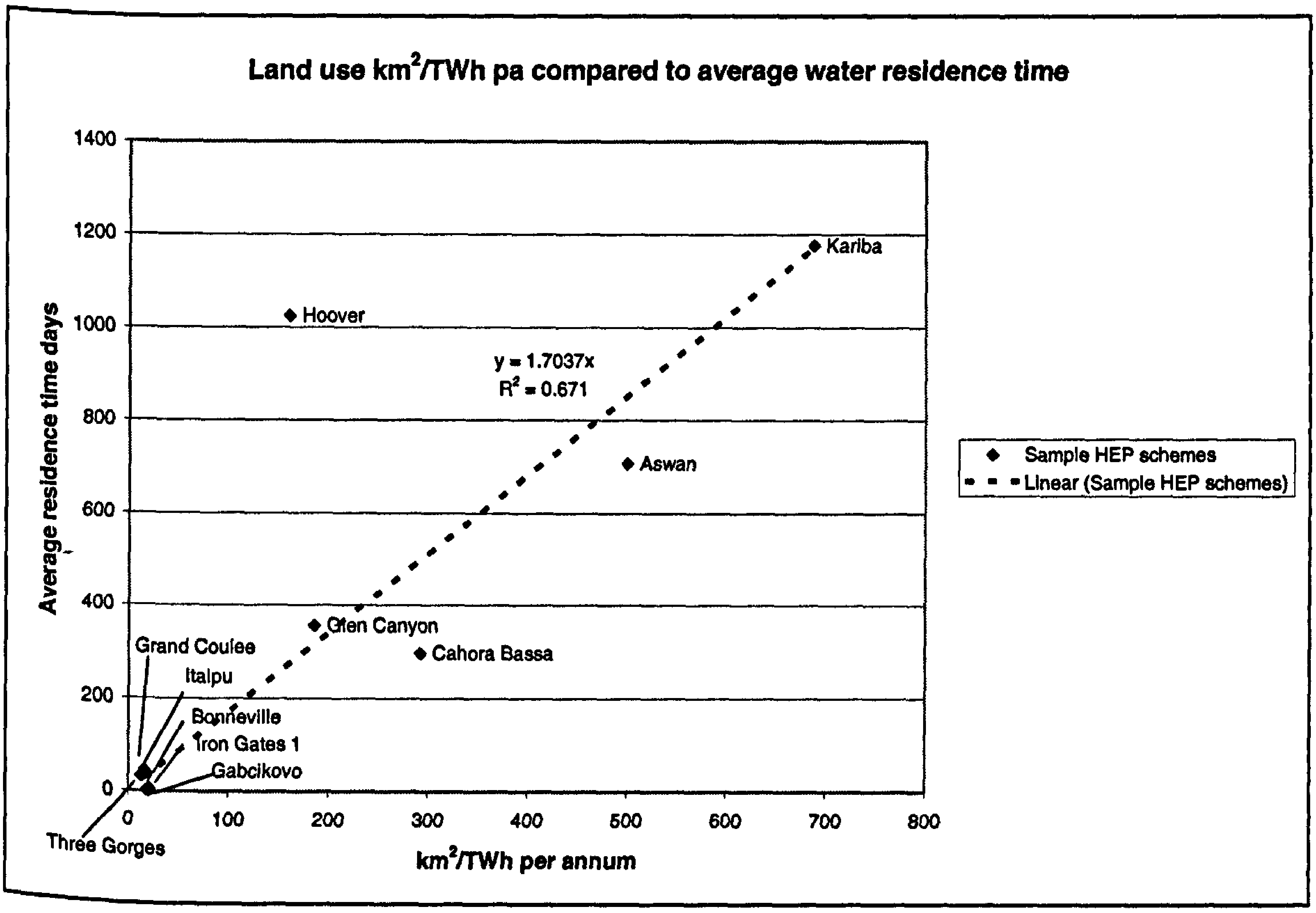


Figure 7.4 Land use compared to average water residence time for the sample.

This shows three of the sample clustered together with low land use and fairly short water average residence times from 31 days to 44, and the run of river examples with low land use and very short residence times of 1.35 to 5.26 days, while the remaining five schemes have high land use and long residence times. A relationship between residence times and land use should exist since water residence times reflect flow rates which are a factor in HEP power equation. A linear trend line fitted for slope y = 1.7037x, shows $R^2 = 0.671$.

This suggests some possibility of a relationship, implying that a storage residence time of one day is ~ 1.7 km^2/TWh pa for the sample, though not statistically significant.

The fifth graph shows land use in km^2/TWh pa plotted against former mean gradient, see figure 7.5 below.

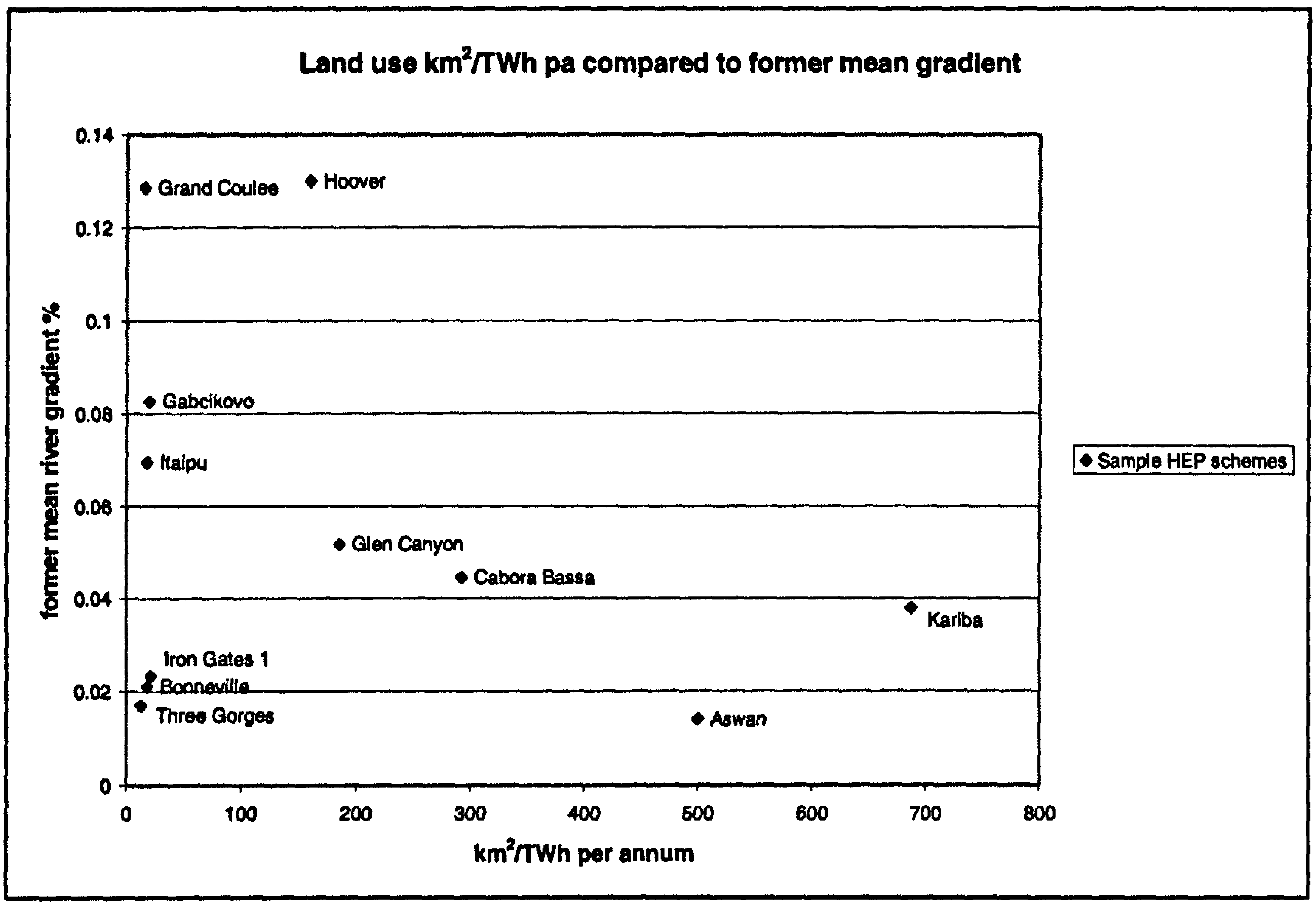


Figure 7.5 Land use compared to former mean gradient for the sample.

This shows quite widely scattered data with no or little pattern evident. Low land use schemes have gradients varying from the lowest at 0.017% (Three Gorges) to the second steepest (Grand Coulee) at 0.128 %. Therefore very little likelihood of a relationship between land use and former mean gradient is shown.

The sixth graph shows land use in km^2/TWh pa plotted against reservoir volume, see figure 7.6 below.

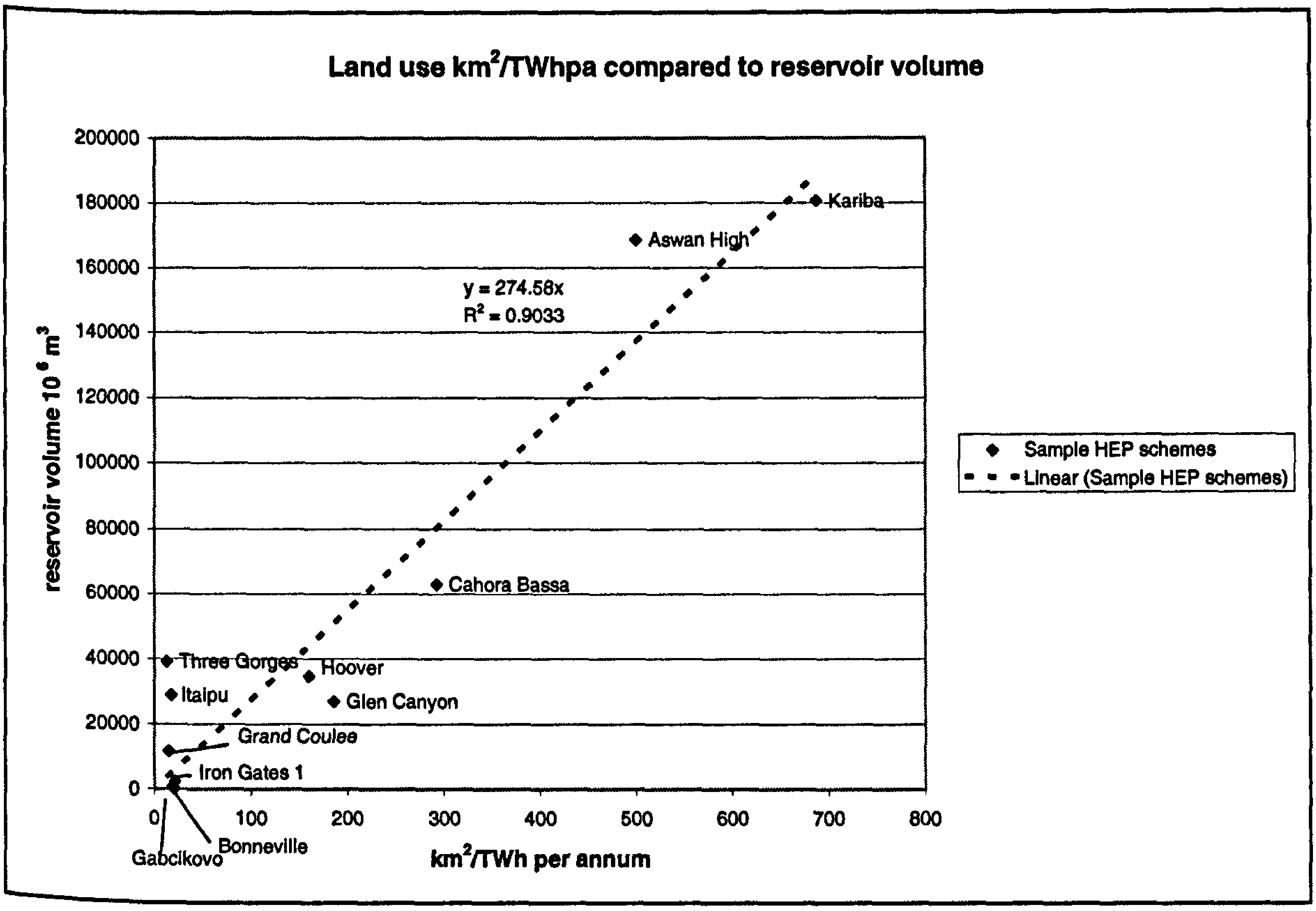


Figure 7.6 Land use compared to reservoir volume for the sample.

This shows most of the schemes with low land use having a range of reservoir volumes from 2500 to 39300 m^6 x 10^6, but with the higher land use schemes with reservoir volumes from 27000 to 180000 m^6 x 10^6. A linear trend line can be fitted with a slope of y = 274.58x, which has $R^2 = 0.9033$. This could suggest a likelihood of a relationship, though there are too few data points to state this categorically. It is reasonable to assume that land use could be related to reservoir volume, i.e. provided reservoir (underwater) shape is fairly uniform.

The seventh graph shows land use in km^2/TWh pa plotted against reservoir average fluid velocity, see figure 7.7 below.

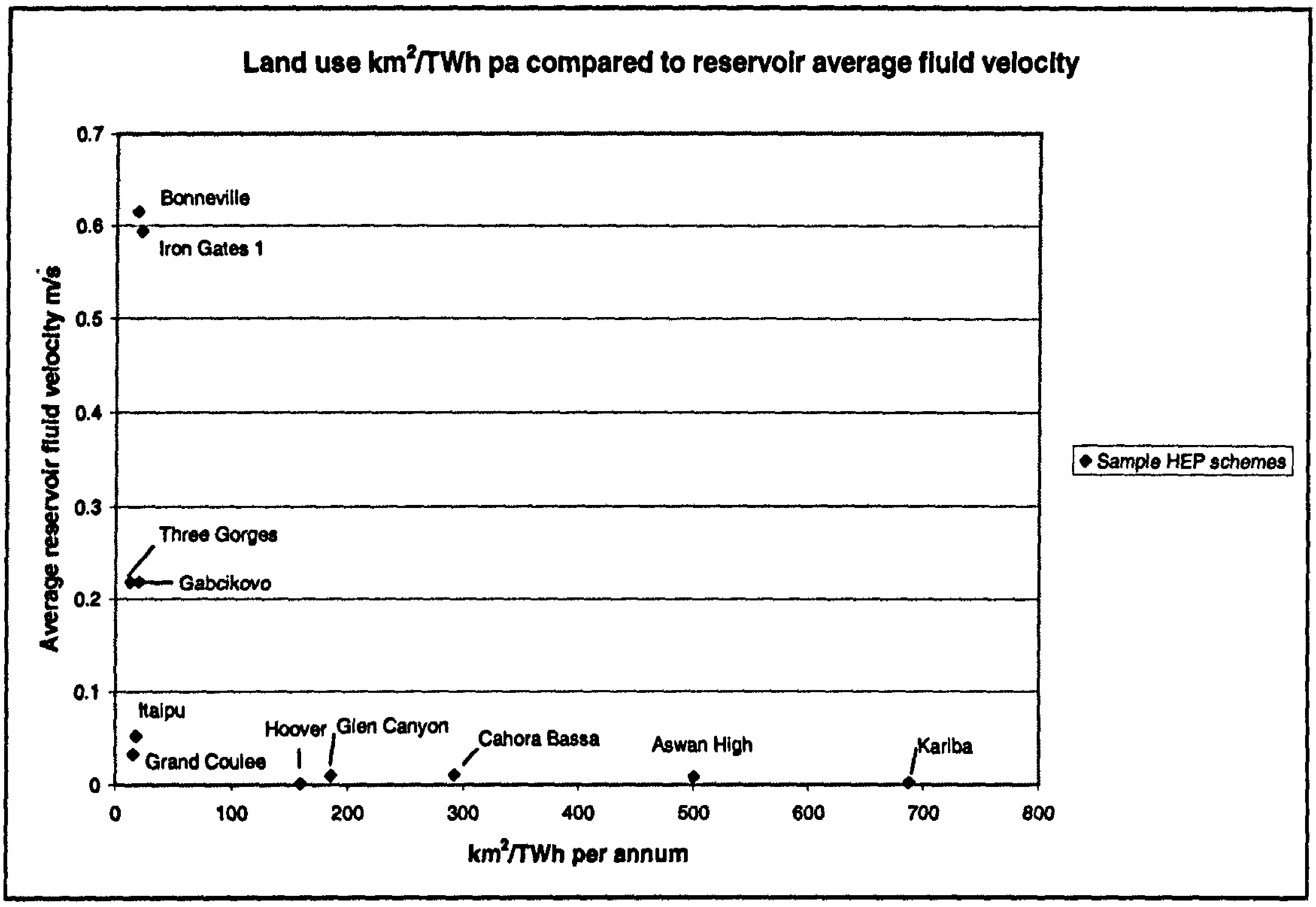


Figure 7.7 Land use compared to average reservoir fluid velocity.

This shows data points distributed with the low land use schemes varying from 0.033 m/s low average fluid velocity (Grand Coulee) to 0.61 m/s the highest average reservoir water velocity. The high land use schemes all have low velocities, varying from 0.0014 m/s (Hoover) to 0.01 m/s (Cahora Bassa), but their land use values are very spread out. It is hard to discern a pattern to the data, given the small size of the sample. However assumption of a relationship might be made on the basis of the connection between flow rate and velocity, though this also depends on the reservoir volume.

The eighth graph shows land use in km^2/TWh pa plotted against the production factor, see figure 7.8 below.

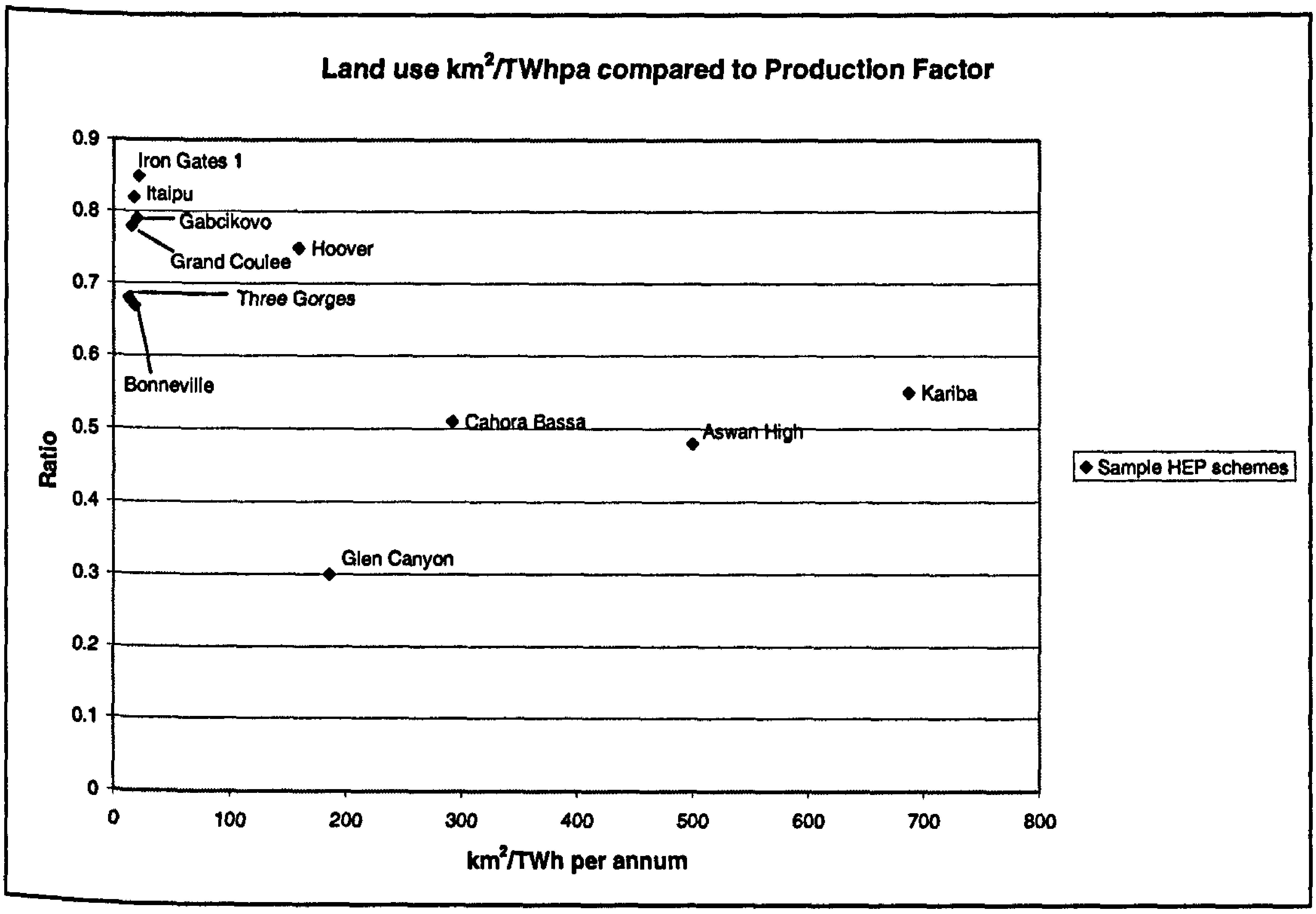


Figure 7.8 Land use compared to production factor for the sample.

This shows seven of the schemes with low to medium land use with high production factors ranging from 0.68 (Bonneville) to 0.85 (Iron Gates 1), and four high land use schemes with low production factors ranging from 0.3 (Glen Canyon) to 0.55 (Kariba). It would be reasonable to assume some relationship between land use and production factor, though the sample data only appears to distinguish between the reservoirs with considerable storage and those without.

The ninth graph shows land use in km^2/TWh pa plotted against mean river flow, see figure 7.9 below.

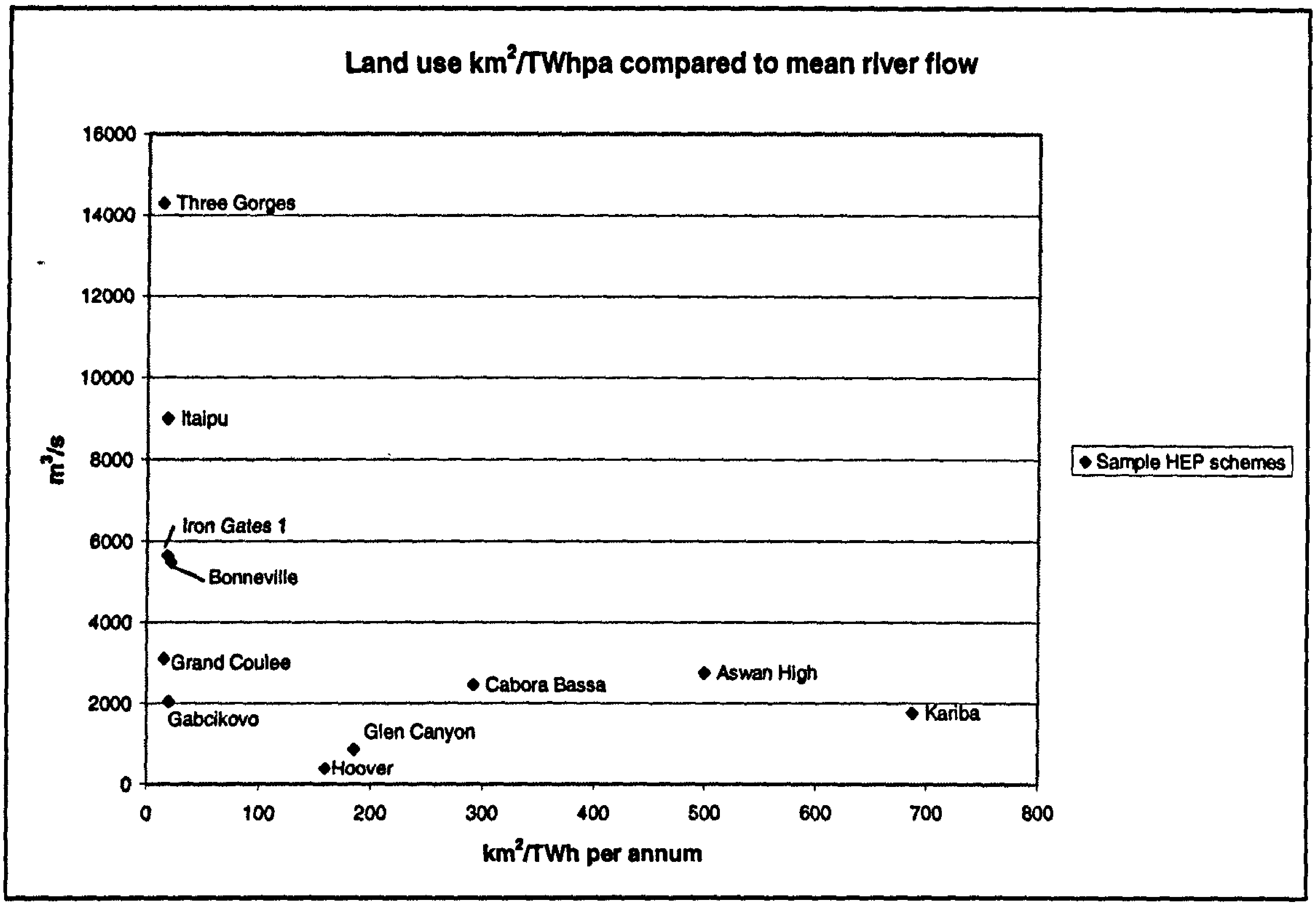


Figure 7.9 Land use compared to mean river flow for the data periods, for the sample.

This shows the low land use group in the sample with considerable spread of flow from 2047 to 14300 m³/s, while the higher land use group varies from 395 to 1775 m³/s. It is reasonable to assume flow rate bears some relationship to land use as it is a factor in the power equation for HEP, though head height is also involved. The data, with the small sample size, does not demonstrate this though.

The conclusion is that there is probably no relationship between land use and the head height as a measure of power flux density. No relationship is indicated between land use and Total Stream Power, for the reservoir reach. There is also unlikely to be a relationship between land use and former mean gradient. However the results suggest there could be an inverse relationship between land use and the Cross-sectional Stream Power, (i.e. with slope and flow rate), although due to the small sample size the nature of the relationship cannot be stated with confidence. Also a linear relationship between land use and water residence time could be indicated by the sample data, though this cannot be stated with much confidence. A linear relationship between land use and reservoir volume is also indicated, suggesting that despite differences in reservoir shape and depth, generally reservoirs of greater volume occupied more land per unit of energy generated. This implies that variations in reservoir shape and depth can be largely discounted as a factor accounting for the data. Again though, due to the small sample size confidence in this is low. No relationship between land use and average reservoir fluid velocity was indicated. No clear relationship between land use and the Production Factor was apparent, though dams designed for considerable storage appeared to be the lower Production Factor schemes. No apparent relationship between land use and mean river flow was shown by the data.

Further interpretations and explanations of these relationships could be made; for example the range in reservoir shape and the small size of the sample.

As stated in Chapter 3 land use per TWh might be expected to be inversely related to power flux density, in that the more intense the power flux, the lower the area required. For HEP schemes this is mainly the reservoir area which is a function of head height, flow rate, river gradient and the topography of the valley, as well as the storage capacity required. In the test sample, the greatest land area values are those of the desert or tropical HEP schemes where low or relatively low flow rates coupled with highly seasonally flow variations are found. The Kariba scheme has the highest land use with 687 km^2 / TWh per annum. This is followed by the Aswan High scheme at 500 km^2/ TWh per annum. The Glen Canyon scheme follows with only 185.6 km^2/ TWh p.a. and then the Hoover dam with 159.75 km^2 per TWh p.a. The average land use for the sample was 175 km^2 / TWh p.a.

These are all high head impoundment HEP schemes, and most have low river bed gradients, in the range of 0.014% for the Aswan High to 0.0519% for Glen Canyon, though the Hoover has a steeper gradient of 0.128%. While the Aswan High has the lowest river bed gradient in the sample, there are other schemes with low former river bed gradients too, but it is apparently the combination of high head schemes and low or relatively low bed gradients with relatively low flow rates that results in reservoirs with large land area per unit energy generation, in this selection.

In the sample the variation in valley topography, mean breadth, and steepness of the valley sides, may not be very conducive to the formulation of any reliable meaningful generalisation, for example relating the land use per unit energy to the head height, flow rate and bed gradient. In general it might be expected that the shallower the gradient, and the broader the valley, together with low flow rates, the greater the land use per unit energy, and this is weakly indicated as a factor for this sample, see above.

However, the lowest land use per TWh per annum is that of the Three Gorges Dam, at 12.8 km^2 per TWh p.a., although this development has a low river bed gradient. The high flow rate is the crucial factor here. As pointed out in chapter six, the steep sides and relatively low reservoir volume compared to the flow rate make for efficient use of land area.

Land Use - Sedimentation Correlation

There might appear to be a correlation between land use and sediment trap efficiency, in the sample, with the Kariba dam using most land per unit of energy and also having the highest Brune trap efficiency. In fact the five highest land use cases all have sediment trap efficiencies of over 96%. The sample average Brune sediment trap efficiency was 76%. The lowest land use cases in the sample had Brune trap efficiencies of 90% or below, though the correlation was less pronounced in some cases. However, comparing Brune sediment trap efficiency to land area km^2/ TWh, produced no clear relationship, since the lower land use group of schemes had the greatest variation in trap efficiency from 18.1% to 87%, and the higher land use schemes all vary considerably from 159 to 687 km^2/ TWh pa.

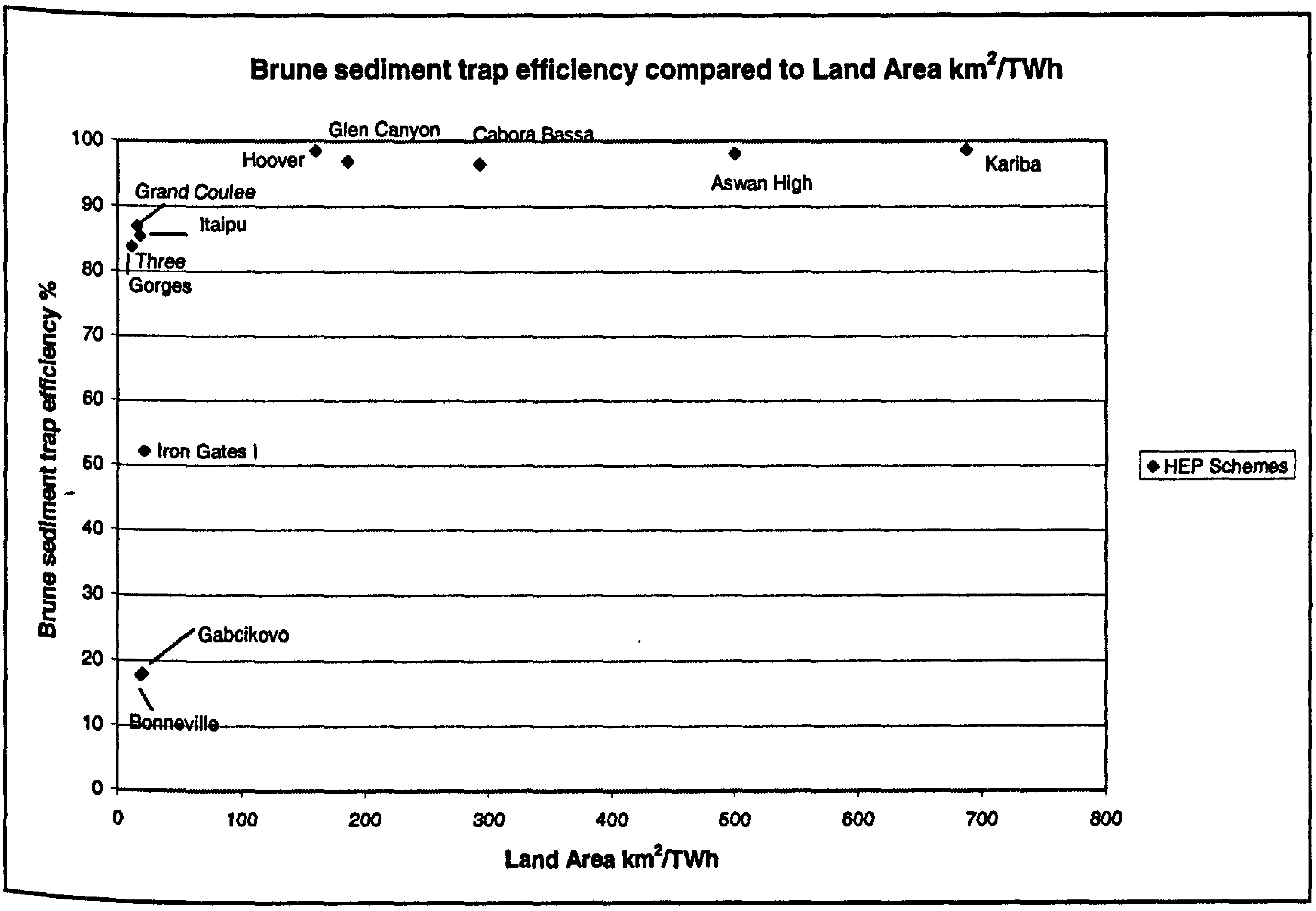


Fig 7.10 Brune sediment trap efficiency compared to land area km^2/ TWh.

7.1.3 Power flux density change in flow rates and head heights

Most impact might be expected where the change in river gradients of the former river bed to that of the reservoir, which is almost level, is greatest. Water residence times (i.e. the reservoir volume divided by the flow rate in the reservoir) may then relate to the greatest impacts.

The Aswan High scheme has the lowest former river gradient and also the second longest water residence time, with low average fluid flow rates. High sedimentation rates with 98% of 127 million tonnes per annum trapped, 125M t p.a. have been recorded (Stanley 1996, Saad 2002, El-Moattassem 1994). The change in power flux density in the large volume reservoir together with long water residence time causes a drop in flow rates, and deposition to occur.

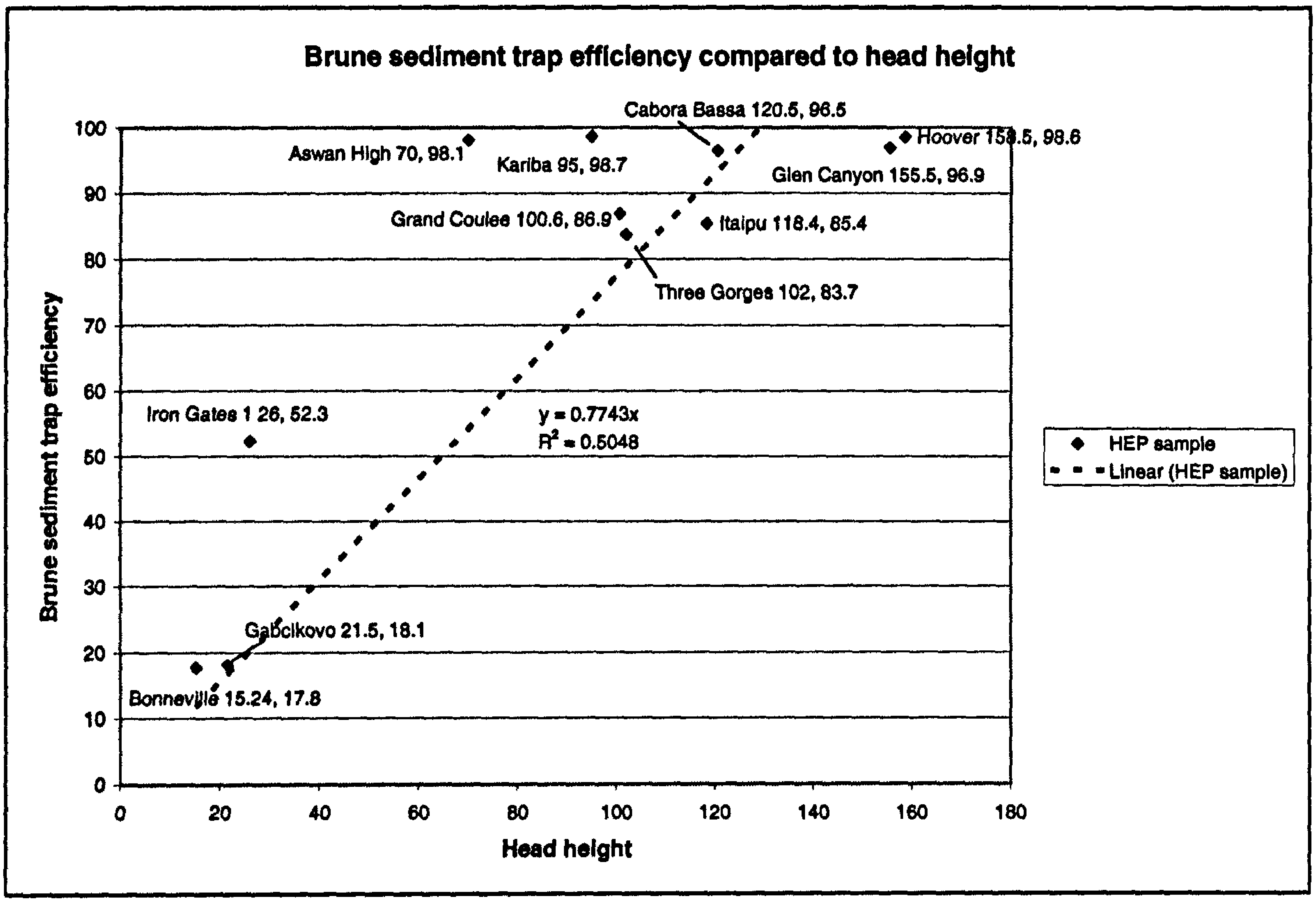


Figure 7.11 Brune sediment trap efficiency compared to head height and hypothetical power flux density as a reflection of head height.

The Brune sediment trap efficiency compared to head height appears to suggest this for the sample, see figure 7.11 above. Were a trend line to be added, a linear relationship with a slope of $y = 0.774x$ and $R^2 = 0.5048$ would be shown, and a power relationship with a slope of $y = 2.9823x^{0.7264}$ and $R^2 = 0.8306$ can be shown. This could appear to accord with the hypothesis, in terms of hypothetical power flux density as resulting from head height. The river Nile might be expected to have a high sediment load, as it flows down from highland areas with high erosion rates, and flows through dry desert areas. The Three Gorges scheme has the second lowest former river gradient; again sedimentation might be expected. The scheme is expected to have high sedimentation rates of 541.16 million tonnes per year (Freer 2001), and 526Mt p.a. at Gezhouba (Yishi 1994). However, this scheme, despite having an average sediment load cited as 1.2kg per m^3 (Freer 2001), has a high flow rate, relatively low reservoir volume and thus relatively fast reservoir flow rate, reflected in the low water residence time, which counters to some extent the rate of deposition. Both of these rivers have high river loads, i.e. 127Mt p.a. and 541.16Mt p.a.

The magnitude of head heights may be related to the change in flow rates, the gradient over the former river bed being the operative factor here; the shallower the former river bed gradient, the greater the flow rate change per metre of head height. However, water residence times, depending on reservoir volume relative to flows, may appear more significant to the parameters of land use and sedimentation. High head height HEP schemes have other impacts, such as water quality, gas super saturation, and fauna barrier effects, parameters outside the scope of this study.

7.1.4 Proportion parameter:

The extraction and conversion of energy from the river power could be expected to result in impacts from loss of mechanical energy for erosion, and sediment load transport. The higher the proportion or ratio of energy extraction, the greater the losses expected. There are a number of different ways that the parameter of proportion of flow can be measured:

-proportion of potential energy at the dam converted into electricity.

-proportion of the river flow abstracted via penstock and turbines.

-proportion of the river flow intercepted and converted to reservoir flow.

In terms of the conversion of river power to electricity, the Iron Gates I and the Itaipu schemes have high energy extraction rates of ~88% and ~82% respectively, and therefore high mechanical energy losses from the river flow, leading to an expectation of losses of erosion and load transport, resulting in deposition. Deposition rates of Iron Gates have been cited as 20Mt p.a. (Schwarz 2008) and Itaipu have been cited as 45M t p.a. (Borghetti 1994).

However, although the proportion of the river's power that is used for electricity produced can be cited, in terms of the functions of the river, these functions are of necessity wholly interrupted when the whole of the river flow is impounded in the reservoir. The changes effected to the flow rates as the river enters the reservoir, exhibit the change in the dissipation of energy from the equilibrium of gravity induced kinetic velocity with bed friction, to near static conditions of potential energy for the larger reservoirs. Since the proportion of interception of the flow, is 100%, (the dam straddles the whole valley), the whole of the river flow is affected. The degree of effect depends on the change in flow rates, and can also be expressed as the reservoir retention time.

The operation of normal impoundment HEP schemes involves varying reservoir levels. This may be done for a variety of purposes, for example to even out seasonal variations, to "load follow" responding to demand fluctuations, to pass through flood flows, or to reduce stresses on the dam. The consequence of lowering reservoir levels or "drawing down", will be to reduce its depth, and shorten the effective length of the reservoir, thereby reducing its volume. This will have the effect of increasing the water velocity and decreasing the retention time. Therefore there will be less change in the river flow than with full reservoir water levels. The lowered head height will mean less power can be converted to electricity. The power flux density at the dam will be reduced, but the power flux density over the reservoir reach will be increased.

The lowering of the reservoir levels in flood conditions is a tactic that has been used on a variety of dams for flushing through sediments (Tesaker 1986, Yishi 1994), and is to be employed on the Three Gorges HEP scheme in order to avoid excessive sedimentation. As water velocity is a function of reservoir volume and river flow, the reduction in reservoir levels will, effectively, allow more of the sediment to be passed through, due to the higher water velocity in the reduced volume and shortened reservoir.

This mode of operation can be described as reducing the proportion of energy abstracted from the river flow, over the reservoir reach, and increasing the proportion available for the river's functions, in this case that of transporting sediment.

Proportion: Case of Gabcikovo

The change in flow rates and reservoir water retention time, are a useful indicator for potential impacts. However, this may not be the case for certain HEP schemes that have a reservoir "off-line", i.e. smaller schemes. The Gabcikovo scheme for example, does not impound all of the flow for the full length of the diversion, but just for 16 km of the main Hrusov-Dunakilit reservoir; the extension of a 17 km long leat, plus some further kilometres of tailrace canal below the power plant, takes about 85% of the flow (Zinke 2004 p1, Liska 1993 p37). This was achieved after more water was allowed to flow in the old river course, as a result of Hungarian government demands (Zinke 2004).

In the case of the Gabcikovo scheme, much of the impact is caused by the abstraction of ~85% of the flow in the sealed raised leat for 17km, leaving insufficient water flow in the side arms and in the old river bed to move sediments and flush through the gravel beds of the wetlands of this "inland delta" section of the river (Zinke 2004).

These effects can be described as both losses of energy, i.e. Total Stream Power, to the reach concerned, and also as hydrology losses; the water table has been lowered.

The effect of the unique (for its size) design of the Gabcikovo scheme is to reduce the land area use (5th highest in the sample at 20km^2/TWh pa) and the reservoir volume in relation to the head height of up to 24m achieved, but at the cost of diverting most of the flow away from the old bed, drying out the old wetlands. Originally in the 1977 Treaty between Czechoslovakia and Hungary, the "ecological" or compensatory flow was agreed as 50 m^{3}s^{-1} in winter and up to 200 m^{3}s^{-1} in the growing season (Liska 1993, p37). This would have provided compensatory flows of only between 3.2 -10% of the seasonal mean. Zinke reports that as a result of (HEP) operations parts of the extended system of braided channels and side arms had fallen dry, and by 2003, artificial methods of increasing water levels in these channels were being used. Small weirs to raise water levels were being used. In order to restore the wetlands of this area, Zinke has proposed that only 35% of the flow should be diverted into the power canal channel, the leat, and that 65% should flow in the river bed rather than the ~15% currently (Zinke 2004).

Proportion: the amount of energy that can be extracted

In seeking to discover how much energy can be extracted, while avoiding significant impacts, one response that can be suggested is: the proportion that leaves enough energy to perform the most critical functions of the river flow. What this could mean in practice can be seen from the examples cited above in chapter 5 and chapter 6 concerning the flood flow pulse releases on the Colorado River (USGS 1996) expressly for the purpose of ecosystem functions, such as sediment removal to preserve vegetation types and to reduce salinity and transport nutrients at the delta area.

Considering the figure 6.28 chart on page 208 chapter 6, of Aswan mean monthly Total Stream Power 1871-1967 and 1970-1984, the skewed distribution of Total Stream Power of the pre dam flow, into the three months August, September and October can be noted. 62% of the total flow occurs in these three months and therefore 62% of the river's energy. After dam construction, the flow rate reflects releases for the purposes of irrigation, water supply and power generation, with only a mild skew of 34% of the total flow occurring in the three peak months of June, July and August.

Were some of the river's energy to be allocated to sediment transport and ecological functions in a similar manner to the Colorado River, pulse releases could be made e.g. in the former peak flow month of September. 25% of the total river flow occurred in September prior to the dam, while this was reduced to just 7% afterwards. A pulse release reflecting a proportion of the inflow to Lake Nasser/ Nubia, would however, incur the loss of water stored for the low winter and spring flow months, particularly of April and May.

The pulse release power should be sufficient to transport sediment to replenish that lost by coastal erosion from the delta, and to counteract salinity incursions. These two impacts might be considered the most critical for the River Nile delta area. However, the stored Nile water allocations are very tightly committed for irrigation, water supply and energy production, and there is generally a water deficit in much of Egypt and the delta area (Stanley 1996). The Aswan High dam scheme was not designed to pass water allocations downstream for river functions and ecological purposes and it is fair to say that environmental impacts were not fully anticipated. Egypt's population has grown, as have industrial activities and water supplies are ever more stretched, making it hard to implement pulse releases.

On the Colorado River just 0.5% of the total run off was considered necessary to allocate to the river's functions at the Delta. (US-Mexico Colorado River Delta Symposium 2001, p41) However, the main impacts being addressed were those of encroaching salinity, and some nutrient transport, as opposed to sediment transport which would require greater flows.

The Aswan High scheme which has the lowest gradient, and the second longest water residence time in the sample, also has a relatively high rate of siltation, with 98% per cent of the river load of 125M tons p.a. (Stanley 1996, Saad 2002) deposited (El-Moattassem 1994).

The sample size of HEP schemes in this study has of necessity been small at eleven main cases and a further seven investigated in part, and hence cannot be statistically representative in relation to proportion of energy extracted and intercepted, but only indicative.

7.1.5 Total Stream Power analysis

The test of changes in Total Stream Power before and after dam construction carried out on four of the rivers in the sample downstream of the dam, appears to indicate some relationship between power flux density and environmental impact. The reduction of the peak flows causes reduced TSP for those months, and thus the high power fluxes from floods are lost. Since most of the sediment transport and lifting of material to be transported occurs then, this function of the river flow is diminished or lost. The flood flows continue down the river, often all the way to the mouth and the sea. As a result the loss of this energy does indeed have consequences all the way down the river on sediment transport. Sediment transport is much reduced or has ceased.

TSP lost through attenuation of flood flows continues on downstream, so that energy required for pick up and transport of material, suspended load and bed load, is not available. The effect of this loss of TSP can be seen in the loss of material to replenish deltas, good examples of which are those on the Nile and the Colorado.

Nile

The Nile mean monthly peak flows have been reduced by over 70% at Aswan, by the High Aswan Dam scheme, with corresponding mean monthly Total Stream Power losses in the reach from Aswan to Gaafra, so that only 29% of TSP is available below the dam. This diminution continues all the way down the Nile to the mouth. Formerly flood flows continued all the way to the sea before the High Aswan dam was built, transporting sediment and depositing it at the delta (Petts 1984). However, continuous data records covering the period before and after the dam were only available at Aswan. The Nile delta is being eroded with 100 metres per year retreat of shoreline in some areas at Rosetta and up to 50 m p.a. retreat in others, at Damietta (Stanley 1996).

Additionally the maximum peak flows before the dam was built have been attenuated; 12345 m^3s^{-1} is the maximum recorded, for the period 1871-1966 at Aswan, to a maximum of 2639m^3s^{-1} since, for the period 1970-1984. This represents a reduction of 78.62%. The corresponding TSP values are 1,030,000 kW pre 1967 and 220,000 kW since, between 1970 and 1984, see below in figure 7.12

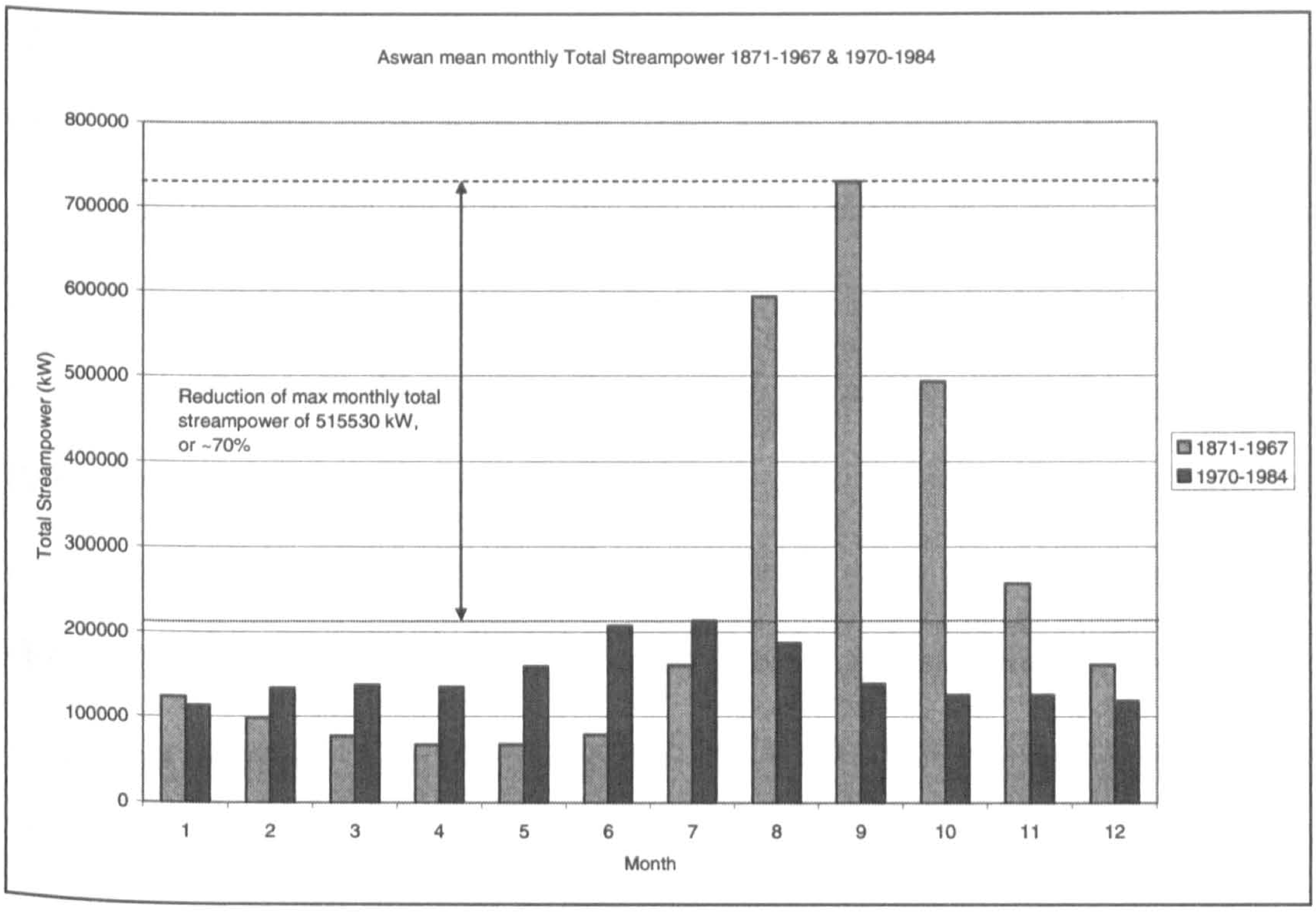


Figure 7.12 Reduction of maximum monthly mean Total Stream Power at Aswan after construction of the High Aswan Dam by ~70%.

Since it is the highest flood flows which are responsible for the highest TSP values, these peak values are responsible for the maximum sediment transport rates and the bulk of transport. The highest flood flows perform most sediment transport and are inordinately important in for example, recharging deltas (Stanley 1996).

The capability of the High Aswan dam reservoir, Lake Nasser and Nubia, to attenuate both flood flows and low flows is considerable, since the mean water residence time of nearly two years (1.94 years) based on its volume of 168,900 × 10^6 m^3, and its mean flow rate of 2760 m^3s^{-1}.

Danube

In contrast to the Nile however, on the Danube, the flood flows are only slightly affected by the HEP schemes, due to the dams being "run of the river" type. Since the reservoirs' volumes are relatively small in relation to flow rates, they are unable to significantly attenuate floods, and the seasonal peak flows are passed on downstream with the effect that the TSP is relatively unaffected and some sediment transport continues downstream and while overall the delta is diminishing, there is still some accretion in the NW part (Panin & Jipa 2002). Sediment transport to the delta has reduced to 30-40% of former rates, subsequent to the Iron Gates I & II scheme (Schwarz 2008).

For the 128.5 km Novo Selo to Lom reach, 29 km below the Iron Gates II scheme, the reduction in Total Stream Power after 1970, for the peak flow months of April, was 6.9 % and for May 10.4%. For the next section from Lom to Jiul, the TSP reduction is 6.14% for April and 8.14% for May.

The Iron Gates I reservoir volume is 2500 × 10^6 m^3, and as a proportion of the mean flow rate of 5500 m^3s^{-1}, the mean water residence time is 5.26 days, which would be likely to result in a certain amount of storage time and thus some attenuation of peak flows, but not very much.

Much further down the Danube, at Zimnicea 336km below the Iron Gates HEP scheme, flood flows on the Danube have been reduced by 22%, after 1970, for April and by 43% for May. This greater reduction in Total Stream Power loss further downstream is possibly the cumulative result of multiple small dams and reservoirs retaining flows on tributary rivers entering the main stream (Schwarz 2008), as well as up stream. Schwarz cites loss of bedload as one of HEP's main consequences on Danube. Also Brune trap efficiencies, of Iron Gates at ~52%, and Gabcikovo at ~18% reduce sediment transport.

At Dunaalmas 87 km below the Gabcikovo HEP scheme, no loss of flood flow effect can be deduced from the data available. This is due firstly to the data set only extending to three years after the scheme was operating, and secondly it may well be that there is little or no attenuation occurring due to the scheme. This may be the case since the reservoir volume is small, at 243 × 10^6 m^3, as a proportion of mean flow rates of 2047 m^3s^{-1}, and mean water residence time in the reservoir at Gabcikovo is only some 32.97 hours. Therefore flood flows could not be stored.

In this case the flood flow rates and hence the Total Stream Power available still allows some material to be transported to the delta, though not enough to prevent the net balance of sea erosion and river deposition from causing diminution of the delta (Panin & Jipa 1999). Diminution of the delta through erosion is also occurring, however, due to channel dredging and jetty protection for improving shipping channels, as well as sea level rise of ~3mm pa (Schwarz 2008). Whereas Panin & Jipa put the blame on the Iron Gates dam project, an EU research project EROS 2000, states that studies show that "most of the river's sediment is trapped by the delta" (EROS 2000). According to the INHGA (2005) as much as a 65-80% drop in sediment transport regime had occurred since the 1930-1965 "natural river" period.

River Columbia

On the river Columbia, in the USA section below the Canadian border, after 1973, mean monthly peak flows reduced from 8175 m^3s^{-1}, to 3630 m^3s^{-1}, i.e. to 44.4%, at the Grand Coulee dam.

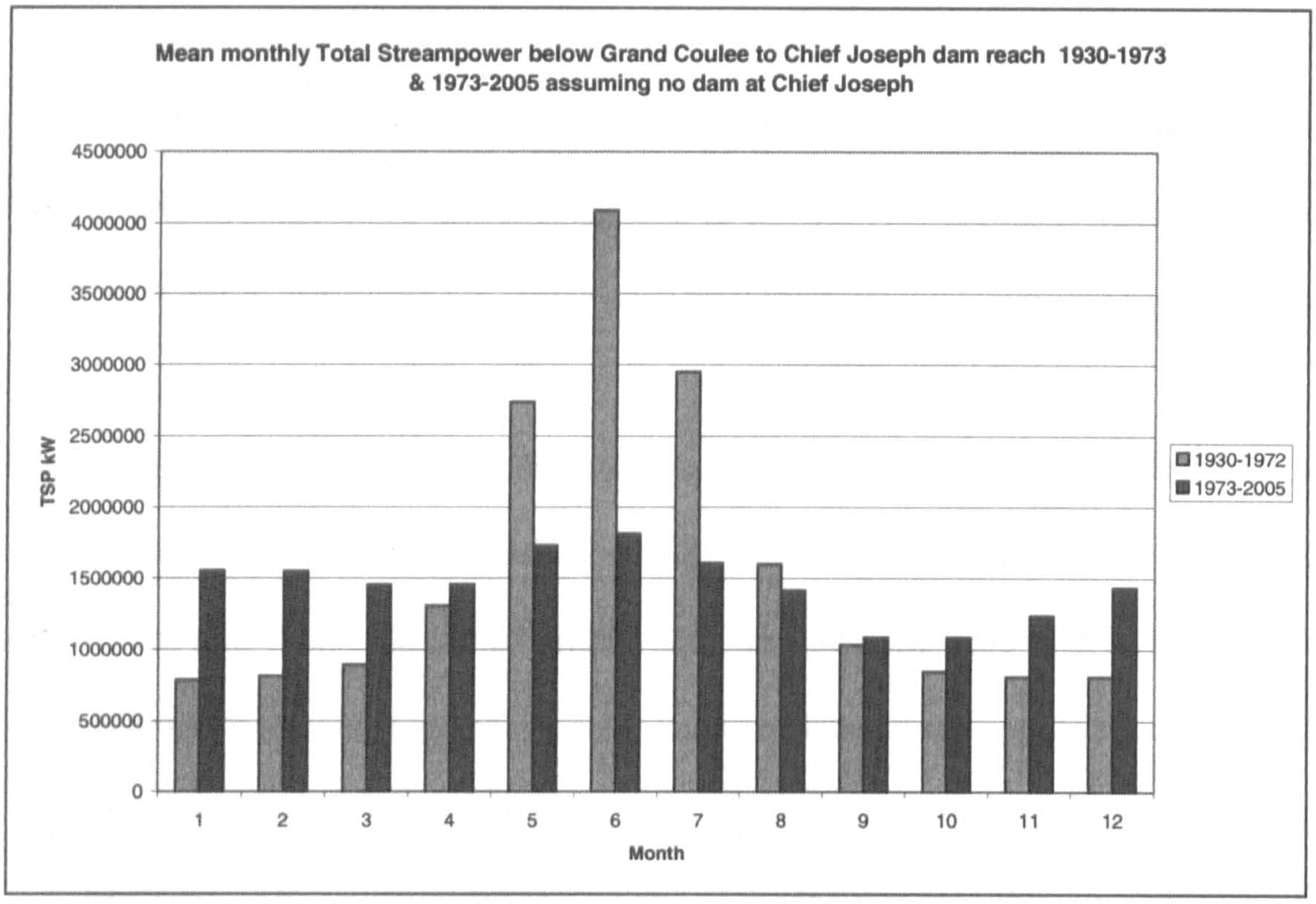


Figure 7.13 Mean monthly Total Stream Power below Grand Coulee to Chief Joseph reach 1930-1973, and for 1973-2005 assuming no dam at Chief Joseph, kilometre 877.

Assuming no dam had been built at Chief Joseph, the diminution of the peak TSP values would have been from 4090000 kW to 1820000 kW, in June for the 82.1 km reach with a fall of 51m, and can be observed from figure 7.13 above. This can also be seen from table 7.1 below, which includes both the actual level gradient of the current Lake Rufus, with TSP values of zero kW and the values assuming the original surface gradient profile. The mean TSP values do correlate roughly with the mean power flux of the river at the dam line, based on the formula: - 'Power in kW = q × g × h', obtained from other sources, allowing for differences in head height due to varying reservoir levels. 1630000 kW is the power flux based on a head height of 54.25 m, for Chief Joseph dam, while the mean TSP values based on 51m height difference comes to 1560000 kW.

1930-1973	1973-2005 assuming original gradient profile	1973-2005 Actual gradient
789000	1560000	0
813000	1550000	0
892000	1460000	0
1310000	1460000	0
2740000	1730000	0
4090000	1820000	0
2950000	1610000	0
1602000	14200004	0
1030000	1080000	0
846000	1090000	0
809000	1240000	0
811000	1440000	0

Table 7.1 Mean monthly Total Stream Power values for the Grand Coulee to Chief Joseph reach of the Columbia River 1930-1973 and 1973-2005, assuming original surface gradient profile and actual surface gradient.

It can be concluded that construction of Chief Joseph HEP scheme has resulted in an almost complete loss of TSP over the reach, with the river power now concentrated at the dam. Formerly this energy was dissipated in friction with the river bed and in the transport and suspension of sediment. Since the US section of the river is almost entirely impounded with dams, the TSP of the river has correspondingly been almost completely lost and the river power is now concentrated at the dams, where it is used to generate electricity, or passed over the dam spill ways.

In the only natural reach left on the US stretch of the Columbia, that of the 95.12km reach from Below Priest Rapids Dam to the headwaters of McNary Reservoir, the maximum mean monthly Total Stream Power has fallen from 2050000 kW in June, between 1930 and 1972 to 1010000 kW between 1973 and 2006, i.e. 49.42%, as a result of the impoundments upstream, especially those in Canada, the Mica Dam particularly. This reduction in peak flows and thus TSP can be observed all the way downstream to the mouth.

In addition to the loss of TSP and its effects on sediment transport, one of the major impacts of the Columbia River is the reduction in Steelhead Salmon fisheries due to the impoundments (Petts 1984). The change in habitat from free flowing river with sections of rapids and waterfalls, with gravel beds to a series of lakes has been profound, with a variety of consequences. One of these, the reduction of seasonal flow variations is connected to the poor breeding rates of surviving salmon, which depend on seasonal flooding for salmonid movement downstream (Petts 1984). The diminution of the mean seasonal flow rate range (i.e. the difference between peak and low flows) from 6597 m^3s^{-1} to 1465 m^3s^{-1}, just 22.21%, is marked.

River Colorado

Although the Colorado has been much less impounded than the Columbia and still has considerable natural gradient reaches, its two major dams have a large volume compared to the mean flow rate and hence long water residence times. For the Glen Canyon scheme the residence time is 357 days, almost a year (0.9785 years), and for the Hoover scheme it is 1024 days, almost 3 years (2.8076 years). The highly variable seasonal flow rate of the natural river is significantly attenuated, and this is partly the purpose of these schemes; that is to ensure a reliable flow for the multiple purposes.

At Lees Ferry 23.4 km below Glen Canyon dam, the mean monthly peak TSP in the period 1911-1963, of 1830000 kW fell to 528000 kW, for the reach Lees Ferry to the Little Colorado confluence. This was 28.85% of the former TSP or a reduction of 71.14%.

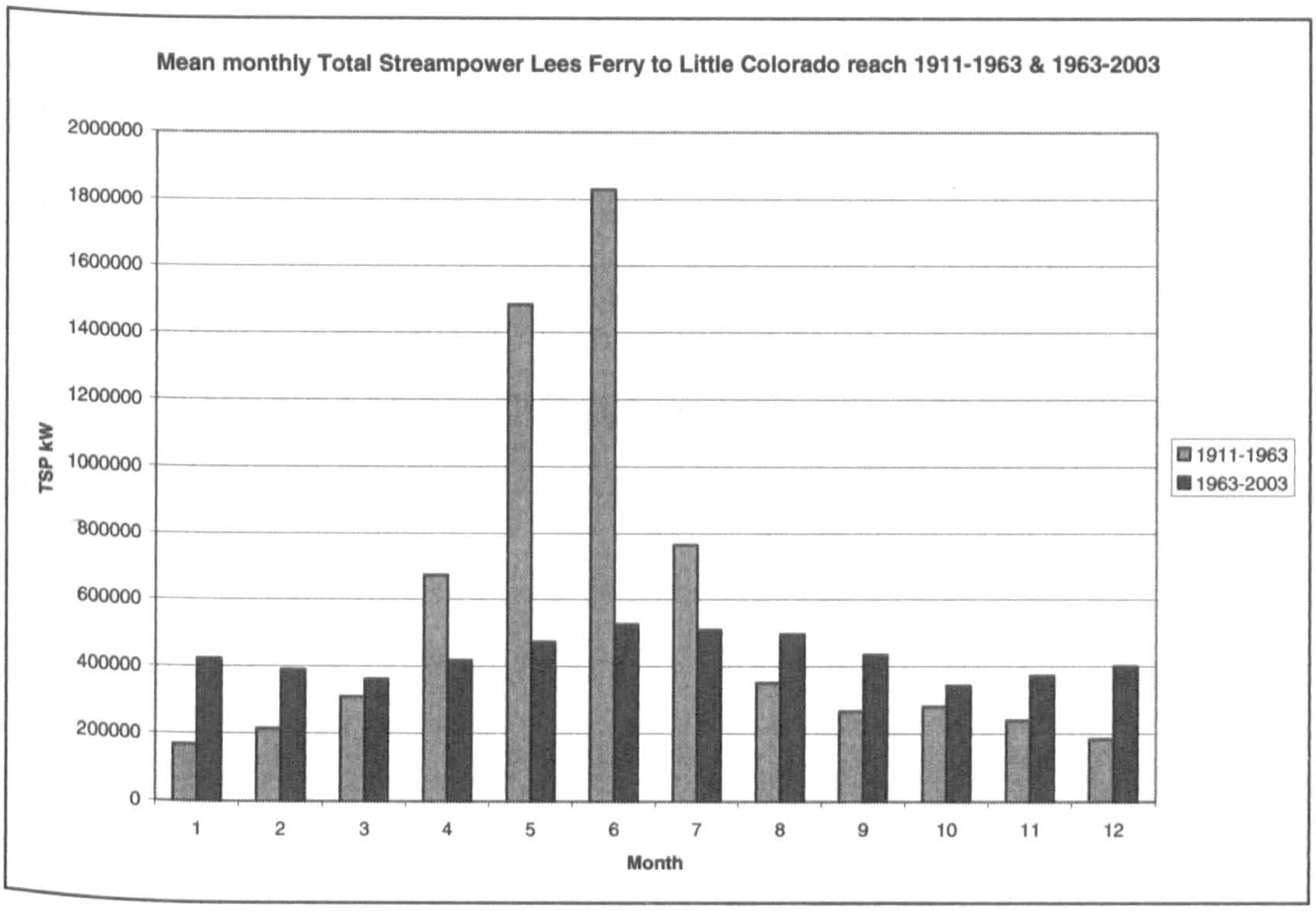


Figure 7.14 Mean monthly Total Stream Power kW, for the Lees Ferry to Little Colorado reach River Colorado 1911-1963 and 1963-2003.

This can be seen from figure 7.14 above, together with the diminution of the monthly seasonal variation from 1660000 kW to 1840000 kW, just 11.07% or a reduction of 88.93%.

Below the Hoover dam, similar reductions in peak flows and thus TSP can be observed after 1933, from figure 7.15 below, an effect which is clearly apparent some 500km lower downstream at Yuma, and then after 1958-64, the building of the Glen Canyon dam adds to the effect. However, the main factor influencing Total Stream Power, at Yuma is the abstraction of water for irrigation and domestic, urban and industrial water supply, shown by the diminution of mean flow rates at Yuma from 613 m^3s^{-1} prior to 1933, to 187 m^3s^{-1} between 1934 and 1959, and then just 18 m^3s^{-1} post 1975.

Although this water abstraction has not been for the purpose of energy, but for water supply, it does impact greatly on the river's available energy to perform its functions. The mean TSP at Yuma Arizona has fallen by 96.18 % with an even greater loss of 98.6 % TSP in the peak flow months and represents an extreme example of the abstraction of a natural energy flow.

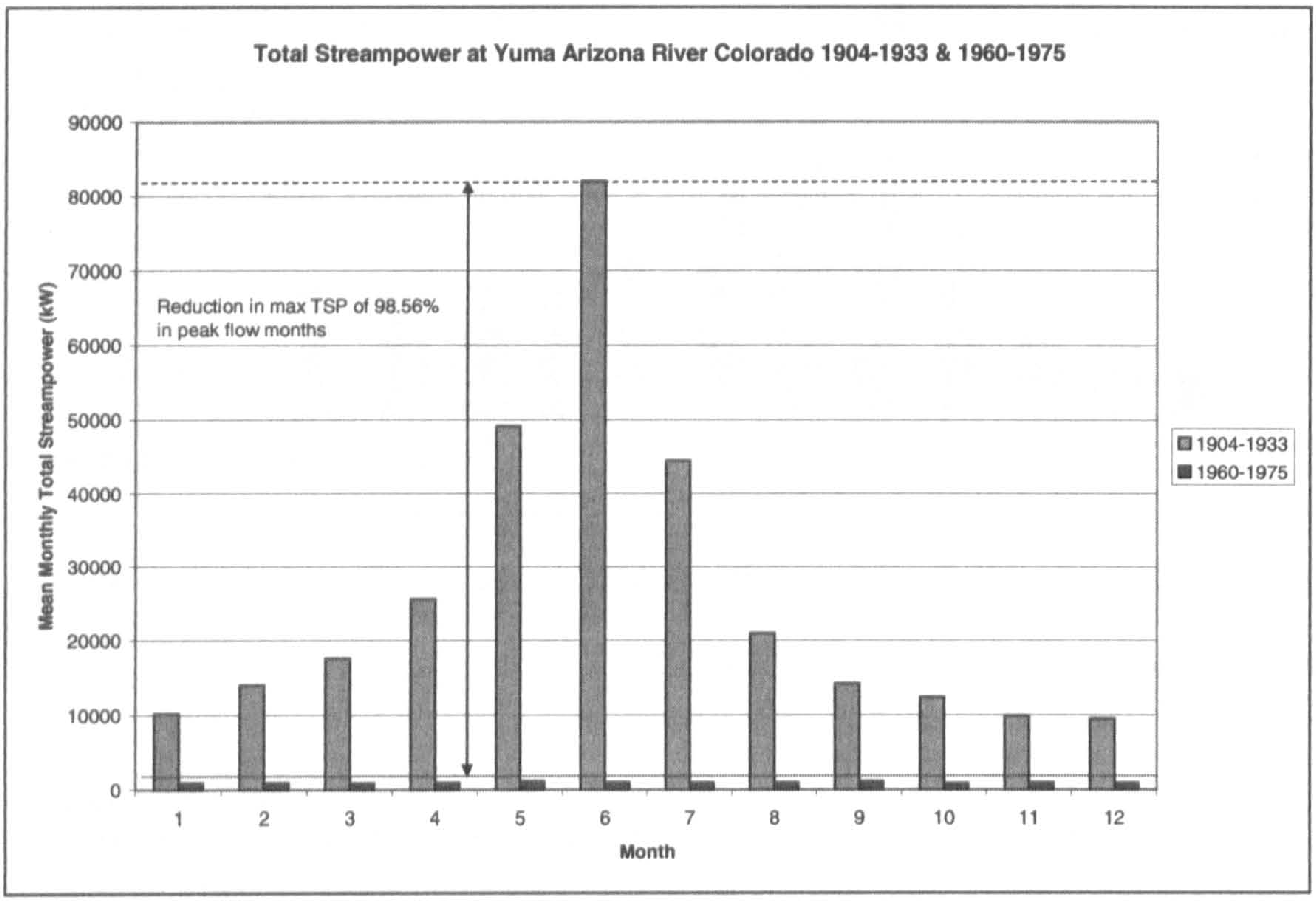


Figure 7.15. Reduction in maximum monthly mean Total Stream Power at Yuma Colorado of 98.56%, 1904-1933, as compared to 1960-1975.

The resulting almost complete cessation of sediment entrainment and transport is reflected in the very considerable losses of the delta area at the mouth of the Colorado in Mexico (International Boundary and Water Commission 2001), as well as river bed and channel effects.

7.1.6 Changes in Total Stream Power compared to delta area land loss

The changes in Total Stream Power before and after dam construction on three of the rivers in the sample downstream of the dam were compared with delta land loss, as a measure of impact from reduced sediment transport.

Peak Total Stream Power change compared to delta land area loss.

River	HEP scheme year	Peak Stream power change	Delta land area change	Land area loss per year
Nile	Aswan High 1967 (Old Aswan 1904)	-71%	112 km^2 to 225 km^2, or 0.5-1% loss since 1900	1.12km^2-2.25km^2
Danube	Iron Gates I 1970 & Iron Gates II	-6.9% -3.36%	19.6 km^2 or 0.24% loss since 1975	0.65km^2
Colorado	Hoover 1933 Glen Canyon 1963 Yuma	-71.14% -98.6%	1874km^2, or 76% loss since 1900	18.74 km^2

Table 7.2 Peak Total Stream Power change compared to delta land area loss

Delta area land loss was ascertained from literature sources with estimations used, for example in the case of the Nile Delta, where no clear figures for land loss were discovered. Land loss rates of up to 100m per year, at Rosetta and 50m pa at the Damietta stream promontories have been cited (Stanley 1996). While overall land area is being lost, some locations are experiencing accretion, due to long shore wave erosion and transport

(Blodget et al 1990). Therefore, perhaps as a result of the dynamic nature of deltas, the author has been unable to find a clear figure for land area loss in the literature. Additionally, other causes of land area loss are also cited, for example sea level rise (Frihy 1991), blocking of drainage channels, and subsidence due to freshwater well pumping and drilling for oil and gas (Frihy and Khafagy, 1991; Stanley and Wingerath, 1996). However, reduced sediment transport by the river is undoubtedly a major factor, as until about 1900, accretion of the promontories by 3-4km over the period between 1800 and 1900 was recorded (Lofty and Frihy 1993). An estimation of land area loss has been made based on these diverse sources. The length of the coast line of the Nile Delta has been cited as 225 km (Stanley 1996), maximum coastal retreat of 3-4km since 1900 has been recorded. If an average retreat of 0.5-1 km is assumed, then ~100-225 km^2 can conservatively be assumed to have been lost since dams were first built at Aswan. This land area loss since 1900 has been turned into a figure of 1.12-2.25km^2 loss per year. However, the major loss has occurred more recently since the High Aswan Dam, and is probably higher, so that this figure is considered conservative.

For the Danube Delta, over the period 1975-2003, about 100 ha per year, over 100km of the Black Sea coastline has been lost, as a result of intensive erosion processes, with 70km of this coastline within the Delta area (Zoran & Anderson 2006). Therefore 28yr x 70 ha = 1960 ha or 19.6km^2 has been lost, which equates to a figure of 0.65km^2 pa.

The Colorado Delta has been cited as having an area of 24 percent of the area it covered in the early 1900s (Hinojosa-Huerta 2004). The land area loss has thus been 1874km^2, or ~18.74km^2 pa.

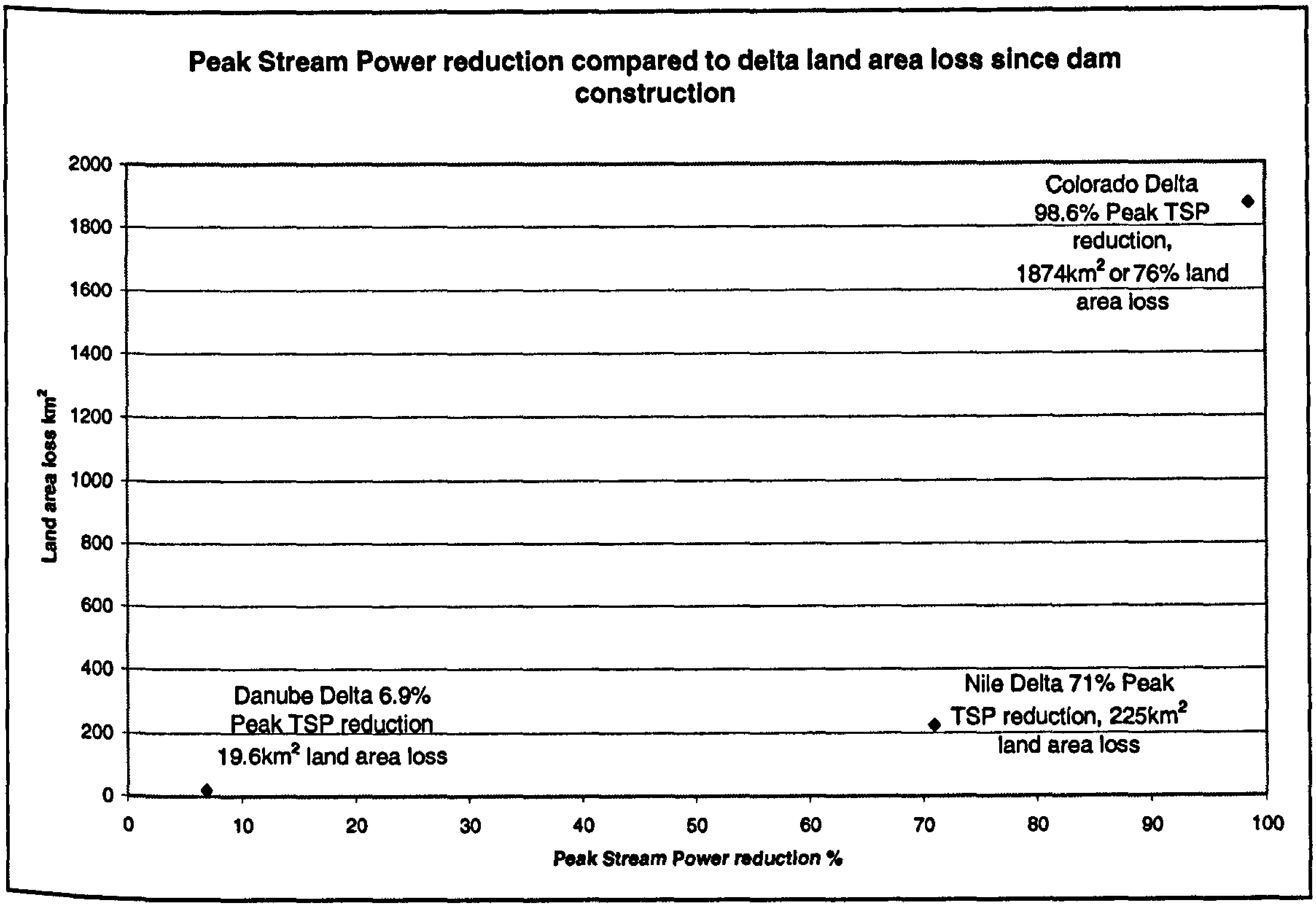


Figure 7.16 Peak Total Stream Power reduction compared to delta land area loss since major dam construction.

Figure 7.16 above shows the reduction in peak Stream Power compared to delta land area loss over periods since impoundment and water management and diversion, for three of the rivers in this study which have deltas. Were a trend line to be fitted, a linear slope of y = 13.564x, with $R^2 = 0.5945$, could be shown but is not significant due to but the very small sample. The land area loss for the Nile Delta is estimated at 225km² but may be considerably higher. A relationship between peak TSP and delta land area loss is indicated, but with only three data points, these figures cannot convey very much certainty. On the basis of rate of land area loss per year, see figure 7.17 below. If a trend line were to be included, a linear slope of y = 0.1358x, with $R^2 = 0.5845$ would be shown, though as the sample is so small, it is not included. If the lower range of the Nile Delta land area loss per year is taken, a similar slope would be shown.

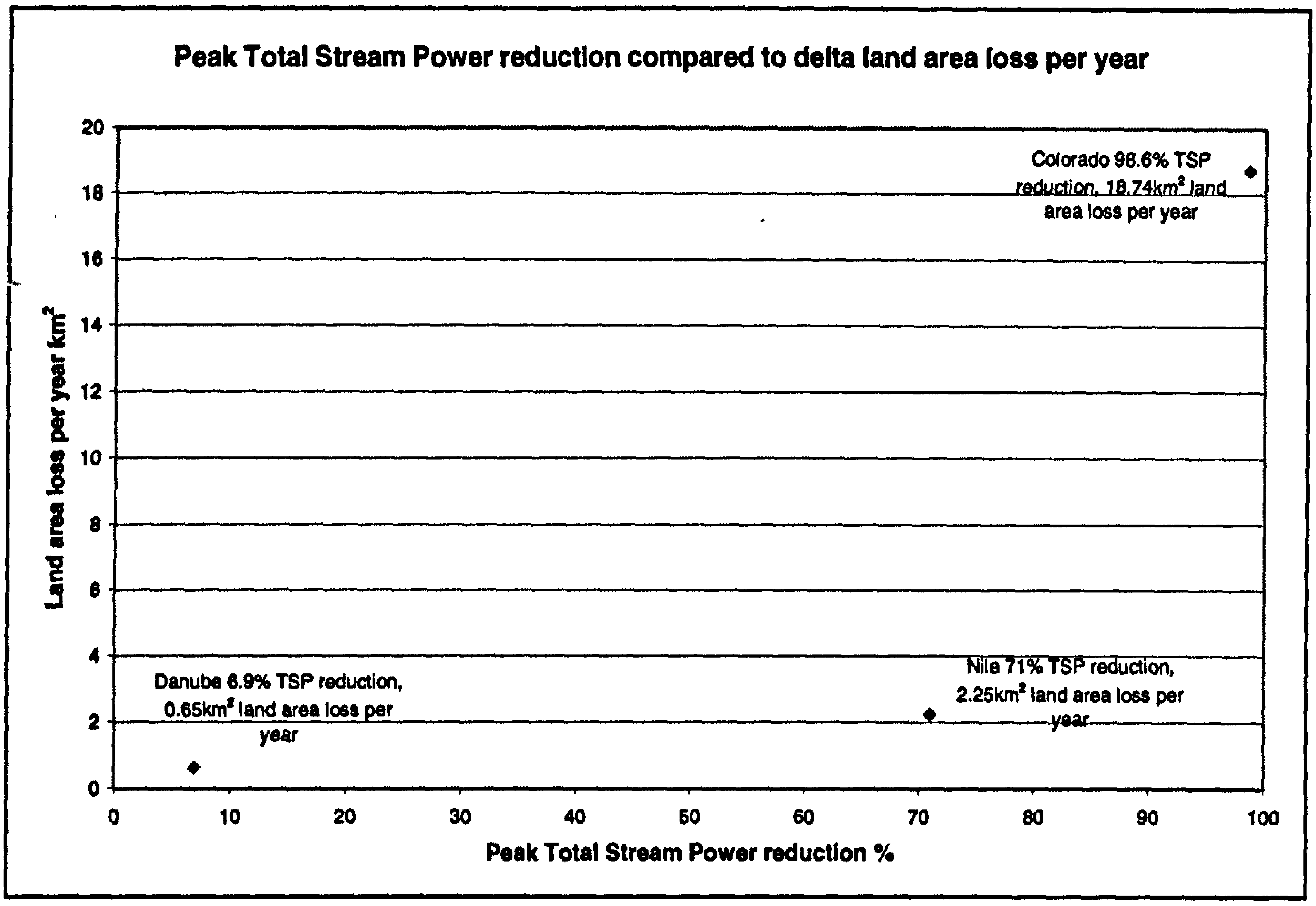


Figure 7.17 Peak Total Stream Power reduction compared to delta area land loss per year.

The peak TSP reduction has been compared with Brune sediment trap efficiency in

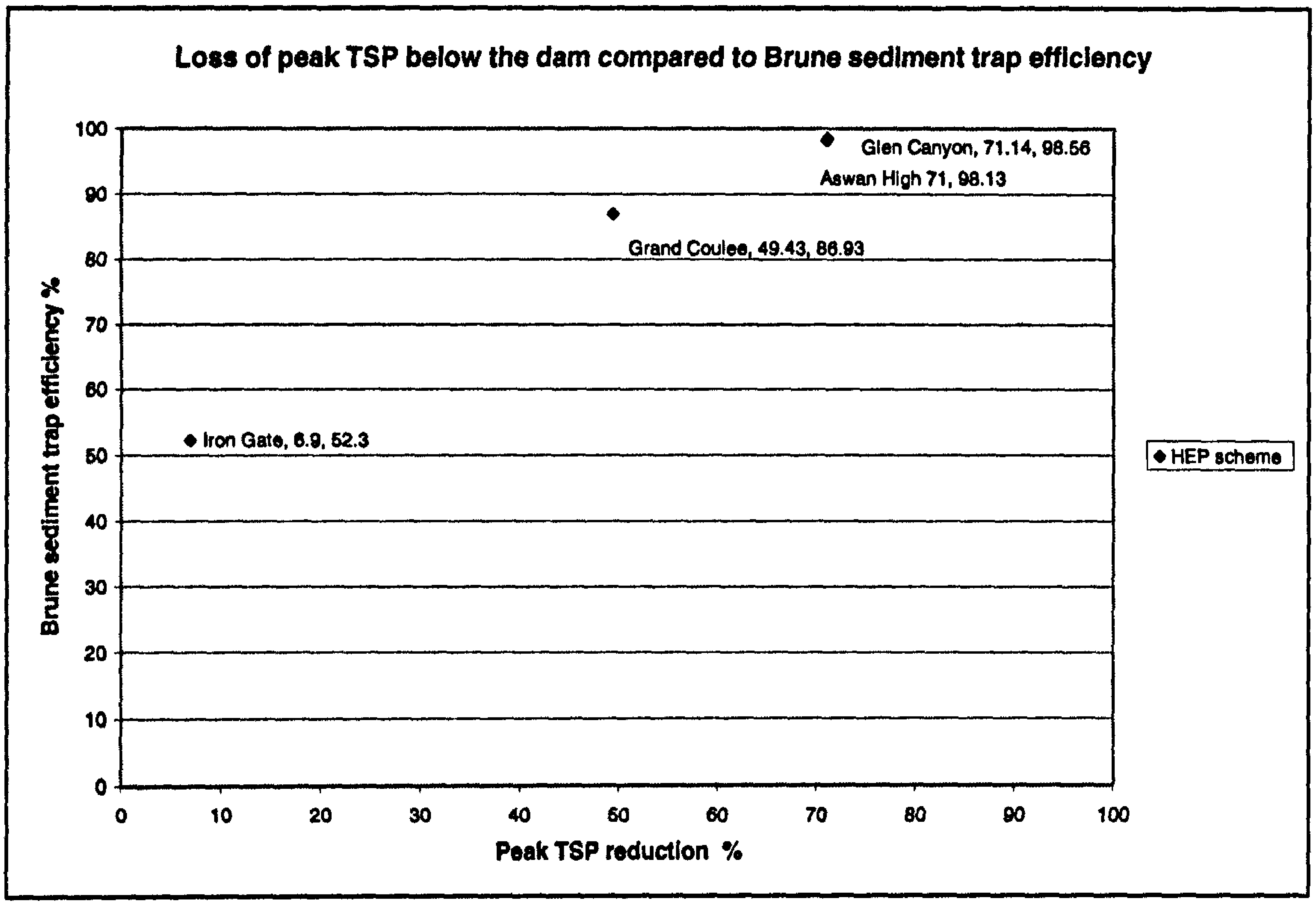


Figure 7.18 Loss of peak TSP below the dam compared to Brune sediment trap efficiency.

figure 7.18 above and appears to indicate a linear relationship; were a trend line drawn, the slope would be $y = 0.7173x + 48.39$ with $R^2 = 0.9911$. However there are too few data points to confirm this.

For comparison the delta area land loss per year has been compared with Brune sediment trap efficiency, see figure 7.19 below. The comparison of Brune sediment trap efficiency with delta land area loss shows some indication of a relationship, though given the small sample of five, and the uncertainty over the Nile Delta land loss area, is not significant.

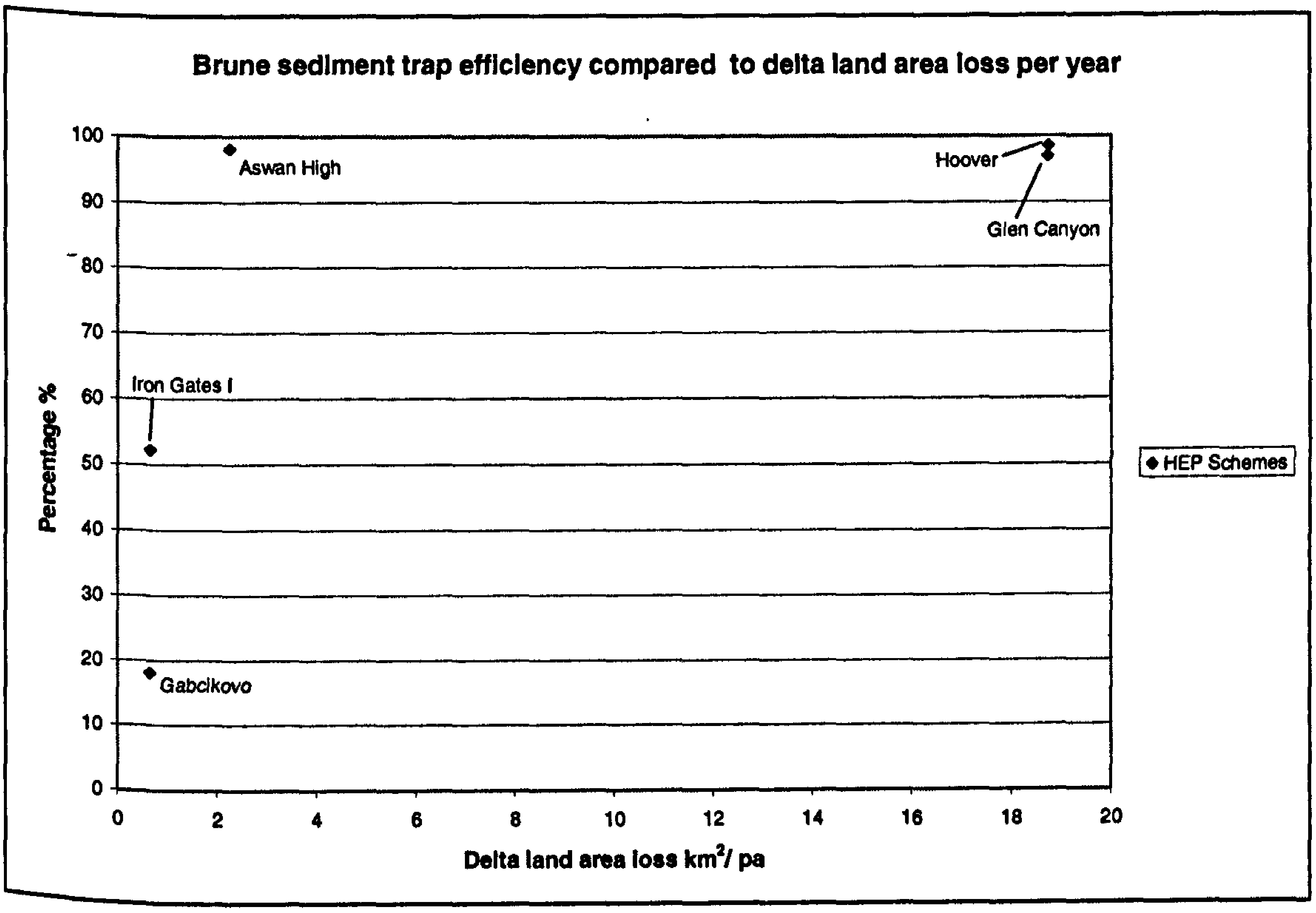


Figure 7.19 Brune sediment trap efficiency compared to delta area land loss per year.

One of the conclusions suggested is that the development of a large number of smaller dams with small reservoir volumes could result in fewer changes to peak TSP downstream, i.e. less change in power flux density, with correspondingly less change to sedimentation, as well as sediment transport, than a few large impoundment dams. In terms of sedimentation in the reservoir reach, and downstream Total Stream Power, the perpetuation of seasonal peak flows and thus sediment transport, fewer impacts would be experienced. The changes to the river bed would be reduced and deltas could still be recharged. Such HEP schemes being of the "run of river" type would result in an overall reduction of electricity production, as the peak flows would be passed over sills or through sluices rather than being stored and released at a constant rate. The power of these peak flows would be available to the river to perform the functions outlined earlier, and available as Stream Power.

This would represent a reduction in the proportion or ratio of energy abstracted from the river as a whole. As an example of this approach, the comparison between different developments of HEP on the four river systems can be cited. The Danube delta has lost some area, 0.24%, and is losing 0.65 km^2 pa, partly as a result of HEP development on the river and its tributaries, while the deltas of the Nile and the Colorado are not being recharged sufficiently and are losing area at a greater rate 1.12-2.25km^2 and 18.74km^2 per year respectively. The Danube's HEP schemes are run of the river ones which do not affect the TSP very much, while the Nile and the Colorado have large impoundment dams which significantly reduce TSP. Conversely, the Danube's dams cannot hold back flooding from large seasonal peak flows, and there have been floods for example in 2001 (Joint Danube Survey 2005).

The Three Gorges scheme is interesting in this regard as it has been decided to operate it by lowering the reservoir level substantially during peak flows in order to prevent silting up (Jisheng 1994). The head height is to be reduced from the 102-105m (~175 m above sea level) optimum, to 71m (145 m above sea level) (Jiazhu 1994) in the flood period (Xuezhong 1996 p24). The lowering of head heights in anticipation of flood flows is common practice worldwide, so that there is capacity to store flood waters, though this is much more marked in the case of the Three Gorges. However it appears, in the author's view, that in this case the water level will be kept at 71m by sluice gate control, rather than store much of the flood. This will effectively reduce the proportion of energy abstraction from the river, and transfer it back to the river to result in increased water velocity in the reservoir (as a result of the reduced cross- section and volume), and hence more sediment transport. The irony here, in the author's view, is that this could to some extent reduce its ability to hold back flood flows, which is one of the claimed purposes of the scheme. Nevertheless, the dam will, it is claimed, have the ability to reduce the 1870 peak flood flow (0.1% flood frequency) of 110,000 m^3/s to below 80,000 m^3/s in the vulnerable Jingjiang stretch, as well as reducing 1% flood frequency events to an acceptable less than 60,000 m^3/s flow there (Jiazhu 1994). The avoidance of silting in the upper reaches is necessary if the advantages of improved navigation conditions are to be maintained at the port of Chongqing at the upper end of the reservoir (Jisheng 1994). At the same time the vital function of recharging of the delta at Shanghai could be better maintained.

Therefore by reducing the power flux density at the dam, it would appear that the proportion of energy abstracted can be reduced and some important impacts avoided. This latter is an important observation, which is considered to endorse the hypothesis.

7. 2 Conclusions for chapter seven

It would appear that a relationship between the power flux density and some environmental impact parameters, but not for others, is suggested here for the sample HEP schemes chosen. However, the results are not statistically significant, due to the small sample.

Land use per TWh pa was suggested to have an inverse linear relationship to power flux density in terms of Cross-sectional Stream Power, but not to be related to Total Stream Power, for the reservoir reach. There was no evidence of a relationship between power flux density in terms of head height and land use for the sample. Water residence time suggested a linear relationship with land use, though not statistically significant. Land use was not likely to be influenced by the former mean bed gradient. Reservoir volume however, was likely to have a linear relationship to land use, which implies that variations in shape and depth can be discounted. There was no evidence for a relationship between average fluid velocity and land use. Some relationship between the production factor and land use was indicated, though only in broad terms distinguishing between water storage schemes and primarily generation schemes. There was no indication that mean river flow was related to land use.

Land area for HEP schemes depends largely on the reservoir size and is much less for the run of the river schemes such as Bonneville and Gabcikovo, and also where flow rates are high e.g. the Three Gorges, gradients steeper, and valley sides steeper. Where there are high head heights but without large storage reservoirs, high power flux densities could result in low land use, however such examples were not included in this study.

The reduction in sediment transport, as reflected by loss of delta land area, indicated a linear relationship to reduction in Total Stream Power for the river downstream of the HEP scheme, when tested for three rivers. TSP can be equated to power flux density and so this part of the test result is considered to be indicative of support for the hypothesis, though given the small sample cannot be stated with confidence.

Large volume reservoirs relative to flows, with long residence times and big reductions in flow rates appear to be better sediment traps. In addition such reservoirs e.g. the High Aswan dam reservoir, the Hoover, and Glen Canyon, attenuate flow variations more. As a consequence of this, downstream of the dam, the changes, i.e. reduction of the power flux density as represented by the loss of the flood flow peaks, can result in reduction or near cessation, in the worst case, of one of the functions of the river flow, the transport of sediment. This has serious impacts on the recharging of deltas on the Nile and Colorado which are both losing area as a result of coastal erosion. In this case it is the loss of power - that is the rate of work -as well as the straightforward extraction of energy from the flow that is causing environmental impact. Extraction of the rivers' energy for electricity generation (or for water abstraction) does also result in losses to the functions, which could result in impacts. The greater the change in power flux density the greater the impact appears to be. This also applies to the reservoir reach, where the conversion of the kinetic energy transporting sediment, to potential energy with a negligible current speed causes deposition of sediment. The larger the reservoir and the lower the current, the better a trap the reservoir is. The case of the Gabcikovo scheme where 85% of the flow is diverted away from the natural bed into a sealed artificial canal, causing drying of wetlands demonstrates how the parameter proportion of interception and abstraction of the flow could be significant.

Compensation flows -conditions

Prioritising the functions of the water flow, as has been done by the Environment Agency in the UK, (Environment Agency 2008) so that wetlands and river flow are protected in low flow times, with the result that HEP operates only in times of adequate flow, provides another example of the employment of the proportion of flow principle (Shaw 2007). The water regulatory framework has introduced use of the PHABSIM (Population Habitat Simulation) suite of programmes to estimate changes in physical habitat of aquatic organisms as a function of flow. This is used to determine minimum, optimum and ecological triggering flows as well as channel habitat maintenance flows, and this is widely accepted practice (USGS 2001).

In energy terms, the case of the Three Gorges scheme employing "drawdown" in the flood period is an example of the reduction of proportion of energy extracted from the flow, so that some of the energy can be expended on silt transport. Another relevant example here is the Colorado pulse releases to provide silt transport for bank conditions (USGS 1996).

Efficiency

HEP plants achieve high overall energy conversion efficiencies, generally in the range 65-90%, (Ramage 1996) and also as evidenced by the high 'Production Factor' of some schemes in the sample. The high efficiency possible enables a large ratio of energy extraction from HEP schemes with the potential for impact resulting from diminution of the energy available for functions.

Number of Conversions.

Several energy conversions are involved in HEP schemes and can be related to impacts. The form of energy of the river flow is that of kinetic energy of flowing water, under the influence of gravity. The flow itself undergoes three conversions, kinetic to potential in the reservoir, then potential to kinetic in the penstocks and then finally extraction of most of the kinetic energy at the turbines, by a slowing of the water. Water speed in the reservoir slows very considerably, resulting in sediment deposition and loss of transport and erosion. Run of the river schemes show smaller differences in energy form conversion (from kinetic to potential) and in change of flow speed and therefore, are less likely to result in the same degree of sedimentation. Therefore it is reasonable to assume that the number and degree of conversions of the form could be related to impacts.

To summarise, reservoirs and dams slow the flow rate, so transportation, erosion and scouring are reduced, more sedimentation occurs and turbidity is reduced, however, it is *how much* it is reduced by, that is important. The longer the water residence times (partly a function of head height, gradient / reservoir volume and flow rates), and the more the flow rate is slowed, the greater the sedimentation. Furthermore, the more the flood flows are attenuated, i.e. peak Stream Power is reduced, the less transportation there is downstream. Therefore it is not just the proportion of the overall energy that is extracted, but it is the reduction in the peak power i.e. rate of work, that is significant. It is the change in power flux density that, in the author's view, leads to impacts. Changes occur in several different ways: extracting energy from the total flow, or changing the distribution of (that energy) i.e. power flux density, in both time and space.

Chapter 8

Conclusions

8. 1 Introduction

This study has attempted to address the broad topic of environmental impact from renewable energy sources, which are very diverse. Environmental impact has been defined as changes beyond the "normal" rate of change, that is faster or greater in extent, or more permanent changes. The term "environment" covers many different concepts from physical surroundings to processes and systems, including the lithosphere as well as the biosphere, atmosphere and anthroposphere. An attempt at some more succinct definitions of sub components has been made here in respect of the different aspects of the environment that are affected by renewable energy sources. The concept of power flux density has been used to characterise renewable energy sources in terms of their environmental effects and impacts. Of necessity there has been considerable simplification and generalisation in application of the concept to environmental impacts, however, the author considers these to be justified.

Nevertheless, an attempt has been made to link the functions of the natural energy flows and their role in the environment, to changes caused by intercepting and extracting energy by renewable energy conversion systems. While it has been proposed that this may apply to all of the different renewable energy sources, the focus of the detailed element of the study has been on hydro electric power, as a suitable case with sufficient available data, to demonstrate the principle. Hence much of the study has been concerned with one renewable energy source, first considering effects at the dam and reservoir and then extending this to downstream effects on available energy and its processes. The specific processes that have been considered here have been those of energy available for sediment erosion and transport, although there are many other impacts related to energy, but more indirectly, such as effects on wildlife. Inevitably, it has only been possible to study the more direct processes of rivers here and their relationship to environmental effects and impacts of hydro electric power, even though many indirect effects such as water quality are related.

8.2 Study Review and findings by chapter

8.2.1 Theory

Most renewable energy sources, (apart from geothermal and tidal), are ultimately derived from the sun, at low power flux densities, <1kW/m^2 at the earth's surface, (average of ~230W/m^2). These energy flows are successively converted into more concentrated forms, such as wind <~12kW/m^2, and water flows such as wave and river flows, successively increasing the power flux density, with waterfalls or HEP schemes up to and over 100kW /m^2. Wave comes in between. Eight different flows are identified in this thesis, solar, biomass, HEP, tidal, marine current, wind, wave, geothermal. They can be characterised by their power flux densities.

The definition of the term 'power flux density' is the rate of work per unit of area. The work that natural energy flows perform in the environment can be classified as a set of roles or "functions" in powering and maintaining natural physical and living systems. By definition, natural energy flows with higher power flux densities will have a higher rate of work per m^2. The hypothesis is that the degree of interference with such flows by extracting energy or changing its distribution will accordingly result in impact, as a result of changing the energy and power available for the natural functions. Furthermore, the intensity or power flux density of the energy flow will be a factor in the land use of renewable energy. The higher power flux density sources, the less land required per unit of energy captured. This may seem obvious in the case of say solar or wind; diffuse energy flows mean larger catchment areas are required. However the precise interaction may be more complex.

Environmental impact is defined as changes. However, in addition to extraction of energy, environmental impact also results from the production of unwanted by-products, as well as perturbation of the flow. Therefore as well as power flux density the following parameters have been proposed:-

-Proportion of energy intercepted and extracted
-efficiency of conversion
-number of conversions of energy form
-changes in power flux density

These four different variables are not independent of each other but interdependent. But power flux density may be the most significant variable since the proportion of energy captured from a particular renewable source appears to depend in part on the power flux density of the flow, as shown in figure 3.3 in chapter 3 on p 76.

The purpose of the project is to compare different renewable energy sources, technologies and schemes with one another in terms of environmental impact, which has been defined as changes, in land use terms, in terms of interference to the natural functions of each energy flow, and in terms of unwanted by-products from conversion processes.

This parametric approach to the theory of environmental impacts from renewable energy sources is considered by the author to be a novel one, which has not been found in the literature, except for previous work outlining the approach by this author.

8.2.2 The HEP test

The hypothesis was tested on a selection of HEP schemes noted for their environmental impacts. Data for a number of parameters was collected and interpreted in power flux density form for the sample. The test consisted of two parts, firstly impacts at the dam and reservoir reach were tested for the parameters, and secondly impacts downstream from the HEP scheme using the Stream Power concept as a measure of power flux density. Over sixty different spreadsheets were employed in assembling the data. Since the topic of environmental impacts is very diverse, two key impacts were chosen for testing for relationship to power flux density -sediment transport and -land use.

Test results

For the first part of the test on the dam and reservoir reach, no apparent relationship between land use and power flux density derived from (hydraulic) head height was found for the sample, nor between land use and Total Stream Power for the reservoir reach. No relationship between land use and former mean gradient was found for the sample. The results suggested that there could be an inverse relationship between the Cross-sectional Stream Power and land use, (i.e. with slope and flow rate), a power equation, $y = 67566x^{-0.4219}$, with a R^2 0.606, i.e. impact (land use) $I = 5E{+}07(CSP)^{-1.4371}$, although due to the small sample size it is not statistically significant and the nature of the relationship cannot be stated with confidence. Also a linear relationship between water residence time and land use (slope $y = 1.7037x$) is indicated by the sample data. That is, the land use of storage is ~ 0.469 days, per km^2/TWh pa, though this is not statistically confirmed. A linear relationship between land use and reservoir volume is also indicated, suggesting that despite differences in reservoir shape and depth, generally reservoirs of greater volume occupied more land per unit of energy generated. This implies that variations in reservoir shape and depth can be largely discounted as a factor accounting for the data. Again though, due to the small sample size confidence in this is low. No relationship between land use and average reservoir fluid velocity was indicated. No clear relationship between land use and the Production Factor was apparent, though dams designed for considerable storage appeared to be the lower Production Factor schemes. No apparent relationship between land use and mean river flow was shown by the data. Brune sediment trap efficiency compared to head height and hypothetical power flux density (pfd), indicated a linear relationship with a slope of $y = 0.7743x$ and $R^2 = 0.5048$, i.e. I (Impact) = 0.7743 $pfd_{hypothetical}$ (hypothetical power flux density), or with a power relationship a slope of $y = 2.9823x^{0.7264}$ and $R^2 = 0.8306$, i.e. $I = 2.9823(pfd_{hypothetical}{}^{0.7264})$, though the sample was too small to confirm this statistically.

The second part of the test on four rivers downstream of the HEP scheme, estimating Stream Power values before and after the HEP scheme. Pre and post dam, Total Stream Power (TSP) estimated for four rivers in the sample, from gradient profiles downstream of the major dams, showed considerable variation in decrease of TSP below HEP dams. The decreases in TSP ranged from a maximum decrease of 98.6% on the Colorado River at Yuma (near the Mexico border) for the periods 1933 to 1975, to a 10.4% decrease in peak monthly TSP on the Danube below the Iron Gates dam post construction, and an almost imperceptible decrease in TSP below the Gabcikovo scheme, though neither of the latter can be stated with confidence due to the relatively short data period. On the Columbia

River a peak monthly TSP reduction of 51% was shown below the Grand Coulee dam, after construction of the Mica dam upstream of this, although 670km downstream near the mouth, only a 23% reduction is seen. On the Nile, a drop in monthly peak TSP of 71% below the Aswan High was seen after construction, which is likely to continue downstream, though long term data was not available to confirm this. The very high TSP decreases for the Colorado are in part also due to abstraction of water flows for irrigation and water supply, with average flow rates decreasing by 96% between 1933 and 1975.

The estimation of TSP was carried out where sufficient data was available, pre and post dam, but there are considerable discontinuities in both the time line and river line data sets that were available, and so this work is far from a complete modelling exercise for the river downstream from HEP schemes. Nevertheless, with the extensive data set, the author considers the validity of the application of TSP in this context to have been demonstrated.

The test compared the reduction in peak Total Stream Power with delta land area loss for three rivers which had deltas, out of the four estimated for TSP. The results were indicative of a relationship between TSP reduction and delta land area loss. The two rivers that had considerable reductions in TSP, the Nile (71% TSP reduction) and the Colorado (98% reduction) caused by the HEP schemes, both showed considerable delta land area loss while the Danube, (6.9%-10.4% TSP reduction) which had small or imperceptible TSP reductions showed a much smaller delta land area loss. Thus those dams that could pass the flood on down the river appeared to cause little loss of sediment transport, while those that attenuated the flood significantly or completely, reduced or terminated transport of sediment. Reduction of peak TSP (pTSPr) compared to delta land area loss impact, produced a linear slope of $y = 13.564x$, with $R^2 = 0.5945$, i.e. $I = 13.564$ (pTSPr). Although the number of cases is too small at only three to be statistically significant, the author considers this indicative of support for the hypothesis. TSP can be interpreted as a measure of power flux density, and the reduction of sediment transport is a reduction in one of the primary functions of the natural energy flow. Thus the change in power flux density appears to be related to environmental impact.

The extent of the task on some of the world's longest rivers precluded a larger sample.

What this would appear to indicate is that the major impoundment dams, which store large volumes of water flow, can cause impacts in terms of loss of sediment transport whereas the run of the river dams whose reservoirs do not store river flow, pass through the sediment, due to the higher power flux density of the unattenuated flood flows. This is not stating that sedimentation occurs but the reverse -that loss of the flood peak stream power causes *loss* of sediment pick up and transport all the way downstream. A common misconception is that sediment originates only upstream, whereas it can originate all along the bed, pick-up and deposition being in dynamic balance (Petts 1984).

8.2.3 Other water based technologies appendix

The hypothesis was extended as an appendix to other water based renewable sources, tidal barrage, marine current, and wave energy, and to the lower power flux density sources, below 1kW m^{-2} average, wind, solar, biomass and geothermal. However, no tests of data were carried out so this section is exploratory and somewhat speculative. These two categories are discussed below in two sections of the Appendix, 1 and 2.

It was proposed that impacts may be related to the power flux density for the other water based sources, as well as to the further parameters employed here, since similar processes i.e. sediment transport and deposition were involved. In comparing tidal barrage and marine current turbines, power flux density differences, proportion of interception and energy extraction, as well as number of conversions, pointed to the relevance of the hypothesis. However, it was beyond the scope of this thesis to verify this with tests of data. The few examples of tidal barrages, marine current and wave energy schemes world wide as yet would make it difficult to verify this.

The much higher power flux density of tidal barrages at the converter of up to 628 kW/m^2 (Severn Barrage), compared to marine current turbine's average of ~<10kW/m^2, appears likely to be reflected in the lower impacts that may be experienced from marine current turbines.

The interception proportion of tidal barrages is ~100%, but probably a maximum of ~<30% for marine current turbines, although the Tidal Fence schemes may be higher. The energy extraction proportion has been cited at 30% for tidal barrages (Charlier2003), for marine current turbines it would be probably be lower, depending on the scheme.

The number of conversions of form of energy in the flow is only one for marine current turbines, compared to three for tidal barrages and this could be expected to result in fewer impacts e.g. sedimentation and tidal range. The efficiency of energy conversion could be higher for tidal barrages, in terms of interception, at ~65-85% as for low head HEP, compared to the marine current turbine of ~45%, see Appendix 1.

For wave energy converters average power flux densities of ~12kWm^{-2} for offshore wave energy converters on the west coasts of the UK and Ireland can be cited. At least 50% of this would be dissipated in bottom friction near shore and up to 80% by the shore line, representing natural functions performed, such as erosion, sediment stirring, oxygenation and beach building. Higher power flux densities could result in a greater rate of such functions and diminution through energy extraction appears likely to result in impacts such as changes in wave height and beach shape and related geomorphic and biological effects. Although studies of currently proposed developments such as the SW Wavehub envisage only small changes at the shore of 2.3% diminution, greater deployment densities would result in greater changes, reflected in the proportion of energy interception and extraction, converter efficiency and number of conversions. A 22-32% reduction in energy levels could be expected 1 km behind a Wave Dragon farm (Wave Dragon 2009). Current on-shore and attenuator devices have estimated energy capture ratios of ~50-93%, though in practice existing devices may have less. Terminator designs could be expected to have higher interception ratios and thereby the potential for higher energy extraction ratios could prove to be a significant factor in impacts. The number of conversions varies from ~3 in the case of the Tapchan and OWC devices, to one in the case of Pelamis.

It is suggested that the hypothesis might be usefully extended to water based renewable energy sources and the environmental impacts appear to be related to the parameters proposed, power flux density, proportion of interception and energy capture, efficiency of energy conversion, and number of energy conversions, though no test of data was made to confirm this.

8.2.4 Lower power flux density renewables appendix

In Appendix 2 section, some of the parameters identified in the hypothesis were applied to the lower power flux density sources, below 1kW m^{-2} average, wind, solar, biomass and geothermal, again on a theoretical basis, without extensive testing of data. Land use data of existing schemes appeared to indicate a potential relationship with power flux density in that lower power flux density sources resulted in greater land use, e.g. for solar and biomass production, while higher power flux densities conversely use less land, though the sample size was insufficient to confirm this statistically. However, as the variation in power flux densities may be less overall, e.g. solar energy fluxes vary by a factor of only ~2-2.5 (WEC 2004 p297) across the globe, the sensitivity of impacts to variations in power flux density may be less.

Low power flux density appears to result in greater compatibility with human habitation, for instance, solar PV involving only one direct energy conversion, has few impacts and panels can be placed on roofs of buildings which are already occupying land. Solar PV then requires no extra land area. Similarly, biomass sources from waste streams can require little further land use too since the land is already in use for productive purposes.

For low power flux sources, flow definition into discrete streams appears to be much poorer; air currents feature as broad flows of great height for instance, while solar radiation flows are like a 'field' in some respects, due to reflection and refraction in the atmosphere. Biomass sources depend on the biome characteristics, of water and heat availability. Therefore the notion of local flows has been proposed, so that the proportion of energy flux intercepted and extracted could then be determined locally.

This could apply to wind or central solar power stations or even biomass. For wind energy the low interception rate, together with the Betz limit and the need to disperse turbines, results in only a small proportion of the energy being extracted, unless the flow is of limited cross section and volume. Solar energy conversion technologies currently achieve maximum efficiencies of <~30-40% (Boyle 2004) and the proportion extractable is limited by this, although the proportion intercepted is often about ~33% for central solar plants whether PV or Concentrating Solar Thermal type. Solar electric conversion rarely achieves efficiencies of 30% and generally ~<15% is more likely for CSP or PV. For biomass very low overall energy conversion efficiency is often found from solar to biomass energy end use units, e.g. about 0.5% (Boyle 1996) to 2% (Tan 2009).

The number of energy conversions as a parameter of impact could be relevant for both solar and biomass and wind too, though maybe to a lesser degree. For biomass, where a large number of conversions are carried out, this parameter also appears to be informative of impacts.

8.2.5 Land use compared to power flux density for the different sources

Examples of the on-shore renewable energy sources' land use were compared with their power flux density for solar, biomass, wind, and hydro electric power. The power flux density for HEP, is based on the head height. The results are shown below in figure 8.1.

The greatest land use was incurred by biomass production at 1752 km^2 / TWh pa which also had the lowest power flux density at 0.00016 kW/m^2 average, (based on 10t /ha pa woody biomass and 33% thermal conversion efficiency, in the UK). The lowest land use was that of the Solar Thermal CSP Nevada 1, at 9.8 km^2 /TWh pa, followed by Three Gorges HEP scheme with 12.8km^2 / TWh pa, and this scheme had the highest power flux density of 1000.6 kW/m^2. However, when all the HEP schemes in the sample were included, the average land use was 175.58 km^2 / TWh pa, which was greater than that for wind energy at 46.97 km^2/TWh pa, (based on 9 MW/km^2, 7.5m/s wind speeds and a c.f. of 0.27). Solar energy required 588.2 km^2/TWh pa, or as little as 9.8 km^2/TWh pa depending on latitude, resource and technology. For higher latitude PV installation, the power flux density was 0.17 kW/m^{2}' (based on Mulhausen solar PV scheme in Germany), while for the lower latitude desert CSP thermal plant it was 0.313 kW/m^{2} (based on Nevada 1).

The results are indicative of support for the hypothesis, in that higher power flux densities are generally associated with lower land use, but do not statistically confirm the hypothesis due to the small sample. The exception in the sample is the CSP plant with relatively low power flux density, but low land use.

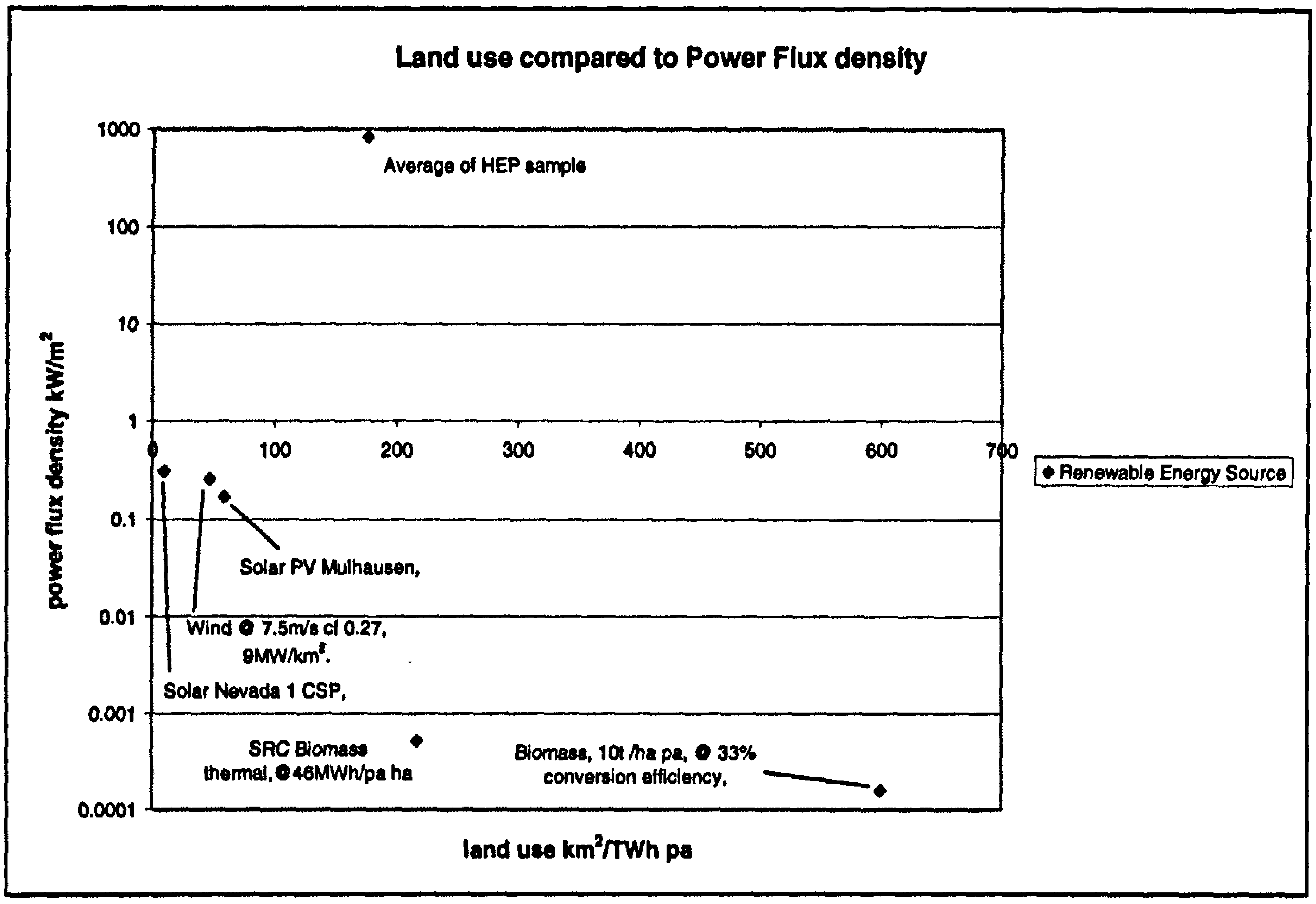


Figure 8.1 Land use compared to power flux density for the on-shore renewable sources

However, when the HEP schemes where the main purpose is water storage, were removed from the sample, (i.e. also those with high land use and low flow rates / high residence times), a clearer pattern could be observed. This is shown below in figure 8.2 below. Were an equation to be fitted, a power equation, $y = 5E{+}06x^{-3.9292}$ would fit best, with $R^2 =$

0.736, or with the axes inverted, (so that Impact = power flux density x by factor) $y = 46.237x^{-0.1873}$ $R^2 = 0.736$.

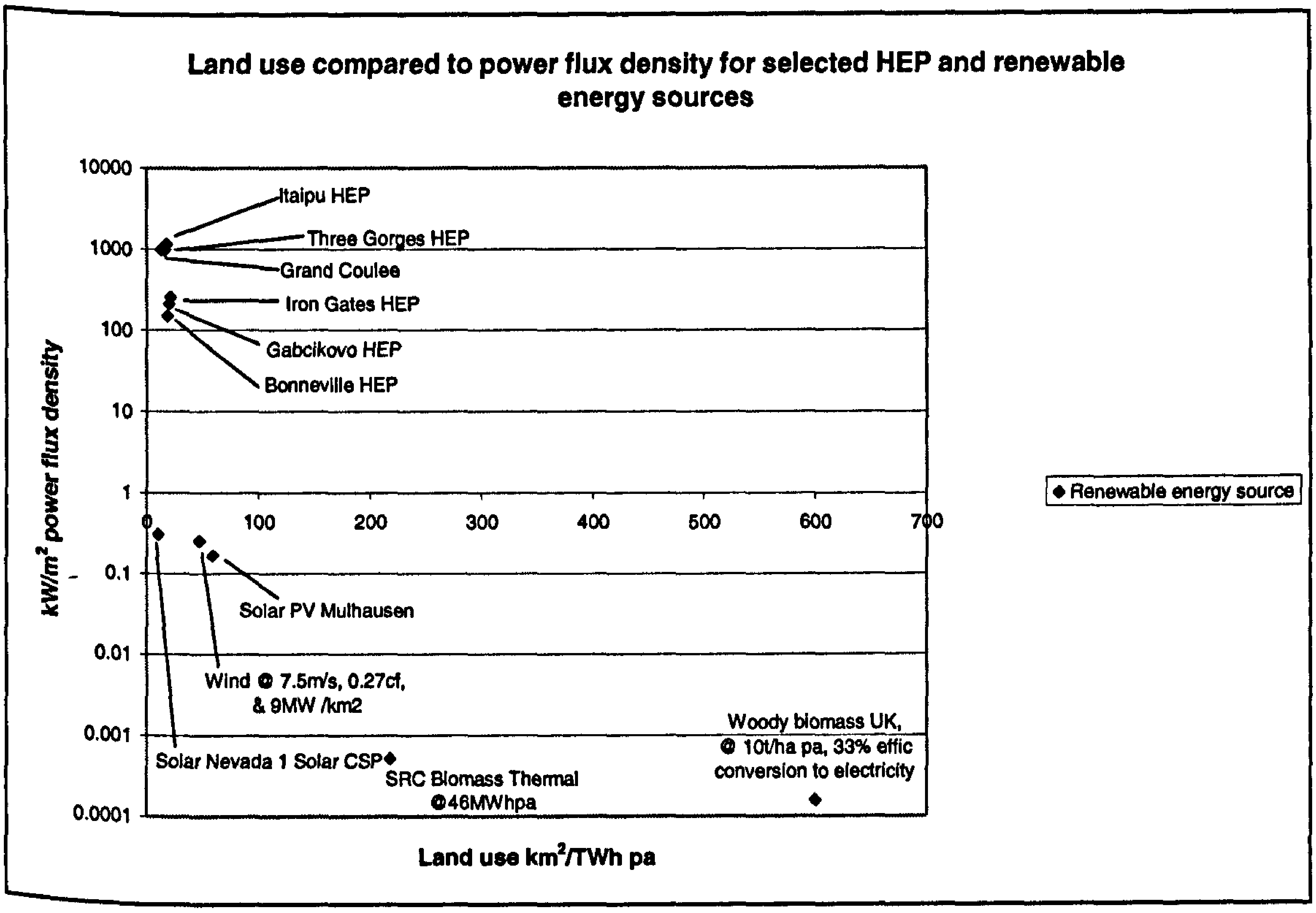


Figure 8.2 Land use compared to power flux density for selected HEP and renewable energy sources.

The use of land area for storage by HEP schemes might be compared with storage in biomass production, though this is an integral part of biomass chemical energy conversion process, whereas for HEP the amount of storage can be determined by design. The somewhat anomalous Solar CSP result could be explained by the use of estimates of output rather than actual performance for Nevada 1 CSP, and additionally HEP schemes incorporate storage involving land use. This HEP storage land use could theoretically be discounted, either by using water residence time in days / land use (km^2/TWh pa), as compared in Figure 7.4 p 241, or in practice by use of leats and zero storage. However, storage confers greater value on electricity generation.

This might indicate a relationship between land use and power flux density for the on shore renewable energy sources, though the sample size is too small to be statistically representative. A T test of the sample gave a result of 0.65 indicating that this is not statistically significant given the sample size and variation.

8.3 Development and assessment of the hypothesis

The hypothesis began with impacts related to the parameter of power flux density, as reflected by the functions of natural energy flow and in land use. It was further developed to include the proportion or ratio of energy extracted from the flow, and interception of flow. The efficiency of conversion was an additional parameter, as reflected in unwanted by-products and also as a factor in the proportion of energy in the flow that can be extracted. The hypothesis proceeded to an additional parameter, that of conversion of the form of the energy in the flow and number of conversions, i.e. discontinuities in the functions.

Is the hypothesis confirmed?

The hypothesis is not statistically confirmed, by the data obtained, since there is not enough data, but some of the results are indicative of support for the hypothesis. Overall, the hypothesis is not clearly contradicted by the data obtained. Of the various parameters tested on the reservoir reach, an inverse linear relationship between Cross-sectional Stream Power and land use was indicated, there was an indication of a linear relationship between water residence time and land use, and a linear relationship between reservoir volume and land use was indicated. However no relationship was found between land use and the parameters of power flux density derived from head height, former mean gradient, average reservoir fluid velocity, production factor, and mean river flow. A relationship between reservoir sedimentation and loss of peak TSP below the dam was indicated, though not statistically confirmed.

For the Stream Power test downstream of the HEP schemes, data was indicative of support for the hypothesis, but not sufficient to provide statistically significant support for the hypothesis. A relationship between reduction in TSP post HEP schemes, and sediment transport, reflected in delta land area loss, was indicated but not statistically supported, due to the small sample size.

In conclusion the study has not confirmed the hypothesis, but has shown some indication of support in certain respects, particularly Stream Power as a reflection of power flux density. When comparing power flux density (pfd) and land use for all of the renewable sources, for land use $I = 46.237(\text{pfd})^{-0.1873}$ $R^2 = 0.736$, there was an indication of support for the hypothesis, though again not statistically significant. In general the higher power flux density sources required less land, as might be expected, however, the solar CSP Nevada 1 is somewhat anomalous having relatively low power flux density, but also low land use requirement.

Further complexities

There are however, additional complications associated with horizontal fluid flows, which are addressed by the second and further parts of the hypothesis, concerning conversions and efficiency. The proportion of the energy extracted from the flow might be a factor in impacts resulting from loss of the energy functions, such as sediment transport, though this was not tested.

Complexities are also introduced by the multiple purposes and uses of dams and reservoirs. Energy generation is rarely the sole purpose of a dam scheme. Flood control practices, navigation, or water supply may result in modes of operation that cause or reduce impact. This has required some careful analysis together with some assumptions as to the impact that can be allocated to the energy component.

Gaps

This study has investigated one main aspect of the hypothesis, that of the power flux density in relation to the mechanical energy function of sediment transport, but has only tested this for selected HEP schemes, for the reservoir and then the river downstream, where data was available. Further mathematical testing of the significance of power flux density on a larger representative sample of HEP schemes would be required to confirm its significance. The additional parameters proposed, proportion, efficiency of conversion, number of conversions could also be tested on a larger sample. The test has only considered sediment transport and land use, however, other impacts such as those on water quality and flora and fauna could be carried out.

The test of Stream Power changes to the river below the HEP scheme, which has only been carried out on four rivers and for three deltas due to the magnitude of the task, could be extended to a larger sample. The Nile Delta land area loss that has been estimated could be studied using satellite photographs.

More precise definitions of the relationship could be sought. For instance do higher power flux densities in general result in more functions being performed? A precise description of the process of sediment erosion and transport and the relationship of water flow to sediment movement might have been incorporated into a larger study.

A computer model might have been constructed to model the relationship between the ratio of energy extracted from a natural energy flow and the impacts. This study has though, largely been one exploring the parameters and dimensions of the concept. Given the complexity of the concept and specific nature of individual river systems and their sensitivity, the relationship between energy extraction and impacts is not likely to be a simple one, and has been outside the scope of this study.

8.4 Main conclusions

It can be concluded in general, that power flux density could be a relevant parameter for determining aspects of impact. It is in general likely that, as might be expected, the greater the power flux density, the lower the land use, or collector area required, once storage area is taken into account. Land use is a prime impact of renewable energy sources.

Power flux density changes could be a relevant parameter, in determining impact from changes caused by the interception of fluxes of high power density, and the extraction of energy from them. This could tend to reduce geomorphic processes such as sediment removal and transport.

In the case of Hydro Electric Power, it is suggested that extraction of energy from the river tends to reduce energy available for sediment transport, but more importantly perhaps, that impacts result from the change in peak energy flow of the river as a continuum, firstly in the reservoir itself, and then where the flood is attenuated, all the way down the river to the mouth. In particular, the reduction in power flux density through attenuation of the flood flows TSP of the river appears to have the greatest effect in reduction of sediment transport, a prime impact.

Central Statement

In bald terms what emerges from this study is that the power flux density appears to relate to some impacts in the case of HEP and possibly other renewable sources, both in land use and in reduction of peak power flux density. However the impact on land use relates inversely to the power flux density while for other types of impacts the relationship appears to be more proportional to changes in the power flux density. The ratio of energy extraction to the energy that would normally by used to perform natural functions, and to the total energy in the flow, may relate to the environmental impact.

8.5 Further Research

The scope of this study has not extended to answering all the questions that the hypothesis might raise. Here the main thrust has been to test for evidence for the hypothesis, and investigate and test for validation of the parameters employed. If the relationship between power flux density and impacts can be fully confirmed there will be many areas it can be applied to which will need to be the subject of further research work. For the parameters to be fully validated, tests would need to be carried out on a fully statistically representative sample of HEP schemes, as opposed to the limited sample, used in this study. However, collecting the extensive data required for this study entailed considerable difficulties, as much of the information is not readily available or even willingly released. It is recommended therefore that a database of HEP data, and their impacts is set up.

However, some of the further questions that can be posed with regard to HEP are provided below.

Further Specific HEP questions

The question of whether rivers that have a greater power flux density are responsible for more erosion and deposition type functions can be posed. This question can be rephrased as 'does siting of HEP schemes on river reaches with steeper gradients lead to more or fewer impacts?' Concerning erosion, transport and deposition, greater flow rates, i.e. kinetic energy of moving water, are the consequence of either i) steeper gradients, or ii) greater cubic flow supply, also lower friction from greater cross sectional areas through increased efficiency of flow, in a viscous fluid.

Couched in geomorphologic terms, what type of rivers are responsible for more erosion / transport? Further questions might be posed based on the functions of the river in nature, that is, sediment transport, oxygenation, nutrient transport, organism transport and flushing.

The topic of sediment transport could be divided into streamload, bedload, and dissolved in solution. Deposition or erosion resulting from the change (decrease or increase) in water flow rate, and TSP downstream of HEP schemes could be further investigated.

Questions concerning water quality and the conditions for oxygenation, could be posed, for instance what velocities and pressure differences are involved. The losses of "white water" conditions resulting from inundation of falls and rapids from HEP plant could be compared to power flux density reductions, in addition to super saturation resulting from high pressures at some HEP schemes.

Other effects of flow rate changes such as to nutrient transport, both inorganic and organic, organism transport, microscopic to plant and animal could be investigated in terms of power flux density changes. Flushing effects of flow rates, and waste product removal could form part of this. The PHABSIM suite of programmes, referred to in chapter 7, relate flow regime and TSP to biological impact through habitat loss, which is an important consideration. Use of PHABSIM has become mandatory practice in the USA and increasingly in Europe and elsewhere, (USGS 2001). Further work in this area regarding HEP is recommended.

Extension of the hypothesis

The extension of the hypothesis in Appendix 1 to other water based renewable sources, tidal barrage, marine current and wave energy converter, suggests potential relevance of the hypothesis. When tidal barrages with higher power flux densities are compared with marine current turbines, impacts appear likely to be lower for marine current turbines. For wave energy the hypothesis appears relevant, higher power flux densities having potentially more functions, e.g. water mixing, bottom sediment movement and oxygenation as well as shore line erosion. Extraction of energy, reducing power flux density, could reduce these functions. Efficiency of conversion affects the energy extraction ratio, and the number of conversions that can be applied effectively to some devices, e.g. Tapchan.

Extension of the hypothesis in Appendix 2 to the low power flux density sources, wind, solar and biomass appears to indicate potential relevance of the hypothesis in terms of power flux density, proportion and conversion efficiency, to an extent. However, due to the low power flux densities in the range of less than 1kW m^{-2}, (~77Wm^{-2} to 10kW m^{-2} for wind and ~0.1-1kW m^{-2} for solar, and ~16W m^{-2}-320W m^{-2} for biomass), differences in impacts, apart from land use may be less apparent. The hypothesis application is complicated by the less defined nature of the flow more akin to a 'field'. Power flux density can be conceived of as a descriptor here of the flow definition, i.e. its cross sectional boundaries.

Further research on other water based renewable energy sources

If the link between environmental impacts and power flux density proves to be true for rivers, does it also hold for other water based flows, for instance wave, tidal, ocean current and other fluid flows e.g. wind, and other flows, e.g. solar and biomass? Or does it only apply to water flows? Further investigation of how such flows differ from those of rivers would be required. The interruption, interception of energy flows and changes in the power flux density might produce a reduction in the functions overall, or fewer functions being performed in total, or possibly different functions. To link the environmental impact to change in functions caused by energy changes, statistical testing of the loss of functions over significant periods would be required.

Further research on low power flux density sources

The application of the hypothesis and its parameters to the other low renewable energy sources such as wind, solar biomass and geothermal, could be explored further in terms of land use, power flux density, interception ratios, efficiency and number of conversions. Statistical tests of the parameters together with impacts would need to be carried out on representative samples.

Further possible impact parameters were proposed but have proved to be beyond the scope and resources available in this study.

8.6 Concluding points

If it is accepted that the environmental impact from renewable sources may be related to power flux density, the implication is that interception and perturbation of a natural energy flow should not attenuate or reduce its peak power flux densities, to any significant extent, since this is when the 'functions' of the flow are largely being performed. That is to say that river flood events perform functions and should be perpetuated, as also should high tidal ranges and flows in estuaries, as well as storm winter waves on beaches. In the design of novel renewable energy developments, the interruption of peak power flux densities should be avoided where high interception ratios and storage of a flow occur. In particular this applies to HEP and tidal barrage technology, while less so to marine current turbines and wave energy converters.

For the low power flux density sources such as wind and solar, the flow is not intercepted or its form changed to the same degree, and the link with 'functions' in nature is possibly less likely to be affected. For instance the power of storm force winds above e.g. 15ms^{-1}, is not harnessed by the turbine, being "spilled" as surplus, most of the energy harnessed would be derived from that part of the wind speed distribution with the most frequent speeds with sufficient power, and not the infrequent storm force winds. Therefore the device does not affect the higher power flux density wind speeds, which can still serve functions in nature. Similarly this could apply to wave energy. It then becomes apparent that it is those sources where a large ratio of the flow can be intercepted and stored that appear to be prone to impacts derived from attenuating peak power flux densities; HEP, tidal barrages, in particular but also biomass and conceivably geothermal. The latter two cases involve further complexities which would require further consideration.

For HEP in particular, the implication is that 'run of the river' schemes without storage, have considerably lower impacts than impoundment dams. This conclusion is not new, but the application of the concept of TSP modelling to HEP schemes, is novel and appears to indicate support for the conclusion. If this conclusion is accepted, even on a per kWh basis, and "on-line" flow storage is to be avoided, (unless of course releases can simulate natural releases), then the increased variability of output from schemes without storage would have to be managed. Variability it seems is good for the environment, if a problem for reliable generation.

References

Abbasi, S. A., & Abbasi, N. (2000) 'The likely adverse environmental impacts of renewable energy sources', Applied Energy, Vol 65 Issues 1-4, April 2000, pp 121-144, Elsevier, London, Amsterdam, New York.

ACT, (2008) 'Solar Power pre-Feasibility Study', Parsons Brinkerhoff Australia pty Ltd ActewAGL and Australian Capital Territory Government, on-line resources: http://www.cmd.act.gov.au/__data/assets/pdf_file/0005/2939/Solar_Power_Plant_Pre-feasibility_study.pdf 2nd September 2008, accessed 28/11/08

Alles, D. L. (2006) 'The Delta of the Colorado River', Western Washington University, On-line resources: http://www.biol.wwu.edu/trent/alles/TheDelta.pdf (accessed 26/02/09)

Alexander, G. (1996) 'Overview', Chapter 1 p28, in *Renewable Energy* ed Boyle Oxford University Press and The Open University. Oxford and Milton Keynes. 0-19-856452-X

American Rivers, (2009) American Rivers website on-line resources: http://www.americanrivers.org/site/PageServer accessed 19/01/09.

Amin, K. (1994) 'Safety considerations, operation and maintenance of existing structures of High Aswan Dam', Water Power & Dam Construction, January 1994, Reed Business Publishing, London.

Andrew, G. (2004) ' The environmental impact of offshore renewable energy', Cranfield University, on-line resources: http://tmm.codecircus.co.uk/assets/798/Cowry_Effects_FINAL.pdf accessed Dec 2008

Bagnold, R.A. (1966) 'An approach to the sediment transport problem from general physics', United States Geological Survey USGS, Professional Paper, pp422-1 1966, Washington DC.

Baker, A.C. (1988) *Tidal Power*, Peter Peregrinus Ltd for IEE, Stevenage. 0 86341 189 4

Baker, V., Kochel, R., Patton, P. (1988) *Flood Geomorphology* Wiley, Chichester. 0-471-62558-2

Barker, D. (2004) 'Modelling downstream change in river flood power: a novel approach based on the UK Flood Estimation Handbook', University of Birmingham on-line resources: www.iem.bham.ac.uk/water/barker.htm 2004-2007 last accessed 22/07/09

Bartle, A. (2002) ' Hydropower Potential and Development activities', Energy Policy November 2002, Elsevier. London, Amsterdam, New York.

Beacon Solar, (2008) 'Beacon Solar energy Project Certification Application Siting Cases Executive Summary', Government of California. on-line resources: http://www.energy.ca.gov/sitingcases/beacon/documents/applicant/afc/1.0%20Executive%20Summary.pdf last accessed 11/2008

Belanger, C. & Gagnon, L. (2000) 'Adding wind energy to hydropower', Energy Policy November 2000, Elsevier. London, Amsterdam, New York

Bell, D., Gray T., & Haggett, C. (2005) 'The 'Social Gap' in Wind Farm Policy Siting Decisions: Explanations an Policy Responses', Environmental Politics 14 (4) pp 460-477.

BERR, (2008) 'Digest of UK Energy Statistics', BERR, Department of Business Enterprise and Regulatory Reform, on-line resources:
http://stats.berr.gov.uk/energystats/dukes5_5.xls accessed 20/11/08.

von Bertalanffy, L. (1968) *General System Theory: Foundations, Developments, Applications.* New York: Braziller.

Berube, G. & Cusson, C. (2002) 'The environmental legal and regulatory frameworks. assessing fairness and efficiency'. Energy Policy, November 2002, Elsevier. London, Amsterdam, New York.

Berube, G., & Villeneuve, F. (2002) 'Ethical Dilemmas and the decision-making process. Is a consensus realistic?' Energy Policy, November 2002, Elsevier. London, Amsterdam, New York.

Betz, A. (1920) 'Das Maximum der theoretisch möglichen Ausnutzung des Windes durch Windmotoren', Zeitschrift fur das gesamte Turbinewesen Sept 20th pp307-209 1920

Betz, A. (1966) *'Introduction to the theory of flow machines'*, Translated Randall D.G., Pergamon Press, Oxford

Blackmore, R. & Barrett R. (2003) 'Dynamic Atmosphere' Ch6 in *Changing Environments* ed Morris et al, Wiley & The Open University, Milton Keynes. 0 470 84999

Blodget, H.W., Taylor, P.T., Roark, J.H.(1990) 'Shoreline changes along the Rosetta-Nile Promontory: Monitoring with satellite observations.' Marine Geology 99, (1991) 67-77, Elsevier Science Publishers B.V., Amsterdam.

Blue Energy, (2008) on-line resources: http://www.bluenergy.com accessed 18/11/08.

Blowers, A., Smith, S. (2003) 'Introducing environmental: the environment of an estuary', in Hinchcliffe S.J., Blowers A.T., and Freeland J.R.,(eds) *'Understanding Environmental Issues'*, Wiley and Open University, 2003. Milton Keynes. ISBN 0-47084-998-3.

Borghetti, R., Perez, D. (1994) 'Socio-environmental actions on the Itaipu Binacional reservoir', International Water Power and Dam Construction, July 1994. Vol 46, no 7, pp36-38 Reed Business Publishing, London.

Borsos, B. (1991) 'Socio-political aspects of the Bos-Nagymaros barrage system', Water Power & Dam Construction, May 1991, p57-59. Reed Business Publishing, London.

Boulder Canyon Operations Office, (2001) 'Lower Colorado River Rivermile Index', US Bureau of Reclamation and US Geological survey, on-line resources: http://www.usbr.gov/lc/region/pao/rvrmiles.pdf last accessed 22/07/09

Boulding, K. E. (1956) 'General Systems Theory –the Skeleton of Science', Management Science, Vol 2 No 3, April 1956, The Institute of Management Sciences.

Boyle, G. (ed) (1996) *Renewable Energy Power for a Sustainable Future,* Ed Boyle, G Oxford University Press in conjunction with the Open University, Milton Keynes. 0-19-856452-X

Boyle, G. (ed) (2004) *Renewable Energy: Power for a Sustainable Future* (2nd Edition), Oxford University Press / The Open University, Oxford, Milton Keynes.

Brandon, M. & Smith, S. (2003) 'Water', in, Morris D., and Freeland J.R., Hinchcliffe S.J. and Smith S.(eds) *Changing Environments,* Chichester John Wiley & The Open University. 0 470 84999 1

Bratrich, C. et al (2000) 'A Multidisciplinary project to reduce environmental impact of hydropower generation', EAWAG Swiss Federal Institute for Aquatic Environmental Science and Technology, on-line resources, http://www.oekostrom.eawag.ch/veroeffentlichungen/ecohydraulics_bratrich.pdf 999/2000 last accessed 7/1/09

Bratich, C. & Truffer, B. (1998) 'Green Power Publications', EAWAG Swiss Federal Institute for Aquatic Environmental Science and Technology, Switzerland, ISBN 3-905484-05-6 on-line resources www.greenhydro.ch last accessed 7/1/09

Brocklehurst, F. (1997) 'A Review of the UK Onshore Wind Energy Resource', ETSU DTI, ETSU-R-99. HMSO. February 1997

Brown, G. (1996) 'Geothermal Energy', in Boyle, G (ed) *Renewable Energy Power for a Sustainable Future,* Oxford University Press in conjunction with The Open University, Oxford. 0-19-856452-X

Brown, C.B. (1944) 'Discussion of sediment in reservoirs by Witzig', ASCE American Society of Civil Engineers, Transactions, Volume 109.

Brune, G.H. (1953) 'Trap Efficiency of Reservoirs', Amercian Geophysical Union Transactions Volume 34 No 3, pp407-418.

Bryden I., Dacre S., Bullen C. (2002) 'Pentland Firth Tidal Current Energy Feasibility Study - Phase 1', Report extended Executive Summary 2002 March, Robert Gordon University/ Scottish Enterprise Ltd.

Bryden, I.G., Naik, S., Fraenkel, P., Bullen, C.R. (1998) 'Matching Tidal Current Plants to Local Flow Conditions', Energy Vol 23 No 9 pp699-709, Pergamon, Oxford.

Bucholz, T., Rametsteiner, E., Volk, T., Luzardis, V. (2009) ' Multi Criteria Analysis for bioenergy systems assessments', Energy Policy 37 p484-495, Elsevier, London, New York and Amsterdam.

BWEA, (2000) 'Planning for Wind Energy- a guide for regional developers', British Wind Energy Association, Professional Engineering Publishing, 1 8 6058 269 9, Proceedings of 2000 22nd BWEA Wind Energy Conference.

BWEA (2001) 'Regional Target Planning Guidance', British Wind Energy Association on-line resources: http://www.bwea.com/planning/uk_planning_legislation.html last accessed 7/08/09.

BWEA (2009) 'Wind energy frequently asked questions', British Wind Energy Association, on-line resources: http://www.bwea.com/ref/faq.html last accessed 11/06/09.

Caetana de Souza, A. (2007) 'Assessment of statistics of Brazilian hydroelectric power plants: dam areas versus installed and firm power'. Renewable and Sustainable Energy Reviews, April 2007. Elsevier

Catlow, J., Thirlwall, C. (1976) 'Environmental Impact Analysis', Department of the Environment Research Report II, HMSO.

Chambers (1974) 'Dictionary of Science and Technology', W & R Chambers, ISBN 0 550 13202 3.

Charlier, R.H. (2003) 'Sustainable co-generation from the tides: A review', Renewable and Sustainable Energy Reviews, 7 (2003) pp 187-213, Pergamon, Oxford.

Charlier, R. H. (2003*b*) 'A "sleeper" awakes: tidal current power', Renewable & Sustainable Energy Reviews 7 (2003) p515-529, Elsevier, New York, London and Amsterdam.

Churchill, M.A. (1948) 'Discussion and analysis and use of reservoir sedimentation data by LC Gottschalk', Federal Interagency Sedimentation Conference, Denver Colorado Proc pp139-140

Cioranescu, G. (1980) 'Harnessing the Romanian section of the Danube'. Open Society Archives On-line resources: http://files.osa.ceu.hu/holdings/300/8/3/text/53-2-83.shtml last accessed 22/07/09

Clarke, A.D. (1988) 'Windfarm Location and Environmental Impact', Charter for Renewable energy and Network for Alternative Technology and Technology Assessment, c/o Energy & Environment Research Unit, Open University, Milton Keynes.

Clarke, A. (1993) 'Comparing the Impacts of Renewables: a preliminary analysis', TPG Occasional Paper Technology Policy Group 23, Open University, Milton Keynes.

Clarke, A. (1994) 'Comparing the Impacts of Renewables', International Journal of Ambient Energy, Volume 15, Number 2, April 1994, Ambient Press Ltd, Swadlincote, UK.

Clarke, A. (1995) 'Environmental Impacts of Renewable Energy: a literature review,' Thesis for a Bachelor of Philosophy Degree, Technology Policy Group, Open University, Milton Keynes.

Clarke, A. (1998) 'Buyer Beware', New Scientist, Forum, 13 June 1998, Reed Business Information Ltd, London.

Clarke, A. (2000) 'Life Cycle Assessment of Energy from Biomass Waste sources', Energy and Environment Research Unit, Report 075, Open University, Milton Keynes.

Clarke, A., & Elliott, D. (2002) 'An Assessment of Biomass as an energy source: the case of energy from waste', Energy and Environment Journal Feb. 2002, Multi Science Publishing Co Ltd, Brentwood UK.

Clarke, C. (2000) 'WCD Cross Check Survey Final Report', World Commission on Dams, on-line resources, http://www.dams.org/kbase/survey/ last accessed 20/07/09, http://www.dams.org/docs/kbase/survey/ccsmain.pdf November 2000

Clausius, R. (1856) *The Mechanical Theory of Heat with its Applications to the Steam Engine and to Physical Properties of Bodies*, London: John van Voorst, 1 Paternoster Row.

Colorado River Delta Bi-National Symposium Proceedings (2001) 'United States-Mexico Colorado river Delta Symposium 11-12 September 2001', 2001, on-line resources: www.ibwc.state.gov?FAO/CRDS0901/EnglishSymposium.pdf accessed 12/2008

Cotrim, J.R. et al, (1994) 'The bi-national Itaipu hydropower project', Water Power & Dam Construction, Pt 1, pp 40-47, October 1977. Global trade Media, London.

Couch, S.J. & Bryden, I.G. et al (2007) 'Survey of Energy Resources' 2007 cit in WEC Survey of Energy Resources 2007, on-line resources: www.worldenergy.org/documents/ser2007_final_online_version_1.pdf (last accessed 06/08/09)

CRES (2002) 'Wave Energy Utilisation in Europe Current status and perspectives', Centre for Renewable Energy Resources (CRES), Pikermi Greece & EU, 960-86907-1-4, on-line resources: http://www.cres.gr/kape/pdf/download/Wave%20Energy%20Brochure.pdf (last accessed 10/6/09)

Cross, N. (1982) 'Methods Guide' Control of Technology, Unit 8, prepared for Course Team by Nigel Cross, Open University Press, Milton Keynes.

Dacre, S. (2002) 'A scoping study to Establish a Research programme on the Environmental Impacts of Tidal Stream Energy', Department of Trade and Industry, Contractor Robert Gordon University Aberdeen. Energy Technology Support Unit, T/04/00213/00/REP 2002

DECC (2009a), 'The UK Low Carbon Transition Plan', Department of Energy and Climate Change, London.

DECC (2009b) 'Offshore Energy SEA Environmental Report', Department of Energy and Climate Change, London.

Department of Energy (1989) 'The Severn barrage Project: General Report', Energy Paper No 57, HMSO, ISBN 0 11 4129525.

Devine-Wright, P. and Devine-Wright, H. (2006) 'Social representations of intermittency and the shaping of public support for wind energy in the UK', International Journal of Global Energy Issues: Special issue on Intermittency 25 (2/4) 243-256.

Dickinson, H. and Wedgwood, K.F. (1982) 'The Nile waters: Sudan's critical resource', Water Power and Dam Construction January 1982. Reed Business Publishing, London.

Dornblut, I. (2000) 'GIS Related monthly balance of water availability and water demand in river basins. Case study for the River Danube'. Global Runoff Data Centre GRDC, Report No 25 June 2000

DTI (2004) 'Atlas of UK Marine energy resources', Department of Trade and Industry, Business Enterprise and Regulatory Reform Department, BERR on-line resources: http://www.renewables-atlas.info/ last accessed 06/08/09

Dubowski, Y. (1997) 'Environmental Effects of the High Dam at Aswan', June 1997, June talk at the California Institute of Technology. June 1997 on-line resources: http://www.gps.caltech.edu/classes/ge148/1997C/Reports/148niled.html accessed 23/07/09

Duckers, L. (1996), 'Wave Energy', in Boyle G. (ed) *Renewable Energy Power for a Sustainable Future,* Oxford University Press in conjunction with the Open University, . 0-19-856452-X

DUKES (2008) 'Digest of UK Energy Statistics', BERR Business Enterprise and Regulatory Reform Department, on-line resources: http://www.berr.gov.uk/energy/statistics/source/renewables/page18513.html (last accessed 11/06/09)

EC Birds Directive (1979) 'EC Birds Directive 79 /409/ EEC ', European Union, on-line resources: http://ec.europa.eu/environment/nature/legislation/birdsdirective/index_en.htm accessed 18/11/08

EEA (1998) 'Life Cycle Assessment, LCA A guide to approaches, experiences and information services.', Report no 6, EEA European Environment Agency on-line resources: http://reports.eea.europa.eu/GH-07-97-595-EN-C/en/Issue%20report%20No%206.pdf accessed 13/01/09.

El-Moattassem, M. (1994) 'Field studies and analysis of the High Aswan Dam reservoir'. Water Power and Dam Construction, Reed Business Publishing, London. January 1994.

Elliott, D. (1994) 'Public Reactions to Wind farms: the dynamics of opinion formation', Energy and Environment, Vol5 No 4 pp343-362 December 1994.

Elliott, D. (1996) 'Tidal Power', in Boyle G. (ed) *Renewable Energy Power for a Sustainable Future,* Oxford Oxford University Press in conjunction with the Open University. 0-19-856452-X

Elliott, D. (2003) *Energy Society and Environment*, London, Routledge.

Ellis, G., Barry, J., and Robin, C. (2006) 'Renewable energy and discourses of objection towards deliberative policy making. Summary of main research findings'. Economic and Social Research Council ESRC grant reference: 000-22-1095 Available at the following website: http://www.qub.ac.uk/research-centres/REDOWelcome/ accessed 20/07/09

Encylopaedia Britannica (2009) 'Colorado River', On-line resources: http://www.britannica.com/EBchecked/topic/126494/Colorado-River last accessed 13/08/09

ENDS (2008) 'ENDS Press Release', Environmental Data Services, on-line resources: http://www.windenergy.org.nz/documents/2008/080702-Growth-in-wind-generation.pdf 2nd July 2008, (date accessed 20/11/08).

Energy White Paper (2003) ' Our Energy Future: creating a low carbon economy', Department of Trade and Industry, The Stationery Office TSO.

Engstrom, S., Pershagen, B. (1980) 'Aesthetic factors and visual effects of large scale WECS', National Swedish Board for Energy Development NE

Environment Agency (2008) 'History of the Dee Scheme', Environment Agency, on-line resources: http://www.environment-agency.gov.uk/homeandleisure/drought/38583.aspx accessed 15/12/08

EREC (2007) 'Renewable Energy Target for Europe: 20% by 2020', European Renewable Energy Commission, on-line resources: http://www.erec.org/fileadmin/erec_docs/Documents/Publications/EREC_Targets_2020_def.pdf accessed 19/01/09

EROS (2000) 'The Interactions between the Danube and the North West Back Sea', Environment Institute, Joint Research Centre, Italy, on-line resources: http://ec.europa.eu/research/intco/pdf/094e.pdf last accessed 17/08/09

ETSU (1979) 'Wave Energy', Energy Paper No 42, Dawson J.K. Head of Energy Technology Support Unit, Her Majesty's Stationery Office.

ETSU (1993) 'Tidal Stream Energy Review Appendices', Engineering & Power Development Consultants Ltd with Binnie & Partners Sir Robert McAlpine & Sons Ltd, and IT Power Ltd, ETSU on behalf of Department of Trade & Industry, Energy Technology Support Unit. T/05/00155/REP A.

ETSU (1994) 'An Assessment of Renewable energy for the UK', Energy Technology Support Unit ETSU Report R-8, Hill et al, ETSU, ISBN 0 11 515348 9.

ETSU & CCE (1992) 'An Assessment of the State of the Art, Technical Perspectives and Potential Market for Wave Energy' ETSU-OPET for the DG17 European Commission

EU Biofuels Directive (2003) 'EU Biofuels Directive, directive 2003/30/3 of the European Parliament and the Council of 8th May 2003 on the promotion of the use of biofuels or other renewable fuels for transport'. Official Journal of the European Union European Union, on-line resources: http://ec.europa.eu/energy/res/legislation/doc/biofuels/en_final.pdf accessed 15/04/09

Europa (2008) 'Memo on the Renewable Energy and Climate Change Package', Europa Press Release Rapid, on-line resources: http://europa.eu/rapid/pressReleasesAction.do?reference=MEMO/08/33&format=HTML&aged=0&language=EN&guiLanguage=en accessed 19/01/09.

EWEA (2008) 'Wind Energy Statistics Windmap', European Wind Energy Association, on-line resources: http://www.ewea.org/fileadmin/ewea_documents/mailing/windmap-08g.pdf accessed 30/12/08.

ExternE (1995) 'Externalities of Energy', European Commission, Vol1, DG12, EUR 16520, Luxemburg, ISBN 92-827-5210-0.

FCRPS (2003) 'Federal Columbia River Power System brochure guide', US ACE, Bonneville Power Administration, Bureau of Reclamation, Agencies, On-line resources: http://www.nwd-wc.usace.army.mil/PB/fcrps.broch.f.pdf accessed Jan 2009

Flessa, K. W., Tellez –Duarte, M.A., et al. (2001) 'Since the Dams: Historical ecology of the Colorado Delta', Centro de Estudios de Almojas Muerlas, Sept 11th, On-line resources: http://www.geo.arizona.edu/ceam/Hecold/hecolcd.htm (accessed 26/02/09)

Ford, N. (2006) 'Seoul leads tidal breakthrough', International Water Power & Dam Construction September 12th 2006, Reed Business Publishing on-line resources: http://www.waterpowermagazine.com/story.asp?sc=2038863 accessed 08/06/09

Fitzgerald, E. & Bowden, B. (2006) 'Quantifying increases in streampower and energy, using flow duration curves to depict stream flow values', Stormwater 7(2) pp88-94 2006

Flessa, K. W. et al (2001) Tellez -Duarte M.A.,et al, 'Since the Dams: Historical ecology of the Colorado Delta', Centro de Estudios de Almojas Muerlas, 2001 Sept 11th, on-line resources: http://www.geo.arizona.edu/ceam/Hecold/hecolcd.htm (accessed 26/02/09)

Fraenkel, P. (2007) 'Marine Current Turbines: an update', MCT Ltd on-line resources: http://www.all-energy.co.uk/UserFiles/File/2007PeterFraenkel.pdf (accessed 18/11/08)

Freer, R. (2001) 'The Three Gorges Project on the Yangtze River in China', Proceedings. of ICE pp 20-28 , Civil Engineering 144, February 2001.

Frihy, O.E. (1991) 'Sea level rise and shoreline retreat, of the Nile Delta', Natural Hazards, Vol 5, no 1, p65-81, Springer, Netherlands, http://www.springerlink.com/content/kvtuv51468601178/ (accessed 07/04/10)

Frihy, O.E. and Khafagy, A.A. (1991) 'Climate and induced changes to shoreline migration trends at the Nile Delta Promontories Egypt'. Catena Volume 18 Issue 2, p197-211. Elsevier B.V., London, Amsterdam, New York

Gagnon, L. (2002) 'The International rivers Network statement on GHG emissions from reservoirs', International Hydropower Association, on-line resources: http://philip.inpa.gov.br/publ_livres/Other%20side-outro%20lado/Hydroelectric%20emissions/Gagnon%20IHA%202002.pdf July 2002, accessed 31/12/08

Gagnon, L., Belanger, C., Uchiyama, Y. (2002a) 'Life Cycle Assessment of electricity generation options: the status of research in year 2001', Energy Policy, November 2002, Elsevier, London, Amsterdam, New York. Vol 30 pp 1267-1278, a. Fig 4 p1274.

Gallagher, E. (2008) 'The Gallagher Review of the indirect effects of biofuels production', July 2008, Renewables Fuels Agency, on-line resources:

http://www.renewablefuelsagency.org/_db/_documents/Report_of_the_Gallagher_review.pdf accessed 31/12/08

Garrard Hassan (2004) Personal communication with Gillian Smith of Garrard Hassan 6 April 2004.

Gasser, M.M., & El-Gemal, F. (1994) 'Aswan High dam: Lessons learnt and on-going research', Water Power & Dam Construction, January 1994. pp35-39. Reed Business Publishing, London.

GWEC (2009) Global Wind Energy Council, on-line resources: http://www.gwec.net/index.php?id=13 last accessed 18/08/09

Goguel B., Mpala A.S. (1992) 'Monitoring and Maintenance at Kariba dam', Water Power and Dam Construction, June 1992, Reed Business Publishing, London.

Graf, W. H. (1971) *Hydraulics of Sediment Transport*, New York McGraw-Hill,. 07-023900

GRDC (2008) 'The Global Runoff Data Centre', D - 56002 Koblenz, Germany.

Greeman, A. (1996) 'Yoking the Yangtse', New Civil Engineer, London. 14th November 1996

Greeman, A. (1999) 'How do they do that?', International Water Power and Dam Construction, July 1999, Vol 51, No 7, pp 26-28, Reed Business Publishing, London.

Hall, D.O. (1991) 'Biomass Energy', Energy Policy, October 1991 pp711-737, Butterworth-Heinemann Ltd, Oxford. UK.

Hammerfest Strom (2008) 'Norwegian technology for tidal energy to be further developed in Great Britain', Hammerfest Strom, on-line resources: http://www.hammerfeststrom.com/content/view/49/72/lang (accessed19/11/08)

Hang, Q., Zhoa, J.,Xiao, Y., Junkui, C. (2007) 'Prospect of Concentrating Solar Power in China, -the sustainable future', Renewable & Sustainable Energy Reviews, 12 (2008) 2505-2514, Elsevier, London, Amsterdam, New York.

Hill, R. & Twidell, J. (1994) 'The Environmental Impacts of Energy Technology', UK Solar Energy Society, Conference C62 University of Westminster, London 11th May 1994.

Hinojosa-Huerta, O. (2004) 'Restoring the Colorado Delta', January/February 2004, Southwest Hydrology, on-line resources: http://www.swhydro.arizona.edu/archive/V3_N1/feature5.pdf accessed 09/04/10

HMSO (2004) ' Planning Policy Statement 22: Renewable Energy', Her Majesty's Stationery Office, London, June 2004.

Holdren, J. P.,Morris, G., Mintzer, I. (1980) 'Environmental Aspects of Renewable Energy Sources'. AR Annual Reviews, Annual Review of Energy, 1980, Vol 5 p241-9.

ICOLD (1989) 'Sedimentation control of Reservoir Guidelines', International Commission on Large Dams.

IEA (2006) 'Renewables in global energy supply', An International Energy Agency IEA Fact Sheet, September 2006, on-line resources:
http://www.iea.org/textbase/papers/2006/renewable_factsheet.pdf
last accessed 7/08/09

INHGA (2005) 'Water flow and Sediment Transport in the Lower Danube River', The National Hydrology and Water Management Institute, Geophysical REsearch abstracts, Vol. 7 05967 2005, European GeoSciences Union, on-line resources:
http://www.cosis.net/abstracts/EGU05/05967/EGU05-J-05967.pdf last accessed 17/08/09

IWBC (2001) International Boundary and Water Commission, 'United States-Mexico Colorado river Delta Symposium 11-12 September 2001', on-line resources:
www.ibwc.state.gov?FAO/CRDS0901/EnglishSymposium.pdf accessed 12/2008

International Water Power and Dam Construction (1996) *Year Book*, Reed Business Publishing, London.

IPCC (2007) 'Climate Change 2007: Synthesis Report Summary for Policymakers', June, Intergovernmental Panel on Climate Change WMO UNEP, on-line resources:
http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf last accessed 20/07/09

ISO (2006) 'Environmental Management -Life Cycle Assessment, Life Cycle Impact Assessment', International Standards Organisation, on-line resources:

http://www.iso.ch/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=23153 accessed 19/01/09.

JDS (2005) 'Chapter 3 2005 Joint Danube Survey', International Commission for the Protection of the Danube River, on-line resources: www.icpdr.org/icpdr-pages/jds.htm last accessed 22/07/09.

Jensen, A (1997) 'Life Cycle Assessment', European Environment Agency, Copenhagen, Denmark. ISBN 9291670790

Jiazhu, W. (1994) 'Major problems with the design of Three Gorges', International Water Power and Dam Construction, August 1994. pp24-32. Reed Business Publishing, London.

Jisheng, C. (1994) 'Sedimentation studies at Three Gorges', International Water Power and Dam Construction, August 1994. pp54-58. Reed Business Publishing, London.

Joint Danube Survey (2005) ICPDR International Commission for the Protection of the Danube River, Vienna, On-line resources: http://www.icpdr.org/icpdr-pages/reports.htm last accessed 22/07/09.

Joint Danube Survey (2006) 'JDS Dams & Structures', ICPDR International Commission for the Protection of the Danube River, Vienna, On-line resources: http://www.icpdr.org/icpdr-pages/dams_structures.htm accessed 19/06/06.

Joint Nature Information Committee (2008) 'Information Sheet on Ramsar Wetlands (RIS) Severn Estuary.' Joint Nature Information Committee, on-line resources:http://www.jncc.gov.uk/pdf/RIS/UK11081.pdf last accessed 06/08/09.

Joint Staff (2006) 'Joint Staff Report concerning commercial seasons for Spring Chinook, Steelhead, Sturgeon, Shad, Smelt and other species and miscellaneous regulations for 2006', Joint Columbia River Management Staff, Oregon Department of Fish and Wildlife, Washington Department of Fish and Wildlife. On-line resources: http://wdfw.wa.gov/fish/crc/jan1806jointstaff.pdf last accessed 13/08/09.

Juwi (2008) 'World's largest solar power plant being built in E Germany', Press Release, on-line resources: http://www.tu.no/multimedia/archive/00036/Presentasjon_av_Wald_36754a.pdf accessed 11/2008

Kammerer, J.C. (1990), 'Largest Rivers in the United States', USGS United States Geological Survey, On-line resources: http://pubs.usgs.gov/of/1987/ofr87-242/ last accessed 13/08/09

Key, M.H., Hutcheon, R.J., Preston D.A. & Donaldson T.P. (1972) 'Ultraviolet and X-ray Spectroscopy of Astrophysical and Laboratory Plasmas', Procs. held in Utrecht. Space Sci. Review 13, 1972, p584.

Klimpt, J., Rivero C., Puranen, H., Koch, F. (2002) 'Recommendations for sustainable hydroelectric development', Energy Policy, November 2002, Elsevier. London, Amsterdam, New York.

Klukovska, J., & Topolska, J. (1995) ' Water Level Regime in the Danube River and its River Branches', GROUND WATER Consulting Ltd. POB 6, 840 00 Bratislava 4, Slovakia, on-line resources: http://www.mpsr.sk/slovak/dok/gn/book/05kap/05kap.htm accessed 30/12/02.

Krcho, J. (1995) 'Gabcikovo Part of the Hydro Eelectric Power Project Environmental Impact Review', Faculty of National. Sciences Comenius University, Bratislava, on-line resources: http://www.mpsr.sk/slovak/dok/gn/book/contents.htm accessed 30/12/02.

Lang, W. (2007) 'Columbia river history', Portland State University, On-line resources: http://www.ccrh.org/river/history.htm accessed 18/10/07.

Langford, T.E. (1983) *Use of Water for any electricity Production, Hydro, Tidal, Cooling, Electricity Generation and the Ecology of Natural Waters*, Liverpool University Press.

Li, F. (2000) 'Hydropower in China', Energy Policy, November 2000, Elsevier. London, Amsterdam, New York.

Liebreich, M. (2008) 'Food price increases: is it fair to blame biofuels?' New Energy Finance, Report 27/05/08 on-line resources: http://www.newenergymatters.com/docs/Press/NEF_RN_2008-05-27_Food_Price_Drivers.pdf last accessed 12/08/09.

Lippschutz, R. D. (1997) 'Intermarium:Damming Troubled Waters: Conflict over the Danube 1950-2000', Institute of War & Peace Studies, Columbia University. Conf Paper for Institute of War & Peace Studies, Columbia University October 1997.

Liska, M.B.(1993) 'Gabcikovo-Nagymaros: a review of its significance and impacts', 45 Water Power and Dam Construction 36, July 1993 Reed Business Publishing, London.

Lofty, M. F., and Frihy, O. E. (1993) Sediment balance in the near shore zone of the Nile Delta coast, Egypt. Journal of Coastal Research, 9, 654-662. West Palm Beach.

Lovenk, V., Szanto, M. (1986) 'The Binational Gabcikovo-Nagymaros project', Water Power and Dam Construction, November 1986, Wilmington Publications.

Lunar Energy (2009) Lunar Energy Ltd, on-line resources:http://www.lunarenergy.co.uk/ accessed 08/06/09.

Lyra, F.H. (1982) 'Planning and Construction sequence at Itaipu', Water Power and Dam Construction, May 1982. Wilmington Publications.

MacKay, D.J.C. (2007) 'Under Estimation of the UK Tidal resource', Cavendish Laboratory University of Cambridge, 17 April 2007, on-line resources: http://www.inference.phy.cam.ac.uk/sustainable/book/tex/TideEstimate.pdf last accessed 6/08/09.

Mackay, D. (2008*a*) ' Sustainable Energy without the hot air', Cambridge UIT, on-line resources: http://www.inference.phy.cam.ac.uk/sustainable/book/tex/cft.pdf last accessed 20/07/09Nov 2008.

Mackay, D. (2008) 'Technical Chapters to Sustainable Energy', Mackay, on-line resources, http: //without the hot air.com/ last accessed 20/07/09.

Manning, R. (1889) 'On the flow of open water in channels and pipes'. Institution of the Civil Engineers of Ireland, Transactions of the Institution of Civil Engineers of Ireland 20, pp161-166.

Mamdouh, S. (1985) *Hydrology of the Nile Basin*, London, Amsterdam and New York. Elsevier. ISBN 0444416692 (series).

McKenzie-Hedger, M. (1995) 'Wind power: challenges to planning policy in the UK', Land Use Policy 12, (1) pp17-28, Butterworth Heinemann Ltd, Oxford. 0264-8377/95/010017-12.

MCT (2006, & 2008), Marine Current Turbines, on-line resources: http://www.marineturbines.com/ (accessed 18/11/08).

Mila i Canals L.,Clift R., Cowell S., et al (2006) ' Definition of best indicators for Land Use Impacts for Life Cycle Assessment: Expert Workshop', 12-13 June 2006, University of Surrey IAS on-line resources: http://www.ias.surrey.ac.uk/workshops/DEFNBEST/cfp.php accessed13/01/09.

Millar, D.L., Smith, H.C.M., Reeve, D.E. (2007) 'Modelling analysis of the sensitivity of shoreline change to a wave farm', Ocean Engineering 34 pp884-901 2007, Elsevier, London, Amsterdam and New York.

Mitchell, D. (2008) 'A Note on Rising Food Prices', Policy Research Working Paper 4682, World Bank, Development Prospects Group on-line resources: http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2008/07/28/000020439_20080728103002/Rendered/PDF/WP4682.pdf accessed 15/04/09

Mollison, D. (1989) 'The European Wave Power Resource', UK ISES Conference on wave energy Devices, Lanchester Polytechnic 28/11/1989.

Mortimer, N. (1991) ' Energy analysis of renewable energy sources', Energy Policy Vol. 19 Issue 4 pp 374-385, Elsevier, London, Amsterdam and New York..

Moxon, S. (1999) 'Closing the Gap', International Water Power and Dam Construction April 1999, London Reed Business Publishing.

NASA (2008) 'RST Section 14 The Water Planet', NASA, on-line resources: http://rst.gsfc.nasa.gov/Sect14/Sect14_1c.html accessed 10/11/08.

Nasholm, T., Ekblad A. (1998) 'Boreal forest plants take up organic nitrogen', Nature Volume 392 30, April 1998. Macmillan, London, New York, San Francisco, Washington.

NATTA (2006) ‘Wave power and tidal current turbines’, Network for Alternative Technology and Technology Assessment, c/o Energy and Environment Research Unit, Open University, Milton Keynes.

New York Times (2008) 'Solar Projects draw new opposition', New York Times 23rd September 2008, on-line resources: http://www.nytimes.com/2008/09/24/business/businessspecial2/24shrike.html?pagewanted=2&_r=1&ref=businessspecial2 accessed 11/2008 .

Newman, G. (2000) 'Cleaning up hydro's act', International Water Power & Dam Construction p14-15, August 2000, Reed Business Publishing, London.

NREL, (2008) 'Overview of Concentrating Solar Power Technologies', national Renewable Energy Laboratory NREL on-line resources: http://www.energy.ca.gov/reti/environmental_com/2008-04-04_CSP_OVERVIEW.PDF (accessed 11/2008).

NW Council (2002) 'Native American Legal Resources', NW Council, on-line resources: http://www.nwcouncil.org/history/IndianTreaties.asp accessed 15/04/09.

O'Connor, J. (2004) 'The Evolving landscape of the Columbia River Gorge Lewis and Clark and cataclysms on the Columbia', Oregon Historical Quarterly, On-line resources: http://www.historycooperative.org/journals/ohq/105.3/oconnor.html accessed Jan 2009.

OECD (1989) 'Environmental Impacts of Renewable Energy', Compass Project Report, Organisation for Economic Co-operation and Development OECD, Paris.

Oud, E. (2002) 'The Evolving context for hydropower development.' Energy Policy November 2002, Elsevier, London, Amsterdam and New York.

Owens, P. N., Batalla, R.J., Collins, A.J. et al (2005) 'Fine -grained sediment in river systems: environmental significance and management issues', River Research 7 Applications 21:693-717 (2005), On-line Wiley InterScience, Chichester John Wiley & Sons.

Ozgener, O. (2006) 'A small wind turbine application and its performance analysis', Energy Conversion and Management Vol 47 Issues 11-12 July 2006 pp1326-1337 Elsevier, London, Amsterdam and New York.

Parsons Brinkerhoff, (2008) 'Severn Tidal Power Feasibility Study', Parsons Brinkerhoff and Black & Veatch, on-line resources: http://www.severnestuary.net/sep/forum/tidalpoweroptions.ppt (accessed 18/11/08)

Panin N., & Jipa D. (1999) 'Danube River Sediment Input and its interaction with the North West Black Sea', Estuarine Shelf & Coastal Science pp551-562 1999.

Pelamis (2009) Wave Power Ltd Company Website, on-line resources: http://www.pelamiswave.com/ accessed 9/06/09.

Petts, G. E. (1984) *Ecology of. Impounded Rivers. Perspectives for Ecological management.*, Chichester John Wiley & Sons. ISBN 0 471 10306 3.

Pimental, D., Fast, S.,Gallahan, D., Moran, M. (1983) 'Environmental Risks of Utilizing Crop and Forest Residues for Biomass energy', International Energy Conversion Engineering Conference, IECEC, Vol. 2 18th IECEC Conf Proc pp580-585 1983.

Qing, D. (1994) *Yangtze Yangtze*, Earthscan Publications, Oxford Taylor & Francis. ISBN 0-919849-22-9

Queens University Belfast (2002) 'Islay Limpet Wave Power Plant Publishable Report', Contract JOR3-CT98-0312, Queens University Belfast and EC Joule III, on-line resources: http://www.wavegen.co.uk/pdf/LIMPET%20publishable%20report.pdf (last accessed 10/06/09).

Ramage, J. (1996) 'Hydroelectricity', in Boyle G. (ed.) *Renewable Energy Power for a Sustainable Future,* Oxford University Press in conjunction with the Open University. 0-19-856452-X

Rammage, J. & Scurlock, J. 1996, 'Biomass', , in Boyle G. (ed.) *Renewable Energy Power for a Sustainable Future,* Oxford University Press in conjunction with the Open University. 0-19-856452-X

Rand, M. & Clarke, A. (1991), 'The environmental and community impacts of wind energy in the UK', BWEA, Wind Engineering February 1991.

Ranganathan, V., 2000, ' Hydropower and the environment in India', Energy Policy November 2000, Elsevier, London, Amsterdam and New York.

Resoft, (1999) 'Wind Farm', Personal communication with Alan Harris of Resoft, 21 January 1999.

Rhoads, B.L. (1987) 'Streampower terminology', The Professional Geographer, Vol 39 Issue 2 p189 May 1987.

Richey, J., Melack, J. M., Aufdenkampe, A.K., Ballester, V. M., Hess, L.L. (2002) 'Outgassing from Amazonian rivers and Wetlands as a large source of atmospheric CO_2', Nature 416 p617-620, April 2002, Nature Publishing Group, London, New York, San Francisco, Washington, Macmillan.

Royal Society of Chemistry (2005) 'Environment, Health and Safety Committee note on Life Cycle Assessment.' Version 2 RSC on-line resources: http://www.rsc.org/images/LCA%20Revised%20Note%20Final%20140205_tcm18-97943.pdf accessed 13/01/09

Rzoska, J. (1978) *On the Nature of Rivers* , The Hague, Boston, London, Dr Junk Publishers. ISBN90 6193 589 X .

Saad, M.B.A. (2002) 'Nile River Morphology Changes due to the construction of the High Aswan Dam in Egypt', 5th Int. Conf. ICHE 2002, on-line resources: http://kfki.baw.de/fileadmin/conferences/ICHE/2002-Warsaw/ARTICLES/PDF/248C4-SD.pdf last accessed 24/07/09.

Soils Incorporated (Pvt) Ltd (2000) 'Kariba Dam Case Study, Final Draft, WCD, Working Paper for the World Commission on Dams', Soils Incorporated (Pvt) Ltd, Harare, Zimbabwe, in assoc. with Chalo environmental & Sustainable Development Consultants, Lusaka, Zambia. World Commission on Dams, on-line resources, http://www.damsreport.org/docs/kbase/studies/drafts/zzdraftx.pdf last accessed 20/07/09.

Schlamdinger, B., & Marland, G. (2000) 'Land Use & Global climate change. Forests, Land Management and the Kyoto protocol', Pew Center on Global Climate Change, on-line resources: http://www.pewclimate.org/global-warming-in-depth/all_reports/land_use_and_climate_change/ last accessed 20/07/09.

Schwarz, U. (2008) 'Assessment of the Balance and Management of Sediments of the Danube', FLUVIUS Floodplain Ecology and River Basin Management. On-line resources: http://ksh.fgg.uni-lj.si/bled2008/cd_2008/05_Floods,%20morphological%20processes,%20erosion,%20sediment%20transport%20and%20sedimentation/211_Schwarz.pdf last accessed 23/07/09.

SDC (2005) 'Wind Power in the UK', Sustainable Development Commission, on-line resources: http://www.sd-commission.org.uk/publications.php?id=234 last accessed 18/08/09.

Sebitosi, A.B., & da Graca, A. (2008) 'Cabora Bassa and Teti Province Mozambique: A great potential for an industrial hub in South Africa'. Energy Policy 37 2027-2032 2008, London, Amsterdam and New York, Elsevier.

Shaw, T.L. Ed.(1980) *'An Environmental appraisal of tidal power stations: with particular reference to the Severn Barrage'*, London, Pitman Publishing.

Shaw, T.L. (2007) 'The Implications of Modern Hydro Electric Power schemes for fisheries'. Water and Environment Journal, Vol. 18 Issue 4 26 July 2007 Wiley InterScience, Chichester.
on-line resources: http://www3.interscience.wiley.com/journal/119923324/abstract last accessed 24/07/09

Smith, D.S. (1981) 'Microenvironmental Responses of a Sonoran Desert Ecosystem to a Simulated Solar Collector Facility', PhD Thesis, University of California LA, October 1981.

Sleigh, A., & Noakes, C. (2009) 'Dimensional Analysis, Notes for Level 1 lecture course in Fluid Mechanics', University of Leeds, School of Civil Engineering, On-line resources: http://www.efm.leeds.ac.uk/CIVE/CIVE1400/Section5/dimensional_analysis.htm last accessed 22/08/09.

Srinivasan, S. (2008), 'The Food v Fuel Debate: a nuanced view of incentive structures', Renewable Energy 43 (2009) 950-954, London, Amsterdam and New York, Elsevier.

Stankovic (1960) 'Yugoslav-Rumanian Iron Gates Project', Open Society Archives Box Folder Report 122-1-230, 1960-5-3. On-line resources: http://www.osa.ceu.hu/files/holdings/300/8/3/text/122-1-230.shtml accessed 29/10/07.

Stanley, D. J. (1996) "Nile Delta: Extreme Case of Sediment Entrapment on a Delta Plain and Consequent Coastal Land Loss." *Marine Geology* 129 (1996): 189-195. Science B.V. London, Amsterdam and New York, Elsevier.

Stanley, D.J. and Wingerath, J.G. (1996) 'Nile sediment dispersal altered by the Aswan high dam: The Kaolinite trace', Marine Geology, vol. 133, pp. 1-9. London, Amsterdam and New York, Elsevier Science B.V.

STPG (1986) 'Tidal Power from the Severn Interim Study Report', STPG, The Severn Tidal Power Group 0 7277 0358 7 .

Sunpower Corp (2008) 'Bavaria Solarpark exceeds energy expectations', Sunpower Corp on-line resources: http://www.sunpowercorp.it/For-Power-Plants/~/media/Downloads/for_powerplants/spwr_bavaria_en_a4_w.ashx accessed 28/11/08.

Suri, M., Huld, T. A., Dunlop, E.D, Cebecauer, T. (2006) 'Photovoltaic Electrical Potential in European Countries', European Commission Joint Research Centre, Institute for Environmental and Sustainability Renewable energies Unit On-line resources: http://re.jrc.ec.europa.eu/pvgis/cmaps/eu_opt/PVGIS-EuropeSolarPotential.pdf (accessed 28/11/08).

Sustainable Development Commission (2007) 'Turning the Tide. Tidal Power in the UK'. Sustainable Development Commission, on-line resources: http://www.sd-commission.org.uk/publications/downloads/Tidal_Power_in_the_UK_Oct07.pdf 2007 accessed 18/11/08.

Sutcliffe, J.V. and Parks, Y.P. (1999) *The Hydrology of the Nile*, International Association of Hydrological Sciences. 1-910502-75-9 .

Tan, K.T., Lee, K.T. Mohamed, A.R., Batia, S. (2009) 'Palm Oil: addressing issues and towards sustainable development', Renewable & Sustainable Energy Reviews 13 (2009) 420-427, Elsevier, London, Amsterdam and New York.

Taylor, D. (1996) 'Wind Energy', in Boyle, G. (ed), *Renewable Energy Power for a Sustainable Future,* Oxford University Press in conjunction with the Open University. 0-19-856452-X

TDW (2004) 'Germany: Siemens PTD and PowerLight Corp. to Build Solarpark in Bavaria', TDW Transmission and Distribution World On-line resources: http://tdworld.com/substations/power_germany_siemens_ptd/ 1/12/2004.

Tesaker, E., & Tevinereim, K. (1986) 'Hydro Electric Flushing of Sediments at small hydro plants', International Water Power & Dam Construction, 2nd International Conference Proceedings Volume 38 pp365-371 No 8 April 1986, Wilmington Publishing.

Thorpe, T.W. & Marrow, J.E. (1990) 'Wave Energy Review Progress Report 1', Chief Scientists Group ETSU Energy Technology Support Unit.

Tidal Electric Limited (2008) 'UK Projects', Tidal Electric Limited on-line resources: http://www.tidalelectric.com/Projects%20UK.htm last accessed 6/08/09.

Toniolo, H., Parker, G., Voller, V. (2007) 'Role of Ponded Turbidity Currents in Reservoir Trap Efficiency', ASCE American Society of Civil Engineers, Journal of Hydraulic Engineering.Vol 133 No 6 pp579-595.

Truffer B., Bratrich, C., et al, (2003) 'Green Hydropower: the contribution of aquatic science to the promotion of sustainable electricity', Springer, on-line resources: http://www.springerlink.com/content/htaa2tfpkfx35ne2/fulltext.pdf last accessed 20/07/09.

Trussart, S., Messier, D., Roquest, V., Akil, S. (2002) 'Hydropower Projects: a review of most effective mitigation measures', Energy Policy November 2002, Elsevier, London, Amsterdam and New York.

Twidell J. & Weir A, (1986) *'Renewable Energy Resources'*, E. & F. N. Spon, London U.K. ISBN 0-419-12010-6.

UNH / GRDC (2007) University New Hampshire / Global Data Run-off Centre, 2002-2007. on-line resources: www.grdc.sr.unh.edu/html/Polygons/P6142200.html accessed various occasions.

US Army ACE (1989) 'Trap Efficiency of Reservoirs', US ACE United States Army Corps of Engineers, Army engineering documents 15-12-1989, on-line resources: www.uace.army.mil/usace-docs/eng-manuals/em1110-2-4000/a-f.pdf accessed 10/07/06.

US Bureau of Reclamation (2001) ' Colorado River Interim Surplus Criteria Final Environmental Impact Statement: Executive Summary', United States Bureau of Reclamation, on-line resources: http://www.lc.usbr.gov/g4000/surplus/SURPLUS_FEIS.HTML accessed 12/11/02.

US DoE (2008) 'Concentrating Solar Power -Parabolic Reflectors', United States Department of Energy, on-line resources: http://solareis.anl.gov/documents/docs/NREL_CSP_3.pdf (accessed 11/2008).

USGS (1996) 'Calculated Hydrographs for the Colorado River Downstream from Glen Canyon Dam during the experimental release March 22nd to April 8th 1996', US Department of the Interior, US Geological Survey, USGS, on-line resources: http://pubs.usgs.gov/fs/1996/fs-083-96/
: www.ibwc.state.gov?FAO/CRDS0901/EnglishSymposium.pdf (last accessed 17/06/09).

USGS (2001) 'Introduction to the Physical Habitat simulation System', US Geological Survey, USGS on-line resources: http://www.fort.usgs.gov/products/Publications/ 15000/chapter1.html (last accessed 13/08/10).

USGS (2004) 'Climatic Fluctuations, Drought and Flow of the Colorado River', Fact Sheet, USGS On-line resources: http://pubs.usgs.gov/fs/2004/3062/ last accessed 13/08/09.

Walker, G. (1995) 'Energy, land use and renewables. A changing agenda', Land Use Planning, 12 (1) pp 3-6, Butterworth-Heinemann Ltd, Oxford. 0264-8377/95/010003-04.

Walker, G. (1995*b*) 'Renewable Energy and the Public', Land Use Policy, 2: 49-59 , , London, Amsterdam and New York, Elsevier.

Wang, J. (1994) ' Major Problems with the design of Three Gorges', International Water Power and Dam Construction August 1994 Vol. 46 No 8 pp24-32. Wilmington Publications.

Wang, R. (1998) 'Environmentally Profound', International Water Power & Dam Construction September 1998, Reed Business Publishing, London.

Warren, C.R., Lumsden, C., O'Dowd, S., and Birnie, R.V. (2005) 'Green on Green: Public Perceptions Wind Power in Scotland and Ireland', Journal of Environmental Planning and Management 48 pp853-875, Taylor and Francis. Abingdon, Oxford.

WASER (2006) 'American Literatures on sedimentation and Erosion', World Association for Sediment and Erosion Research, On-line resources: www.waser.cn/Literatures%20 on%20sedimentation%20and%20Erosion/America.jsp accessed 7/07/06.

Water Power and Dam Construction (1987) 'Bonneville dam celebrates 50 years', Water Power and Dam Construction September 1987. Wilmington Publishing.

Watt Committee (1990) 'Renewable Energy Sources', Watt Committee on Energy Ed Laughton, M.A., Report No 22 1990, London and Paris, Elsevier.

Wave Dragon (2009) Wave Dragon Aps website -environment, on-line resources: http://www.wavedragon.net/index.php?option=com_content&task=view&id=5&Itemid=6 (last accessed 10/06/09).

WCD (2000) 'Does Hydropower reduce Greenhouse Gas emissions?', World Commission on Dams Press Release Nov 27 2000, on-line resources: http://www.dams.org/news_events/press357.htm, last accessed 20/07/09.

WEC (2004) World Energy Council, ' Comparison of Energy Systems Using Life Cycle Assessment', Special Report, World Energy Council, London. ISBN 0 946121 16 8

WEC (2004/2007) '2004 Survey of Energy Resources', World Energy Council, Elsevier, on-line resources: http://www.worldenergy.org/documents/ser2004.pdf accessed 20/07/09.

Whittaker, T.J.T, Beattie, W., Folley, M., Boake, C., Wright, A., Osterried, M., Heath, T. (2005), 'The Limpet Wave Power Project -the first years of operation', Heriot-Watt University, on-line resources: http://www.sbe.hw.ac.uk/staffprofiles/A/bdgsa/shsg/ Documents/2004sem/limpet.PDF last accessed 10/06/09.

Windpower Monthly (1998) 'Windfarm design at the touch of a button', Windpower Monthly A/S. September. Haymarket, London.

Wizellius (2008) 'Developing Wind Power Projects', on-line resources: http://books.google.co.uk/books?id=eTaNk1VaQTYC&pg=PA36&lpg=PA36&dq=Height+of+UK+Low+pressure+weather+systems&source=web&ots=z_QKtWOiKc&sig=3Iwknak7ci93_xsGgFnvSkRT5H0&hl=en&sa=X&oi=book_result&resnum=3&ct=result#PPR5 M1

Worthy, M. (2005) 'High Resolution Total Stream power Estimates for the Cotter River', Namadgi National Park, Australian Capital Territory, CRC LEME Monographs Regolith on-line resources: http://crcleme.org.au/Pubs/Monographs/regolith2005/Worthy.pdf accessed 22/07/09.

WWF (2008) 'Danube Delta Fact sheet', WWF World Wide Fund for Nature, July 2008, On-line resources: http://assets.panda.org/downloads/danube_delta _factsheet_july2008_en.pdf last accessed 13/08/09.

Xiatao, W. (1986) 'Environmental impact of the Sanmen Gorge Project', Water Power and Dam Construction, Nov. 1986, London, Reed Business Publishing.

Xuezhong, L. (1996) 'Accentuate the positive', International Water Power & Dam Construction, Nov 1996, p24-25. London, Reed Business Publishing.

Yishi, L. (1994) 'The Gezhouba project in operation', International Water Power & Dam construction, August 1994. London, Reed Business Publishing.

Yonfu, Z. (1994) 'The River diversion design for the Three Gorges Project', International Water Power and Dam Construction August 1994, London, Reed Business Publishing,.

Zinke, A. (2004) 'Hydropower station Gabcikovo: Deficits in hydrology (sediment transport, groundwater) and biology'. Int IAD Workshop 14-16 Oct '04, on-line resources: www.zinke.at/Zinke.data/Images/Zinke-IAD.Gabcikvo.122-04.pdf

Ziyun, F. (1994) 'Environmental issues of the Three Gorges project', International Water Power & Dam Construction, London Reed Business Publishing.

Zoran M., Anderson, E. (2006) 'The use of multi-temporal and multispectral satellite data for change detection analysis of the Romanian Black Sea coastal zone'. Journal of Optelectronics and Advanced Materials Vol. 8, No. 1, February 2006, p. 252 - 256.

Appendix 1

Extension to water based Renewable Energy Sources

A.1 Introduction

In chapters seven and eight the conclusions from the test of the hypothesis on selected cases of HEP developments and downstream rivers were described. Using a variety of parameters at the reservoir reach and the Stream Power concept for the river downstream, it was tentatively concluded that the greater the change in power flux density the greater the impact was likely to be. The other parameters of the hypothesis -proportion of energy extracted, efficiency of conversion and number of conversions, were proposed as related to impact though not tested. In this chapter the hypothesis is extended to other water based renewable energy flows.

Extending the hypothesis from HEP to other water based renewable energy sources, which have relatively dense power fluxes, the next most comparable source to HEP is tidal barrage technology, being akin to low head hydro plant (Elliott 1996). Related to tidal barrages are marine current turbines, which also harness tidal currents, but without a barrage and so this technology is also considered in terms of the hypothesis. Although tides are often perceived as currents, they can be considered to be very low frequency waves with very long wave lengths (MacKay 2007). Progressing on from "tidal" waves, wind derived wave energy is the third technology considered here in terms of the hypothesis.

Applying the parameters of the impact model proposed in this thesis, i.e.:-

The power flux density of proposed tidal and lagoon schemes.

The proportion of the energy in the flow abstracted

The number of conversions

The conversion efficiency

The changes to the existing flow patterns.

These parameters are applied to the non HEP water based renewable energy technologies below.

A.1. 1 Tidal barrages

While tidal barrages may resemble hydro electric schemes, they differ in that energy is abstracted from a very low frequency oscillating wave motion, occurring approximately twice per twenty four hours, although in certain locations only once (Baker 1988). Generation is performed by a low head hydro plant, from a continuously varying head height obtained (usually) by the capture and retention of the flood tide in a reservoir, generation being on the ebb tide. As such, tidal barrages are both intermittent and highly variable sources of renewable energy, though completely predictable (Baker 1988). There are a number of different operating modes for a tidal barrage scheme. They can generate on the ebb tide only, or on the flood tide, or in a combination of these two modes. At both the high tide, pumping can raise the basin head height and at low tide, pumping from the basin can increase the differential in the head heights (Baker 1988). Furthermore, a multiple basin arrangement can be designed in order to produce more continuous generation by timing the alternate filling and emptying to coincide with tides. However, experience so far has determined that the maximum energy can be generated by ebb only operation (Baker 1988, Charlier 2003).

Tidal Barrages around the world

There are as yet very few full scale tidal barrage schemes anywhere in the world, with the only full scale scheme operating at the time of writing being the Rance Barrage in France with a 240MW capacity dating from 1966 (Charlier 2003). This is followed in order of size, by the Annapolis tidal plant of 18 MW in the Bay of Fundy, E Canada, then the Janxia Creek 500 kW in E. China Sea, followed by 400kW Russian Kislogubsk plant, and a number of micro plants in China (Charlier 2003). There have been numbers of schemes for tidal barrages planned around the world, as the technical potential has been assessed at 2.6 TW, about one tenth of that of HEP (Baker 1988). Examples include the Korean Sihwa Lake (S coast) 254MW Tidal barrage plant under construction since 2004, in an existing embankment (Ford 2006), and the Chinese planned 300MW Tidal Lagoon at mouth of Yalu River (Ford 2006). In the UK the existence of the second highest tidal range in the world at the Severn estuary has led to numerous plans and studies for a barrage of 8.6 GW generating capacity. Studies have been carried out for other sites such as the Mersey, the Solway Firth and Morecambe Bay, as well as numerous smaller estuaries (Sustainable Development Commission 2007).

Generally, the economics have not proved favourable yet for most of these schemes, due to the lengthy major civil engineering work of the lengthy barrage required, and the low and varying head (Ford 2006). However, as the successful operation of the Rance Barrage since 1966 demonstrates, as well as other smaller examples, the technology is proven and practical.

A.1. 1.2 Environmental Impacts of Tidal Barrages

In the UK environmental considerations have also played a part in preventing construction of tidal barrages as yet. The Severn Estuary scheme with ebb generation would involve continuous submersion of roughly half of the area of mudflats uncovered at low tide, which provides an important feeding ground for bird species (Shaw 1980). The area has the international designation of a RAMSAR site, under which a site is "*considered internationally important if it regularly supports 1% of the individuals in a population of one species or subspecies of waterbird.*" (Joint Information Committee, 2008). Five species of bird have more than 1% of their NW or UK population supported at this site, Shelduck (1.8%), Dunlin (2.7%), Curlew (1.0%), Bewicks Swan (5.0%), Widgeon (1% of UK population) (Joint Nature Information Committee, 2008). The Severn Estuary is also designated as a European Special Protection Area under the EC Birds Directive (EC Birds Directive 1979).

While a reduced tidal range inside the barrage is a feature of tidal barrage schemes, the individual sites will very considerably; some will involve long barrages across broad bays or inlets, others may have only short barrages across narrow mouths leading to long and in some cases deep estuaries. Hence the precise impacts will tend to be site specific, for example the extent to which mud banks are immersed, will depend on the depth and steepness of the sides of the basin as well as variations in the tidal range.

A comprehensive review of impacts is contained in Clarke 1995, by the present author, as well as elsewhere, and it is not proposed to repeat all of these here. General impacts likely to be expected are summarised in the Table A.1.1 below.

Reduced tidal range -50%
Loss of mud flats
Tidal changes downstream
Reduced/raised water speed
Siltation
Scouring
Lacustrine environment created
Changed salinity
Changed turbidity
Fish migration barrier
Fish pressure damage
Wildlife changes
Drainage effects
Water table effects
Raised water level for shipping
Flood protection
Shipping hazard

Table A.1.1 Summary of impacts from tidal barrages (Clarke 1993)

A.1 1.3 Power Flux Density of Tidal Barrage Schemes

Tidal barrages have significantly lower power flux densities than most large HEP plants. This is due to the relatively low head heights and their variability over the tidal cycle. Considering power flux densities for tidal energy, this is cited in the figure 3.3 on page 76 chapter 3, as having a ~35kW /m^2 (Clarke 1993) maximum power flux density and an average of 6kW/m^2 (based on power fluxes in the estuary before entrainment by barrage structure, or capture). However as described below this may be too low, in the case of the Severn Barrage.

According to Charlier, (2003)

The potential energy is given by the equation:

$$E_p = K \times 10^6 \times A \times R^2$$

where K = constants of 1.92, or 1.97
A = area of basin
R = average tidal range
(Bernshtein 1961, Gibrat 1966,
Mosonyi 1963. cit in Charlier 2003)

For the Severn Barrage the potential energy available according to this method is:-

$$E_p = 1.92 \times 10^6 \times 70 \times 9.8^2 \quad \text{(in kWh per year)}$$

$$E_p = 12.908 \times 10^{10}\,\text{kWh pa} \quad \text{or } 12.908\,\text{TWh pa}$$

This value of ~12.9 TWh pa is roughly equivalent with the 17 TWh of electricity per annum that it is estimated a barrage at the Severn estuary would generate, given the assumptions of 70km^2 basin area and a mean tidal range of 9.8m, (from Hubbert 1969 cit in Twidell & Weir 1986 p353). (Elsewhere the Severn estuary barrage reservoir is cited as 480km^2 in area, which would result in 88.51TWh.) (Department of Energy 1989).

Charlier (2003) describes capacity factors as a "type of utilization factor which is based on the system selected: for a single or double basin plant and a single tide it is 0.224, double tide 0.34 but 0.21 for a double basin; for a double basin, single tide with reverse pumping it is 0.277 and with pumps 0.234."

A capacity factor of about 0.224, accords roughly with the capacity factor quoted for the Severn Barrage scheme. This value, a little under 1/4, relates the average power output to the peak power output.

Another method of calculating the average potential energy available: is the equation:-

$$\textit{average potential energy} = \rho \times A \times R^2 \times g / 2T$$

where ρ = the density of water 1000kg/m^3
A = the area of the reservoir
R = the mean tidal range
g = acceleration due to gravity 9.8ms^{-2}
T = time

(Twidell & Weir 1986, Elliott 1996)

This equation though makes assumptions of constant basin area and total drainage of the basin and does not take other losses into account, and thus produces a greater value than would be achieved in practice.

Charlier states that only about 30% of the potential energy can in fact be retrieved (Charlier 2003 p191), although he does not make it clear whether the "energy losses" are from the low efficiency of the turbines at low head or the need for at least 2-3m head height, or friction losses.

As Baker states, a greater total energy capture could be made through a larger number of turbines and generators able to pass a greater proportion of the flow, over a shorter period, but this would prove uneconomic (Baker 1988, p20). "Because the turbines would be operating for a very short time each tidal cycle, the energy produced per unit installed capacity would be small and the cost of the energy very high." Additionally the rapid release of large quantities of water "would reduce the effective head across the turbines because there would be a slope in the water surface down towards the barrage on the basin side..." Baker states that there would also be various environmental problems resulting from the rapid release of water, presumably scour and turbulent "white water" conditions.

In practice there is an optimum number of turbine generators for each site which represents a compromise between these factors and the need to utilise the turbines in an efficient and economic manner, i.e. retaining sufficient head height.

The output of the most recent 8.6GW capacity Severn Tidal Barrage scheme is cited as 17 TWh pa., and if only about 30% of the potential energy available as Charlier states, would imply a theoretical potential energy total of about 50TWh. Turbine and generator losses, incomplete drainage of the basin, and friction are assumed to account for the remainder of the potential energy.

The Severn Barrage would have 216 x 9m diameter turbines rated at 40MW each.
The swept area of each turbine is 63.617 m^2,

$$\text{hence} \quad 40{,}000\text{kW} / 63.617 = 628\text{kW/m}^2$$

is the maximum power flux density at the turbine. The average power flux density would be 141.7kW/ m^2 at the turbine. In practice the power flux density would be greater since bulb turbines would be used, so reducing the effective swept area, and turbine and generator losses need to be factored in.

This value $628 kW/m^2$, would then represent the maximum power flux density, after entrainment of the flow into the turbine tubes. The average power flux density would be lower, $141.7 kW/ m^2$ at the turbine, since head heights vary between 4.4m and 6.6m, under the ebb only generation, maximum energy output operation option (the most likely operating regime). Over the quarterly tidal cycle head heights vary between 11m spring tide range and 4 metres of the neap tide, i.e. by over a half.

These power flux densities can be compared with those occurring without a barrage. Currents in the Severn estuary at the site of the proposed barrage at Barry are cited as up to about 5.5 knots or nautical miles, or $2.8 ms^{-1}$ (ETSU 1993 p44), although elsewhere in the estuary up to about 8 knots or $4.116 ms^{-1}$ are said to occur. Assuming that the whole volume of the basin achieves this velocity, the kinetic energy per tide can then be calculated as:

$$KE = 0.5 \times 2.084 \times 10^9 m^3 \times 4.116^2$$

Where volume is $2.084 \times 10^9 m^3$ as cited (Elliott 1996)

$$KE = 1.7653 \times 10^{10} J$$

which could roughly accord with the values given above, given that the tidal current velocity includes friction losses. As tidal energy is both kinetic and potential, only the kinetic component has been accounted for here, and the value would in fact be greater.

Per square metre, at a velocity of $2.8ms^{-1}$, the maximum kinetic power flux density before the barrage is constructed is:

$$0.5 \times 1000 \times 2.8^3 = 10.98 kWm^{-2}$$

On this basis the maximum power flux density is increased from 10.98 kWm^{-2} to ~628kWm^{-2}, or by ~57 times. According to the hypothesis, this increase in maximum power flux density could result in impacts.

For currents of 8 ms^{-1} which occur elsewhere around the British Isles, e.g. Pentland Firth, and to almost this velocity at Alderney Race, (in fact up to 10 ms^{-1} in some locations at Pentland Firth), (ETSU 1993), the power flux density would be:

$$0.5 \times 1000 \times 8^3 = 256 \text{ kWm}^{-2}$$

The maximum power flux densities would be found at Pentland Skerries where currents reach 16 knots or 8.2 ms^{-1} in the eastward direction, (ETSU 1993 p30) which would be 275.68 kWm^{-2} power flux density, though this is exceptional.

The maximum power flux densities before and after construction of the Severn Barrage, can be compared i.e. 10.98 kWm^{-2} which is relatively low, and then after construction 628 kWm^{-2} (in the turbine housing itself).

The proportion of the energy extracted has been stated by Charlier as ~30%.
Interception of the flow at the barrage would be nearly 100%.

The number of conversions can be described as comprising:
-the conversion of the kinetic and potential energy of the "tidal wave", behind the barrage into mainly potential energy, for the three or so hours of still water period at the height of the flood tide, so as to achieve the head height necessary for generation.

-the next conversion is from potential to kinetic energy, where the mainly still water is accelerated by gravity and its velocity increased also by the design of the turbine runner tubes up to a maximum of about $10ms^{-1}$ (Baker 1988 p171) then being decelerated smoothly after the turbines to about $2ms^{-1}$. There is a pressure drop to below atmospheric pressure at the turbines where the energy extraction occurs, but this recovers afterwards. Baker states that conversion back to potential energy occurs.

-Energy conversion of the flowing water from kinetic to the rotating turbine blades mechanical form occurs, and thence secondary conversion from mechanical to electrical in the generator.

The number of conversions of the flow can be said to amount to three; kinetic and potential to solely potential, potential to kinetic, and then back to potential. The energy abstracted itself undergoes two further conversions, from kinetic to mechanical and mechanical to electrical. At each stage there could be discontinuities in the functions of the energy flow and efficiency losses.

The efficiency losses: Baker states that the barrage being highly porous, with multiple sluices would impede the flood flow only slightly. HEP turbines and generators are generally highly efficient at around 90%, though for lower head heights this drops. For the ranges in question, i.e. around 3 - 7m, lower efficiencies could be assumed, e.g. perhaps 60-70%. For the overall scheme, it could be argued that the 30% extractable cited by Charlier energy represents the efficiency, though this has been identified here as the *proportion* of the energy abstracted.

A.1 2 Tidal Lagoons

This concept is similar to that of tidal barrages, except that instead of employing a barrage to enclose an estuary in order to create a reservoir, the reservoir is created by embankments enclosing an area of shallow water, set off at some distance from the coast and making no contact with it. The water of the high tide would be retained at a level above that of the surrounding sea once the tide falls, and the potential difference in height is used to turn a turbine and generate electricity in the normal manner. Inside the bounded area, the reservoir could be split into several pounds by further embankments or bunds. Each pound could then be kept at a different level so that continuous generation could be achieved. As yet no tidal lagoons have been built, although there have been proposals for lagoons off the coast of S. Wales, and in China (Tidal Electric 2008).

There are various advantages and disadvantages to this approach. Firstly, many of the impacts of tidal barrages can be avoided, for example the loss of inter-tidal mudflats, through inundation. The tidal lagoon would be constructed in an area with continuous water cover, and which it would still retain. Another advantage is that of continuous generation, as opposed to the great bursts of power that a tidal barrage produces, some in the middle of the night when demand is at its lowest and thus the electricity is worth least. The barrier effect of the barrage on the estuary would be avoided and thus the impact to migratory fish. Since the tidal lagoon would not make a landfall, there would be no effects on land drainage, or water table. As the lagoon would not enclose an estuary, which is usually a precious environment due to its mudflats, shallow waters and part fresh part saline water, as well as the high energy levels of tidal currents providing nutrient transport and mixing of waters, -it could avoid interference with these processes and thus the associated impacts.

However, it cannot be assumed that tidal lagoons would be entirely impact free. There are some disadvantages to the tidal lagoon concept. The ratio of the embankment or bund to the enclosed water volume would be higher than for a barrage since the entire perimeter of the reservoir would be bounded, as well as the subdivision into different pounds. As a result construction costs and impacts could be greater than tidal barrages, per installed unit of power. Undersea cables required to connect to the on-shore grid would be required and these can be expensive, in the region of £1m per km (MCT 2008). Tidal lagoons would probably not be sited in the areas of highest tidal range, as these are found higher up in the estuary, as a result of resonance effects from the shore line shape. An example of this is that of the Severn estuary where the highest tides are to be found at the English Stones, near to the second Severn crossing (Baker 1988). Tidal range is an important factor in the economics of tidal energy and a reduced range would increase costs.

These are mainly economic issues associated with tidal lagoons; there are also environmental issues -which are described below.

A.1 2.1 Potential Environmental Effects of Tidal Lagoons

Impacts from construction could be potentially significant since the ratio of reservoir volume to embankment length would be increased. Embankments would consist of clay / sand hardened with a rock and then concrete coating (Tidal Electric 2008). Increased turbidity from stirring up sediments might result from the depositing of thousands of tons to form embankments. A tidal lagoon might still obstruct the tidal flows of water into and out of nearby estuaries, although to a lesser degree than a tidal barrage, depending on its position and size relative to the estuary. Some reduction of currents and reduced tidal range up stream in the estuary might be expected. The lagoon itself may have the effect of increasing some currents locally, as an obstruction in the estuary, as water flowed around the embankments of the bounded area. There would be a certain change to the sea and sea bed in the area of the reservoir, which might involve some sedimentation if the currents are lower than those of the pre-existing ones.

To a certain extent there might still be some wildlife effects as the reservoir area will be converted from open estuary to lacustrine conditions. Some of these may indeed be beneficial in terms of reduced wave, and wind conditions providing shelter compared to pre-existing conditions. However, fish may still be liable to damage by turbine blades or pressure changes when the reservoir pounds are discharging water for generation. Fewer fish are like to be involved as the migratory path is not blocked and fish will find their way into the reservoirs accidentally, rather than intentionally. Tidal lagoons would also constitute obstructions to shipping lanes, fishing and recreational boats, and would require careful siting to minimise this. Potential tidal lagoon impacts are shown below in table 8.2.

The parameters of the impact model proposed in this thesis, that is, the power flux density of proposed tidal lagoon schemes could be considered, though this is not done in this thsis.. The proportion of the energy in the flow abstracted, the number of conversions, the conversion efficiency and changes to the existing flow patterns, could be assessed, as has been done above for tidal barrages.

Reduced tidal range -50% internally

Tidal changes upstream -small

Reduced/raised water speed -small?

Siltation -in bunded reservoir area

Scouring

Lacustrine environment created -in reservoir area

Changed turbidity

Fish pressure damage -small

Wildlife changes -small

Construction impacts

Table A.1.2 Potential tidal lagoon impacts.

A.1 3 Tidal / marine current turbines

Marine current turbines are another method of harnessing tidal energy or other marine currents, but without a barrage. These turbines are somewhat similar to underwater wind turbines, and extract energy from the kinetic energy of the flow of the current rather than the potential energy of the tidal range stored behind a barrage, thus differing considerably from those in a tidal barrage. Generally, larger numbers of turbines would be required, dispersed through the flow channel. However, apart from the numbers required, there is much less civil engineering involved in installation compared to tidal barrages. Tidal current or marine current turbines are still a novel technology with few working examples, and these are mainly prototypes at the time of writing (MCT 2008). Nevertheless there is world wide interest with over sixty projects underway (Charlier 2003*b*). Now post 2000, the concept has now been proven, using propeller type designs, both by the MCT turbines off Lynmouth and Strangford Narrows in Northern Ireland (MCT 2008) and those at Hammerfest in Norway (Hammerfest Strom 2008). Other designs have also emerged such as the Open Centre Turbine developed by Open Hydro and oscillating hydrofoils systems (Stingray, Pulse Tidal) (NATTA 2006). In what follows however the discussion focuses just on the more common 'propeller' designs. While there are designs that employ ducts to concentrate the flows at the turbine, these are outside the scope of this study (Lunar Energy 2009).

It is envisaged that marine current turbines would be sited in "farms", akin to wind farms but immersed. In common with wind turbines they would need to be dispersed, to avoid each other's turbulent wake. Although it has been proposed to site such turbines in a "fence" i.e. intercepting most of the flow (Blue Energy 2008), it is not yet known whether this would prove feasible or indeed desirable. However, the proposed Severn tidal fence would only partially intercept the estuary (Parsons Brinkerhoff 2008).

At present marine current turbine designs are limited to usually 20-40m water depth, and hub heights 10-20m above the sea bed, since near the sea bed, boundary layer friction reduces the current significantly. Total immersion is required taking into account tidal range and wave height, together with possibly a margin for shipping, imposing an upper limit (Bryden et al 1998). 20m diameter is considered an upper limit due to cavitation, for rotary turbine blades.

There will be an economic limit to the distance that marine current turbines can be sited away from the shore since the cost of underwater power cables is in the region of £160,000 plus (at 1998 figures) per km (Bryden et al 1998).

Since the marine current turbines are taking energy from an "extended fluid flow", the Betz Limit of ~0.59 applies. This is the theoretical maximum energy that can be extracted from the flow, before extra resistance becomes counter productive by slowing the flow the turbine "sees" to too great an extent (Twidell & Weir 1986 p216). Furthermore the turbine power coefficient, will apply. Since the flow velocity is relatively low, the turbine efficiency will be less than that of high head HEP turbines (90% plus). Therefore the proportion of energy that marine current technology can abstract is limited by the turbine power coefficient, including the Betz limit of ~59%, and the spacing of turbines, not intercepting whole flow. The factors above limit the overall power flux density, for energy extraction from the overall broad flow. Marine current turbines have low rotational speeds 10-15 rpm cited for MCT converter, so that fish strikes are less likely (Bryden et al 1998, MCT 2008).

- Removal of kinetic energy from coastal currents
- Tidal flow interaction
- Scouring effects on benthos
- Converter device installation disruption
- Fish strikes: - low rpm, 10-15 rpm
- Inshore fishery effects
- Possible spawning ground disruption
- Visual impact
- Acoustic emissions
- Coastline bird nesting site disruption
- Possible effects on tourism
- Highway access implications

Table A.1.3 Potential environmental impacts of marine current turbines.

Overall environmental impacts could be assumed to be relatively low since apart from the removal of kinetic energy from coastal currents, there are no other fundamental changes incurred to the flow. Dacre (2002) has identified potential environmental impacts as have MCT (2008), and Fraenkel (2007), but these will depend on the packing density of the siting. This could be expected to increase the impacts. The potential impacts are shown above in table 8.3.

A.1 3.1 Power flux density of tidal current schemes

The power density flux of a marine current turbine is considerably less than those of tidal barrages. For example the maximum power flux m^{-2} of the marine current turbine off the coast of Lynmouth in Devon is ~ 9.8 kWm^{-2}, while the mean power flux density is ~ 3.7 kWm^{-2}. This has been calculated from a water speed of
2.7ms^{-1} and a capacity factor of 0.375 (MCT 2008).

The maximum power flux density of the Severn tidal barrage is thus ~64 times that of the MCT tidal current scheme, although the difference in the two sites' currents and hence fluxes (the current velocity at the marine current site is one third to one half of that of the tidal barrage site), accounts for some of this difference.

Bryden et al (Couch & Bryden et al 2007 and others cit in WEC 2007) have done work analysing the effect of tidal current energy extraction on channel flow as part of overall resource estimation and on wider effects e.g. sediment transport.

In extracting energy from flowing water in a channel, the kinetic energy of water is being captured. The kinetic energy of flowing water can be expressed by the equation:

$$P(in W) = 1/2 \rho A V^3$$

Where ρ = density of sea water (kgm^{-3})
A = cross-sectional area of the flow (m^2)
V = velocity of flow (ms^{-1}) (Boyle, 1996)

This equation is the same as that for wind energy. However, the density of water is about 835 times greater than that of air at sea level, while the velocity of marine currents will be in the range of 2-5ms^{-1}, rather than 5 to 25 ms^{-1} of wind. Additionally there are considerable differences between the broad and very high (or deep) flows of air in the atmosphere and the relatively shallow and limited width channels where marine currents occur. The common factors of laminar flow boundary friction from surface roughness and turbulent flow apply to both wind energy and marine current energy, but differ considerably in practice.

Marine current turbines operate by effectively slowing down the water flow, by a counter resistance and thus the extraction of energy, i.e. the velocity is reduced (at least in the vicinity of the turbine). Tidal flows are driven by small variations in water height, or depth, and hence the water can be thought of as flowing down a (shallow) slope. A further effect of this slowing down of the current is to raise the water height, or depth, upstream of the turbine device with a corresponding resultant drop in the depth downstream (Couch, Bryden et al 2007).

Couch and Bryden et al have proposed a parameter for assessing the sensitivity of a channel to energy extraction, which employs the proportion, described as 'ratio', of energy extracted from a flow, combined with elements of Manning's equation.

$$B = \left(\frac{f}{1 + \frac{2gLn^2}{R^{4/3}}} \right)$$

Where B = sensitivity parameter

f = the ratio of energy extracted to the energy in the kinetic flow

(i.e. proportion of energy extracted)

L = the channel length (m)

g = the acceleration due to gravity (ms^{-2})

n = the Manning's roughness coefficient

R = the hydraulic radius (m)

(Bryden, Couch, Owen, Melville, 2007)

This equation employs the concept of the proportion of energy extracted in the kinetic flow, re-termed here as the ratio, a parameter first proposed by this author in Clarke (1993).

A.1 3.2 Tidal Current Resource Estimates

Both Salter (DTI Energy Review, Salter 2005), and MacKay (MacKay 2007) have suggested that the resource estimates for tidal currents have been considerably underestimated. Salter has proposed that bed surface roughness dissipates a large proportion of the energy of the tidal flows of the Pentland Firth, between the North of Scotland and the Orkney islands, and that marine current turbines would extract energy that would have previously been dissipated in turbulence. The horizontal water flow velocity would then remain relatively unchanged, with lower effective energy loss, since the flow would now be much less turbulent and of a laminar nature, it is argued.

This may well be the case; however Salter appears to be considering the availability of energy that can be captured from the tidal flow and not the environmental functions of that energy and its implications. If as much as 100GW peak is dissipated in the Pentland Firth area by turbulence and surface roughness, as Salter suggests, the question of what that energy is doing and whether it is environmentally significant, needs to be posed.

To be environmentally significant, such functions as scouring and lifting and entraining of sediment by the energy flow could be sought. Turbulent flows, involving eddies of high velocity and pressures can be very effective agents of scouring and erosional processes (Graf 1971). Turbulence, consisting of vortices can have locally high power density fluxes.

If this proves to be the case, then abstracting energy from the flow and reducing the turbulence there, might have significance for the lifting and transport of sediment and deposition elsewhere. Of course, it may transpire that the sea bed of the Pentland Firth is composed of scour resistant beds, and that there are no significant volumes of sediments being entrained and transported.

However, it cannot be assumed that because the energy is dissipated in turbulent flows, it is then "incidental" and has no function in the local environment. On the other hand, where such flows perform functions, abstraction of a proportion of the energy available, without significant impacts, may be possible. The determination of the critical proportion that can be extracted would be required, through modelling exercises and the use of sensitivity analyses such as that of Bryden Couch et al (2007).

MacKay (2007) also thinks the overall resource might have been significantly underestimated, but for a different reason. MacKay suggests underestimation of the resource (MacKay 2007) due to incorrect estimation of the power available, from considering only the kinetic energy involved in the flow, rather than assessing the resource in terms of a "tidal" wave. Wave energy has kinetic and potential energy components

(Duckers 1996). He points out that Black and Veatch (Parsons Brinkerhoff 2008), who carried out the resource estimation for The Carbon Trust, have employed only the kinetic component, i.e.

$$P(in\,W) = 1/2\rho A V^3$$

as cited above. This formula has been used to obtain a figure of 12 TWh/yr, as a total UK tidal current estimate. MacKay however, states that "the power in tidal waves is not equal to the kinetic energy flux across a plane". He goes on to demonstrate mathematically that this is not so by comparing the power estimates from the kinetic energy equation, with those from using the wave power equation

He states that "the potential energy of a wave (per wavelength and per unit width of wave front is:

$$\mathrm{PE} = 1/2\rho g h^2 \lambda$$

Where ρ = density of sea water
g = gravity
h = wave height
λ = wave length

This equation, is similar to that given by Duckers (Duckers 1996 p323) for the power in watts per metre width of wave front of a pure sinusoidal wave.

$$P = \frac{\rho g^2 H^2 T}{32\pi}$$

Where P = power
ρ = density of sea water

g = gravity
H = wave height
T = wave period

A.1 3.3 Applying the hypothesis to marine current turbines

The maximum power flux density in terms of the kinetic energy available in the current, at the converter will be in the range of 2.7 kWm^{-2} - 72.35 kW m^{-2} based on currents of between 1.75ms^{-1} and 5.25ms^{-1} (MCT 2006, ETSU 1993 p5-7). However, in practice the very fast currents occur infrequently. Typical ranges might be more like that of the Lynmouth MCT turbine maximum of ~9.8 kWm^{-2} and an average of ~ 3.7 kWm^{-2}.

The proportion of the energy in the flow that can be abstracted will be limited by the power coefficient Betz upper limit of 0.59, and proportion intercepted by the spacing of turbines, though given the viscosity of water, the effect of the turbines will be to slow a water column cylinder of greater diameter than the turbine itself. The proportion of the flow intercepted would perhaps not be more than 25%-30%, if turbines were stacked for maximum effect, unless a "tidal fence" arrangement or successive arrays of turbines were sited downstream and upstream.

The efficiency of the device will probably not be more than ~40-50% overall, due to turbine power coefficient cited as >0.45 (Fraenkel 2007) and gear train and generator losses.

The number of energy conversions of the flow is limited to a reduction in velocity, plus some change of angle; though a corkscrew wake pattern will result directly down stream of the turbine, this will dissipate and a widening of the "cylinder" of water affected. Since the kinetic (and potential) energy is not converted into either one or the other, as with tidal barrages, fewer impacts might be expected. Energy conversions are from kinetic energy of the water, to the rotational mechanical energy of the blades and shaft and thence via the gearbox to electrical conversion in the generator. The smaller number of conversions could imply fewer impacts according to the hypothesis.

A.1 3.4 Comparison of tidal barrage and tidal current technology

It would appear that a tidal barrage has the potential to capture a greater proportion of the energy available than do marine current turbines and this is achieved by entrainment and capture of the water and its potential energy, at high tide point. This energy is then converted by opening sluices into kinetic energy under the influence of gravity to turn the turbines and generator. By comparison a marine current turbine converts the kinetic energy of the water directly into rotary (or oscillatory) mechanical motion of the blades (or hydrofoils) and so turns a generator, via a gear train (or hydraulic drive).

The environmental impacts of tidal barrages have been well documented and on occasion are cited as one of the reasons for not proceeding with construction (Clarke 1995). The case of tidal barrages illustrates how a number of energy conversions, i.e. from kinetic to potential energy, then back to kinetic, can have environmental consequences. The holding of the water volume at the high tide point for a period in order to achieve a useful head height, i.e. potential difference, also arrests the current and with the drop in current speed, transported sediments will be deposited (STPG 1986, Shaw 1980). In effect the oscillatory flow of the water is being accentuated by being periodically stored then released in sharper bursts.

A result of retaining the water flow is that the tidal range inside the barrage is reduced by ~<50% (STPG 1986). The change in the estuary to a semi lacustrine environment is caused by this water retention. This can be considered as one of the major impacts of tidal barrage schemes, and represents the greatest change from inter tidal mudflats to a continually immersed "lower energy" environment. Impacts such as fish strikes, or strikes to eels, could also be connected to pressure change across turbine. That is, the higher power flux density and pressure, and greater changes to these conditions could cause impacts.

By contrast a tidal current turbine is likely to have much less impact: the blades rotate more slowly at 10-15 rpm (MCT 2008) so there is less risk to fish, power flux density is much lower and it is not necessary for estuaries to be blocked , so there is likely to be much less impact on tidal range, or flooding .

However there could be some minor impacts, in terms of for example visual intrusion if they have an above water aspect, and constraints on shipping movements and fishing. Installation involves potential impacts to marine life and in operation there may also been some impacts on sea mammals e.g. due to low frequency noise (MCT 2008).
This suggests that the lower power flux densities of marine current turbines, and the reduced changes in power flux density that are involved could lead to reduced impacts.

A.1 4 Wave Energy

Wave energy conversion has a little more developmental experience than marine current turbines, though it is barely beyond the prototype stage. At the time of writing the first commercial offshore wave energy converters have been commissioned in Portugal in 2008 (Pelamis 2009) and there are more than fifteen years of experience with prototype on-shore wave devices. The variety of device designs indicates that the technology is still relatively immature. Although most projects have their antecedents in the 1970s, progress has been intermittent due to inconsistent government support.

A.1 4.1 The wave energy resource

The UK's potential wave energy resource is substantial, the UK being one of seven countries in Europe having significant wave resources. Europe's wave energy resource has been estimated at 50GW total power in waves kW/m (Mollison 1989), while the UK has an estimated 12GW, or a 7-10 GW (technical potential) (ETSU 1993), which would be equivalent to ~20-25 % of electricity supply. In practice, constraints would reduce the amount available. The total world resource has been estimated at between 1-10 TW. At 2TW this would be equivalent to approximately twice world electricity generation (DTI 2004, WEC 2004).

For the UK, off-shore resources of 30-90 kW per metre of crest width constitute the major part of the total resource, with the maximum output 10km offshore (DTI 2004). The size of waves depends on wind speed, duration of wind, and length of fetch, the distance over which the wind has blown (Duckers in Boyle 1996 p320). As a consequence, the European resource occurs mainly on the western Atlantic coast. Waves near the shore dissipate much of their energy in friction with the sea bed, which eventually causes waves to break.

The challenge of harnessing wave energy lies partly in the fact that waves have very variable patterns of length, height and period as well as direction. The structural forces can be up to 100 times greater than the average in storms (Twidell & Weir 1988 p312), and the device must survive this hostile environment. Thirdly, the irregular slow motion of waves, e.g. of 0.1 Hz frequency, needs to be transformed into 500 times the frequency for generators, requiring elaborate gear train and accumulators or conversion into other forms to produce an even energy output.

A.1. 4.2 Environmental impacts

These characteristics of wave energy and wave energy conversion contribute to the environmental effects. Wave action on the shorelines can be important agents of functions in the natural environment, such as erosion and deposition, as well as oxygenation of water and the contribution to currents. Beach shapes are the consequence of wave action, and change in shape from summer to winter due to greater wave action in the winter period (ETSU 1979).

Although there are few or no environmental impacts recorded as yet from the handful of wave converters, since the impacts would be at almost imperceptible levels, some effects can be anticipated as deployment increases.

A CUC/UEC study of the impact of wave energy converters from the South West Wave Hub on surf heights in Cornwall found only a small reduction in energy levels at the shore of a maximum change of 2.3% or 4cm, for an energy transmission rate of 90%, i.e. the proportion of energy extracted at the wave energy converter was 10% (Millar et al 2007). More realistically average changes were in the region of 1cm in significant wave height. The study considered energy transmission ranges of 0%, 70% and 90%, for a reference array of wave converters of ~3900m, with 7 × 300m long units spaced out at 300m intervals (Millar et al 2007). The Wave Hub is an experimental "plug in" facility so that prototype wave machines can be tested at sea in offshore wave conditions. A commercial wave farm would perhaps be similar or larger in scale and there would be numbers of them, so that more of the incident wave energy would be extracted and greater effects on shore could be expected.

Wave energy converters can be expected to reduce waves in their lee, even if only slightly. Onshore devices would involve changes and modifications to the shore line, and there would be direct impacts from construction at those locations. Offshore devices do not suffer from this characteristic, though tethering and anchoring on the sea bed are needed as well as cabling connections to the shore. Some near shore devices would be sea bed mounted however.

A certain amount of work has been done on the potential environmental impacts of wave energy, which has been reviewed by this author (Clarke 1995). A summary of the main anticipated impacts is given in Table A.1.4 below.

Onshore devices:
- -some land use,
- -some visual,
- -noise,
- -cable landfall / grid connection,

Near-shore / offshore devices:
- -visual,
- -safety,
- -shipping obstruction,
- -wildlife,
- -cable landfall / grid connection
- -geomorphic effects:
  - beach and shore changes possible
- -long shore currents
- -anti fouling coating

Table A.1.4. Potential environmental impacts of wave energy.

(Clarke 1995)

A.1 4.3 Applying the hypothesis to wave power

Power flux density for wave energy

In terms of power flux density, wave energy is cited as having a 20-40kWm^{-1} mean power density in the UK context (Clarke 1993). Translating this value of kW per metre to kW per square metre requires sea depth and wavelengths data. In Clarke (1993), wave depths of 10m were assumed and the mean value of 20-40kWm^{-1} was divided by the wave depth to obtain the values cited of ~3kW/m^{-2} and a maximum of ~50kW/m^{-2}. Since 95% of the energy is in the top layer to a depth of 1/4 (Duckers 1996 p326), of the wavelength, the power flux density can be cited as roughly four times this amount, i.e. 30kW m^{-1} / 2.5m for a 10m wave depth = 12kW m^{-2} .

Waves have an orbiting water "particle" motion and the orbits decrease in size exponentially with depth (Duckers 1996 p326). A difficulty in assessing the power flux density per square metre arises because wave energy is in part kinetic energy and in part potential energy (Duckers 1996).

Power in Waves

The equation for the power in watts per metre width of deep water wave for an idealised sinusoidal wave is given by Duckers. (Duckers 1996)

$$P = \frac{\rho g^2 H^2 T}{32\pi}$$

Where P = power
ρ = density of sea water
g = gravity
H = wave height
T = wave period

As a general approximation:

P (in kW) = H^2 T (in seconds) (Duckers 1996)

since the value of ρ is ~1000, and g^2 is ~96.2 and 32 π is ~100.5. Deep water is defined as greater than 1/2 of the wavelength.

Hence the power in the waves increases as a square of the wave height. Long wavelength type waves or swell, produced over long reaches, contain the most power.

For real seas, which have varying waves, the significant wave height or H_s is used, i.e. the average of the highest one third of the waves (Duckers 1996).

The power can be estimated as:

$$P = 0.55 (H_S)^2 T_z$$

Where P = kWm^{-1}
H_s = significant wave height in metres
T_z = wave period in seconds
(ETSU & CCE 1992)

Types of Wave energy converter

Applying the hypothesis to different types of wave energy converters, the power flux density of the main categories can be compared. Duckers groups wave energy converters into three types:

Terminators which face the wave front, attenuators which are perpendicular to the wave front, and point absorbers which have small dimensions and absorb energy from surrounding waves (Duckers 1996 p329). Further categories are: on-shore, near-shore and off-shore. Some designs of wave energy converters concentrate waves, amplifying them in the process, such as the Tapered Channel converter or Tapchan. This latter type stores the potential energy of the wave in a reservoir some two or so metres above the mean sea level, and uses a low head turbine to generate constant power.

Terminator designs seek to extract the maximum energy from the wave by absorbing it head on and leaving flat water behind. An example of this approach is the Salter's 'Duck' design, which could achieve high efficiency energy conversion, of over 90%, in suitable conditions. Lines of Salter's Ducks were proposed for large scale wave energy developments off the NW coast of the UK.

Power flux density reduction on-shore.

Power flux density of 67kWm^{-1} of wave front is found offshore from the Outer Hebrides in deep water (Mollison 1989). If it is assumed that 95% of this energy is in the top 2.5m of 10m deep waves, this would equate to ~25kW per m^2 power flux density. By contrast only a fraction of this energy per metre would reach the shoreline due to bottom friction. Duckers states that "waves of 50kWm^{-1} in deep water would have only 20kW m^{-1} or less when they are closer to the shore or in shallow water, depending on the distance travelled in shallow water and the roughness of the sea bed" (Duckers 1996). Much lower power flux densities occur at onshore wave energy converters than for offshore. Examples of on-shore wave energy converters exist, such as the Limpet 500kW Oscillating Water Column device on Islay. Here the power flux density of the waves was assessed at only about 20 kW m^{-1} but in practice proved to be less (Queens University Belfast 2002), and the device has proved capable of only ~<150kW output (Whittaker et al 2005). The energy of the original deep water waves has been absorbed by friction with the bed (Duckers 1996) resulting in shear and turbulent forces with locally high power flux density that can pick up sand and sediments and abrade further the sea bed. The erosional and sediment mixing processes that occur in this energy dissipation constitute some of the functions of wave energy in nature.

It is suggested then, that although onshore wave converters result in other impacts, such as changes to the shore, fewer impacts from removal of energy from the waves may result from this type of converter, since much of the energy has already been dissipated already as the wave travels through shallow water.

Proportion of flow extracted

For offshore wave converters how much of the wave's energy reaches the shoreline will depend on the proportion extracted which will in turn depend on the efficiency of the device and the interception ratio. Salter's 'Ducks' were conceived as long lines of converters attached to each other by a spine, off shore in deep water facing the waves. Assuming that high efficiency energy extraction were to be achieved, such long lines with few gaps could conceivably change the wave environment at the shore considerably (ETSU 1979). However, gaps would be required for shipping, fishing and other access. Additionally it is unlikely that as much as 90% of the wave energy could be extracted, since wave length and height vary considerably (Duckers 1996 p324). Thirdly the highest power flux densities would occur during storms with the result that the majority of the functions would in fact be performed then. The energy of the waves would be too great to be captured by the device since such devices would be matched to the most productive per annum (i.e. balancing frequency with productivity) wave regimes rather than the highest.

In practice, wave energy technology has not yet matured to the point of developing off-shore terminator devices; having started with on-shore devices, it has moved to near-shore and more recently to offshore attenuator devices with the Pelamis. Survivability through storms is a considerable challenge for off-shore terminator devices.

Offshore Pelamis Device- an example

The Pelamis wave energy converter consists of several 3.5m diameter, thirty metre long cylindrical sections linked by hinged hydraulic pump joints, which pump high pressure oil to hydraulic motors to drive a generator (Pelamis 2009). The attenuator Pelamis units, 120 metre long, lie parallel to the wave direction, i.e. perpendicular to the wave front and by design aim to capture a lower proportion of the energy available than e.g. the Duck.

Pelamis units are rated at a maximum output of 750kW each. At their first commercial application site in Portugal, at Agucadoura, 8 km offshore, the 2.25 MW installation of three units, plus a further 20MW expansion, is expected to supply power for 1500 households (Pelamis 2009). At ~1.5kW continuous demand from the households, this would imply an average output of 1.5 × 1500 = 2.25MW. The capacity factor would be ~0.10 .

Calculation of proportion of wave energy extracted by Pelamis development

The wave power level is 46kWm^{-1} offshore of the NW of Portugal (CRES 2002).

At a packing density = 30MW km^{-2}

assuming wave front = 1km

total power in waves per km^2 = 46 MW

At a capacity factor of 0.10, as for the Agucadoura scheme, the ratio of wave energy converted into electricity per km would equal 2.25MW / 46 MW = 0.049.
The efficiency of the Pelamis energy conversion chain, from hydraulic pumps to hydraulic generator and electrical generator as well as cable connections and transformer would need to be factored in.

Assuming 60% efficiency, and since lower efficiency results in greater interception of energy for a given output,

0.049 / 0.6 = 0.08

On this basis the proportion of average wave energy extracted at this location is approximately one twelfth, for the Pelamis device.

This would be a lower proportion of energy abstracted than for terminator devices and depending on the overall packing density for the shore line, could be expected to result in fewer impacts.

Studies carried out by Wave Dragon, another type of offshore wave energy converter, have indicated that "wave heights are expected to be reduced by 22%-32% 1 km behind a Wave Dragon farm", though this will depend on local conditions (Wave Dragon 2009).
Presumably this reduction would decrease to some extent with further distance, depending on the proportion of wave front interception.

Efficiency of conversion

Salter's Ducks could achieve ~90% efficiency in optimal conditions (Thorpe & Marrow 1990). The Tapchan scheme planned for Mauritius is cited by Twidell & Weir as achieving a theoretical 30% efficiency from wave to electrical busbar (Twidell & Weir 1986 p334). The Oscillating Water Column (OWC) device efficiency will be reduced by the conversion to compressed air, since this will produce heat, air as a gas being compressible; furthermore the turbine itself and duct will result in more losses.

Capture efficiency and power chain efficiency estimates were given in the Wave Energy Review 1990 (Thorpe & Marrow 1990), for several wave converter devices, the NEL Breakwater, NEL Floating Terminator, NEL Floating Attenuator, Vickers Terminator, Vickers Attenuator, Belfast Device, SEA Clam, the Lancaster Flexible Bag and the Edinburgh Duck and Bristol Cylinder. This is shown below in table A.1.5.

Device	Proportion captured	Power Chain efficiency	Availability
NEL Bottom standing OWC:	over 50%	55-63%	90%
S.E.A Clam	0.62 (derived)[1]	59-65%	70%
Edinburgh Duck	0.93 (derived)[1]	70-82%	92%

Note 1 Based on (kWm^{-1} × device length)/ (average annual generation / power chain efficiency/ availability),

Table A.1.5. Capture and power chain efficiency and availability for several wave converter devices (Thorpe & Marrow 1990).

Number of Energy Conversions

The wave energy converters of 'Terminator' design such as the Duck or the Clam, attempt to harness the energy in one conversion from the wave, head-on resisting the force mechanically without transforming the wave into another form or entraining it. The Tapered Channel devices concentrate the wave, channelling it up a flume of resonant dimensions; the flow overtops the reservoir where it is converted to solely potential energy. Thereafter the water falls under the force of gravity to attain kinetic energy and turns a turbine. The number of energy conversions of the flow is three, from the kinetic & potential of the wave to potential only, then to kinetic energy and then extraction of kinetic energy. The process might be compared to wave action in rock pools.

The Oscillating Water Column OWC wave energy converter channels the wave into a tapering chamber or cylinder which then compresses air (Duckers 1996). The air is pushed through a turbine generator. When the wave column falls, air is sucked back through the turbine. By using a dual direction turbine with symmetrical blades (Wells turbine), continuous rotation in one direction is achieved, without rectification of the air flow. Energy conversions comprise the change in kinetic & potential wave energy to compressed air, then to kinetic energy of the air passing through the turbine, and so rotational energy, i.e. three conversions. There will be some concentration of the wave into the narrow chamber. The wave itself undergoes only one conversion, the change from the kinetic and potential energy of the wave to a potential only form, as the vertically rising and falling piston of the water column, although, the water would flow out again indicating conversion back to a largely kinetic form.

For the Pelamis device, the number of conversions of the wave is only one, transforming some of the kinetic and potential energy of the wave to mechanical motion of the device and reducing wave height and period. The effect would be to attenuate the wave, rather than produce calm water to the landward side.

A.1 5 Conclusion to appendix 1.

The hypothesis has been extended to other water based renewable sources and this suggests ways in which impacts could be linked to the power flux density of these sources as well as the further factors employed here. As yet there are too few wave and marine current converters in existence for evidence of impact to have been gathered. A comparison between tidal barrage and marine current turbines, demonstrates how the hypothesis could be applied. However, it is outside the scope of this thesis to verify this with tests of data linking impacts to power flux density. The paucity of tidal barrages, marine current and wave energy schemes world wide as yet makes it difficult to collect actual data. Tidal barrages have much higher power flux density at the converter than marine current turbines, between up to 628 kW/m^2 (Severn Barrage), as compared to marine current turbines average of ~10kW/m^2, and this would appear likely to be reflected in the impacts likely to be experienced, which appear to be lower for marine current turbines.

The proportion of the energy flow intercepted is greater for tidal barrages at ~100% compared to marine current turbines at probably a maximum of ~<30%, although the Tidal Fence schemes may intercept higher proportions.

The proportion of the energy abstracted has been cited at 30% for tidal barrages, for marine current turbines it would be probably be lower, depending on the scheme. The number of conversions of form of energy in the flow is lower for marine current turbines, only one compared to three for tidal barrages and this could be expected to result in fewer impacts and disruptions of existing functions and conditions such as sediment movement and tidal range.

The efficiency of energy conversion, at the converter would be higher for tidal barrages, as the low head HEP type turbines could be expected to be ~65-85% efficient, compared to the marine current turbine efficiencies which would be limited by their overall coefficient of performance $C_{p,}$ up to the Betz limit, in common with other turbine types.

For wave energy converters, average power flux densities of ~12kWm^{-2} for offshore wave energy converters on the west coasts of the UK and Ireland can be cited based on 20-40kWm^{-1} average power levels per metre of wave front. At least 50% of this would have been dissipated in bottom friction near shore and up to 80% by the shore line. Since the dissipation of this energy represents the natural functions performed by waves listed above, higher power flux densities could be expected to give rise to more functions, and a diminution of them through extraction of energy could be likely to result in impacts, such as changes in wave height and beach shape, and related geomorphic and biological effects, as well as water mixing and oxygenation. Currently studies envisage that less than 10% of the energy will be extracted by offshore devices, and with present anticipated deployment densities this will incur only small changes at the shore e.g. the SW Wave Hub maximum of 2.3% change at the shore. However, greater deployment rates would increase this. Wave Dragon converter studies indicted that a 22-32% reduction in energy levels could be expected 1 km behind a Wave Dragon farm and even sited further offshore, significant recharging may not be possible as the fetch would be limited to several kilometres.

The interception ratio and the proportion of energy extraction appear likely to be relevant factors in overall impact. The proportion extracted relies partly on the efficiency of energy conversion by the device. Currently onshore and attenuator devices have estimated energy capture ratios of ~50-93%, though in practice actual devices may have less. Terminator designs could be expected to have high interception ratios and thereby high energy extraction ratios.

The number of conversions could prove to be a significant factor in impacts. This varies from ~3 in the case of the Tapchan and OWC devices, to one in the case of Pelamis and other undeveloped designs such as Salter's Ducks.

Therefore the above suggests that the hypothesis might be usefully extended to other water based renewable energy sources, if the environmental impacts (e.g. beach shape, sediment erosion and transport as well as use of sea area) prove to be related to the parameters proposed, power flux density, proportion of interception and energy capture, efficiency of energy conversion, and number of energy conversions, in a manner analogous to HEP.

Appendix 2

Extension of the hypothesis to low power flux density sources

A.2. Introduction

The previous section Appendix 1 showed how extension of the hypothesis from HEP to other water based renewable energy sources, tidal, marine current and wave with lower but relatively comparable power flux densities could be applied. The hypothesis might be relevant in determining impact, though the paucity of available examples precluded tests of empirical data. In this section the hypothesis is extended to the lower power flux density sources, i.e. wind, solar, biomass with power flux densities in the range ~200Wm^{-2} -12 kW m^{-2}, and to geothermal. The parameters proposed, power flux density, proportion of interception and energy capture, efficiency of energy conversion and number of energy conversions, are applied to these sources' impacts.

The consequences of low energy flux density are generally to necessitate larger areas of energy collector, and greater numbers of them, as discussed in chapter 3. This can lead to greater land use, depending on the collector characteristics; though this is not always the case e.g. roof top solar photovoltaic. The large collector area may need to be a prominent structure, as in the case of wind energy, or power tower concentrating solar, which will have environmental implications. Apart from the collector area, there are other effects of low power flux density.

A.2. 1 Wind Energy

Wind turbines harness the energy of moving air currents caused by pressure differences whose original source is the differential heating of areas of the globe, both at global and local scales; greater at the tropics and lowest at the poles (Taylor 1996).

Moving air is a fluid, though with an average density of 1.23kg/m^3 at sea level (Taylor 1996) it is some 813 times less dense than water. Wind turbines therefore need a much greater swept area to harness equivalent amounts of power from the kinetic energy of moving air than water turbines do from moving water.

Wind energy is an almost mature technology now, which is competitive on good sites with some of the conventional fossil fuels. There is now over ~120GW of wind energy installed around the world (ENDS 2008, GWEC 2009) with some twenty five years or more of commercial experience. Over this period turbines have been getting larger and more reliable, resulting in falling generation costs. Some European countries now generate large amounts of their electricity from wind energy, such as Denmark 23% (EWEA 2008), Spain 11% and Germany 7.8%, with the UK at ~1- 2%.(DUKES 2008) with over 3.7 GW installed at the time of writing, including offshore.

Environmental impacts of wind energy have been much studied with an extensive literature built up, including works by this author (Clarke 1995). In the UK particularly, resistance to wind developments on the basis of environmental impacts has been slowing the development of wind capacity and leading to moves to site more capacity off-shore (SDC 2005).

The most apparent effects of wind energy are from the highly visible large structures with long rotating blades. Landscapes can be significantly altered by wind farms, especially as the scale of turbines has increased. The visual impact of wind turbines has been extensively studied. Other impacts include noise, though this is receding as an effect due to improved design. Electromagnetic interference to radio transmissions of various types is also possible and can influence siting. Safety and wildlife effects have further effects on siting as does grid connection. Such impacts have been extensively described by this author and others (Clarke 1988). The impacts of wind energy are summarised in table A.2.1 below.

Visual
Noise
Electromagnetic
Safety
Wildlife
Land use / use of space
Incompatibilities
Construction
Grid
Planning / compatibilities

Table A.2.1 Environmental impacts of wind energy.

(Clarke 1995)

A.2 1.1 Wind energy power flux density

The power flux densities of wind energy are cited in Table 3.3 as 800W m^{-2} to 12kWm^{-2} maximum (Clarke 1993), and a rating of 0.471 kWm^{-2} of wind turbine converter area has been achieved (Brocklehurst 1997).

The power in the wind is described by the equation:-

$$P(in W) = 1/2\rho \times A \times V^3$$

Where P = power in watts

ρ = pressure at sea level kgm^{-3}

A = swept area of turbine blades

V = wind speed in ms^{-1}

(Taylor 1996 p276)

It can be seen from the equation above that the power in the wind increases as a cube of the wind speed. Therefore there is an accent on higher wind speed sites, in choosing locations for wind turbines which vary greatly in available power, and hence wind energy is site specific. Power from the wind is also proportional to the swept area and so increases in blade size result in more power.

The actual power harnessed by a wind turbine is less than the power in the wind resulting from its kinetic momentum energy because the wind behaves as an extended fluid flow, and the Betz limit of 0.59 applies (Betz 1920 & 1966). Typically the overall efficiency of wind turbine's energy performance is likely to be ~42-45% at optimum wind speeds (Ozgener 2006).

A.2 1.1 Power Flux Density

Applying the key parameters of the theory, and considering the first parameter, power flux density, the consequences of low power flux density of ~77Wm^{-2} - ~10kWm^{-2}, derived from the 5ms^{-1} to 25ms^{-1} wind speed operating range and power equation for wind, require a large area of the flow to be intercepted in order to convert significant amounts of energy with many collectors each sweeping a large area. This results in many large structures spread across a large area. The number of turbines and land area required has been calculated at 0.3-0.5% of the UK land area, with less than 1% of this used for foundations and roads, for 10% of UK electricity supply (BWEA 2009).

Land use

The type of land use is significant for wind energy due to incompatibilities with the following categories, all unavailable for wind development; see table A.2.2 below. This is largely for reasons of visual impact, obstruction of wind flow, safety issues or physical obstruction from the large structures. However, wind energy is compatible with agriculture either arable or grazing.

-Designated landscape areas.

-Designated Nature Reserves.

-Within built up areas.

-Within military zones.

-Within forested areas.

-Within designated amenity areas.

-Within quarries and earthworks.

-Steep slopes

Table A.2.2. Land categories unavailable for wind energy.

(Rand & Clarke 1991)

Very little land is actually occupied by wind turbines, only about 0.3-2%, of the perimeter area of the farm, (BWEA 2009, Clarke 1988) including the access tracks. Due to the need to space out turbines to avoid each other's wakes, (BWEA 2009) wind farms occupy relatively large areas, although farming can continue around the turbines. It could therefore be said that wind turbines are spread *across* landscapes; occupation does not preclude all other uses.

The use of larger turbines which intercept more wind at greater heights can reduce the number of turbines required for a given output. Correspondingly greater power flux densities can be achieved than for smaller turbines.

Larger turbines being more visible from afar will, however, have a more extensive zone of visibility, and greater zones of visual impact (ZVI) (Engstrom & Pershagen 1980). Additionally larger turbines will be more intrusive in relation to the scale of other features in the landscape, and the largest machines e.g. total heights over 100m can "belittle" hills of similar heights. Higher power flux densities for wind energy can result in reductions of direct use of land, as described below, but some indirect effects on land uses may rise in proportion to scale. For example bigger foundations will be required, though fewer per installed capacity.

The effective power density for wind energy has been cited at 9 MW/km^2, based on six turbines of 1.5 MW each per km^2, and a wind speed of 7.0 to 7.5 m/s at a height of 45m (BWEA 2000). Employing a 500m buffer zone, for a 10% UK target for wind contribution to UK electricity, 2515 × 1.5 MW turbines would be required. In the SW Region the share would be 10% of the UK's 10% wind target, a 0.18% land area, requiring turbines to be spread across 41.9 km^2, but only occupying ~1% of this (BWEA 2009).

The BWEA report above refers to the ETSU report reviewing the wind resource, ETSU R-99 (Brocklehurst 1997). This shows the effect of increased power flux density for wind turbines due to large turbines. In Brocklehurst's (1997) 'A Review of the UK Onshore Wind Energy Resource', an updated and revised version of previous wind resource estimate is made. This takes into account the increasing size of commercial wind turbines, -at that time 600kW and hub heights of 45m above ground level, as compared to 300kW and 25m hub above ground level for the previous estimate. Due to the reduced ground friction at higher levels, air flows are significantly greater at the higher hub height, due to the ~1/7th power rule (Twidell & Weir 1986 p232), and the power flux density of the flow is higher. This has the effect of increasing the power resource density per km^2, capable of being exploited, to 9 MW/km^2 from 15 turbines $/km^2$, compared to $3.6MW/km^2$ from nine turbines of 400 kW.

Mackay states that wind energy across the UK has typically a power density of $2Wm^{-2}$, i.e. 2 MW/km^2, based on a wind speed of $6ms^{-1}$, which he takes as an average value (Mackay 2008 p 35). The mean annual wind speed of $6ms^{-1}$, is higher than many inland low lying areas of the UK, though standard wind speed height monitoring usually refers to 10m above ground level. Typical commercially available turbines are now in the range of 1.5-2 MW or even up to 3.6 MW with hub heights of 50-100m. Prototype 5MW turbines are being developed (Wizellius 2008). Models of boundary shear employ a 1/7 power rule, depending on ground roughness, and so greater wind speeds and hence power flux density can be found at current typically greater hub heights. Additionally, windier locations will preferentially be chosen, so although the average of $2Wm^{-2}$ might prove representative of the whole country, in practice wind farms will tend to have higher power flux densities. Packing densities for wind farms are assumed to be no greater than 5 diameters by Mackay

(2008c p266), and although this is a standard value, closer spacing perpendicular to the predominant wind direction of 3 x diameter may be possible, depending on the wind rose distribution of wind direction.

A.2 1.2 Proportion

Applying the second parameter, proportion of the flow intercepted and abstracted, it can readily be appreciated that for wind energy, in most circumstances, only a small proportion of the flow can actually be intercepted. This is due to the great volume and extent of the flow itself. For example a low pressure wind system in the UK may extend to a height of up to 3000m or more. Some weather systems can occasionally reach 24000 m in height (NASA 2008), though this is the upper range. The lower layer of the atmosphere, the troposphere extends to ~10,000m, (Blackmore & Barrett 2003) and most weather systems occur in this layer. Up to about 1000m, friction with the ground influences air circulation considerably, and boundary layer processes apply. Surface roughness and relief features greatly affect flows near the surface. As pressure decreases with height, the mass per cubic metre of air at 5500m, will only be ~half that at sea level, which will halve the energy output from turbines for a specific wind speed.

There are many different types of airflow; in the UK most of the stronger winds are associated with low pressure weather systems associated with the Gulf Stream, or on the outer edges of high pressure systems. However, other parts of the world may experience different types of wind and air currents. For instance the differential warming rates of land and sea produce on-shore and off-shore breezes. Mountainous areas or deserts can produce air flows of a more limited nature than the large weather systems rising to high altitudes. In some cases valleys conduct significant air flows. In certain locations the proportion intercepted by wind turbines may be significant, where the flows are of limited overall height and extent.

The size of turbines affects the proportion of the flow intercepted, for example the increase in exploitable resource cited above in Brocklehurst (1997), per square kilometre is in part due to larger turbines of e.g. 45m diameter rather than 30m diameter machines, an increase of ~707m^2 to 1590 m^2 per turbine, an increase of 2.25 times. So a greater proportion of the flow is intercepted.

However, although the largest currently available wind turbines exceed ~100m total height, only a very small proportion of the total flow of a low pressure weather system is actually intercepted and this is only a fraction of the flow available in the 100m above ground level. Nevertheless, this flow represents the current technical potential, i.e. the maximum attainable with current technology blade diameter limit and total height limit of turbines. So the measure of proportion intercepted, could be taken only from the flow in the lowest ~120m from ground level.

The fraction of the flow intercepted could be ascertained by:-

-optimum maximum turbine density
-optimum maximum commercial turbine scale
-overall coefficient of power including the Betz limit: 0.593,
e.g. 0.40 (Twidell & Weir 1986)

as a proportion of the energy in the flow available in the first 120m above ground level, taking into account the coefficient of friction with the ground.

It can be seen that the proportion of the current technical maximum flow intercepted is much greater than of the total flow. For instance in the diagram below, A-B represents the technical (current) local flow and C-D represents the ratio intercepted. EF represents the total height of moving air current.

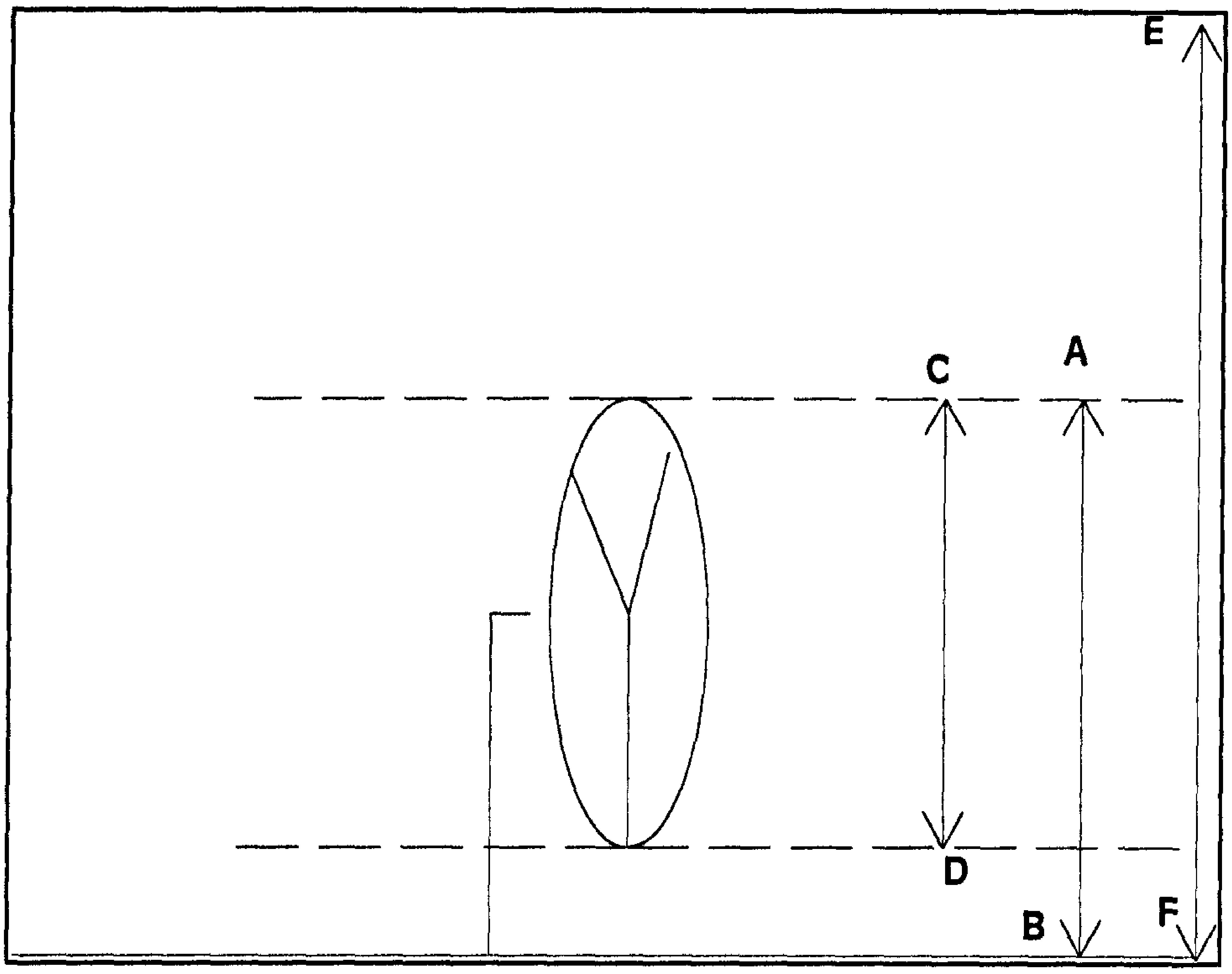


Figure A.2.1 Ratio of intercepted and total air current flow.

The ratio AB:CD is much greater than CD to EF where EF extends to the height of the total air current flow.

Application of this concept of proportion of flow to wind energy, concerns not so much impacts from physically abstracting energy, i.e. reductions of functions of the flow, as this will usually be a very small proportion, but impacts from the conversion technology, i.e. turbines' -unwanted "by products", e.g. visibility, and noise. In this case it is the proportion of the flow, accessible within technical limits, intercepted that will be significant. In practice the full technical potential wind resource is rarely exploited even for relatively small areas. The translation of these concepts into ones that could be of use for planning concerns the determination of the local flow.

Local Flow

For any given area and scale the wind flow can be determined. E.g. a house or vantage point, village or settlement has a breadth in relation to the prevailing winds. If the height of the flow is assumed to extend to ~120m, i.e. the current approximate technical height limit to flow interception, then the total volume of the flow can be calculated by multiplying the frontal area (of the area in question) breadth × height. From any house, vantage point or settlement, the proportion of the local flow intercepted by turbines can then be calculated. What this can provide is the relative proportion of the flow as experienced at that point.

Resource Density Proportion Intercepted

Another method of considering the concept of proportion of the flow intercepted, is to consider the fraction of the resource intercepted compared to the maximum technical resource exploitation possible. This could be done for different scales. The appropriate scale would depend on the purpose; e.g. measuring impact at a single building, or a settlement or other land use.

A.2. 1.3 Concentration of Conversion

The hypothesis holds that changes in the power flux density of the flow as a result of interception could cause impact. However this may apply more to the functions of the flow rather than 'conversion by-products', such as turbulence or noise, and more to defined flows with distinct boundaries, e.g. river water flows. Concentration of the energy conversion, after interception, in one location, e.g. with a larger turbine, might be said to concentrate impacts at that location, aside from the higher proportion of the flow being intercepted there. However, entraining the flow to achieve higher power flux density up-stream of the converter could alter the flow's functions. To what extent impacts will be concentrated at a single large turbine depends to some extent on the type of technology employed, however, it will also be intrinsic to the larger turbine. Offsetting this is the fact that fewer turbines will be required and larger turbines convert more wind energy per square metre due to intercepting higher wind speeds at a greater height with lower ground friction (Twidell & Weir 1986).

Impacts derive from by-products from conversion at each turbine, so the impact for a windfarm could be the sum of each turbine's noise and visual and other effects. Although higher intensity impacts may be found locally in the vicinity of a larger converter, spread across the broad area of the flow, impacts may be reduced by larger converters, since fewer conversion processes (with their by-products) are occurring.

A.2. 1.4 Application to Size of Turbines and Impact

Addressing the issue of size of turbines and impact, the parameters can be applied to wind energy as follows:

Power flux density for Regional Target Planning Guidance (BWEA 2001) has been assumed as 9MW per square km, based on 6 × 1.5 MW turbines, with wind speed of 7.5m/s at 45m height, i.e. a 234 W per square metre power flux density. This is a greater power flux density than if smaller turbines had been employed, as wind speed increases with height above ground on approximately a 1/7th power rule, due to lower ground friction. This might imply a slightly greater impact but the difference in power flux density is small, and possibly not significant.

Proportion of the flow intercepted is greater for a larger turbine e.g. 45 m diameter turbines with a greater surface area than e.g. a 30m diameter turbine. This would imply an increased impact, though depending on what is taken as the total flow.

Efficiency of conversion device can be greater for a larger diameter turbine, e.g. in terms of visual impact, due to the higher power per square metre of blade area. Additionally the inevitable losses of conversion are reduced with fewer converters required per unit of electricity, implying a reduced impact. The number of energy conversion processes is therefore reduced by having fewer turbines overall. This gives rise to an overall lower level of by-products such as noise, again implying a reduced impact. Finally, there is no increase in the power flux density of the flow for wind energy, in that the flow is not concentrated by ducting or concentrators, as compared to hydro electric power schemes. As can be seen, no values are attributed here to the increased or reduced impact. If it is assumed that visual impact is the main effect, and larger turbines are to be employed, there will be gains from needing to use fewer but some losses in their vicinity as they could be more intrusive at close quarters.

Hypothesis as related to impacts from Wind energy

The much lower density of air at sea level (1.23 kg/m^3) compared to fresh water (1000 kg/m^3), means that the environmental effects of exploiting wind energy do not affect geomorphic processes in the same way that moving water does. Although in desert areas wind blown sand is an agent of erosion and geomorphic processes, the total proportion of energy extracted from the flow by wind energy development is likely to be small, with correspondingly small effects on geomorphic processes. Thus this suggests that the environmental impacts of wind energy may affect mainly the human environment or anthroposphere, and the biosphere in terms of wildlife, mainly birds, and the plant habitat at the site to some extent, depending on site characteristics.

A.2 2 Solar Energy

Solar energy is one of the most diffuse of the direct renewable energy flows, with a power flux density of 1.367kW at a mean earth distance from the sun and normal to the solar beam, known as the solar constant (WEC 2007). At the earth's surface, the maximum intensity is 1kWm^{-2} (Twidell & Weir 1986) due to atmospheric absorption and the mean is ~170 Wm^{-2} when averaged over the surface of the earth and over the year (WEC 2007), as the sun's angle changes diurnally, and seasonally. The low power flux density requires a large collector area to harness significant quantities of energy.

There are various different types of solar energy conversion technology: flat plate thermal, photovoltaic (PV) (electric), parabolic concentrator thermal (electric), power tower thermal (electric), and dish concentrator thermal (electric). Solar energy installations and applications are widespread across the globe (Boyle 1996), particularly in the case of flat plate thermal solar heaters for water (or air) heating, and photovoltaic panels. Such applications have been growing fast with over 100GW of solar thermal and more than 9GW of photovoltaic capacity employed worldwide by 2006 (IEA 2006). Solar thermal electric applications have also been expanding in recent years though the technology dates from the 1970s.

A.2.2.1 Solar Impacts

These different types of solar converter have different impacts and different power flux densities. This author has reviewed the impacts of solar energy in Clarke (1995), including hypothetical applications such as orbiting solar satellite PV with micro wave transmission of the power to earth. It is outside the scope of this study to repeat this review of impacts here. A summary is included below in table A.2.3.

Land use / use of space
Incompatibilities
Planning
Manufacture
Decommissioning
Some Noise (for concentrating thermal conversion)
Visual
Safety
Glare
Wildlife

Table A.2.3 Summary of environmental impacts from solar energy.

(Clarke 1995)

Land Use

Although a large area is required to harness solar energy, (due to its diffuse nature) and thus the land requirement would appear to be large, in practice this only applies to non-building based collector systems, such as solar power stations. For example, solar electric conversion technologies such as photovoltaics or solar thermal-electric systems, such as parabolic concentrating collector installations (e.g. Luz in California) and power tower systems, examples of which exist in California, and Spain (US DoE 2008), are used in systems independent of buildings.

Most direct solar energy usage is expected to occur in decentralised applications on the surface of the buildings (roofs or walls) where the energy will mostly be used on-site. That this can be done is due to the thin flat collectors of photovoltaic systems, and solar thermal systems, which in turn derives from the low power flux density and the technology employed. This technology involves direct conversion of solar radiation to electricity for photovoltaics and direct conversion to heat in flat plate thermal collectors, without the need for further conversions into other energy forms, or further concentration, i.e. increases in power flux density.

Hill et al (ESTU 1994) calculated that the south facing roof area of buildings in the UK was sufficient at that time to generate 120% of the UK electricity demand then prevailing, and even at the relatively low efficiencies of solar PV. Hence there could, in practice, be little land use associated with solar photovoltaics application on a large scale in the UK if building mounted collection were adopted, despite the low power flux density.

While this would appear to contradict the general trend of lower power flux density sources requiring more land area, this feature can be related to power flux density in the following manner. The solar radiation energy flows of PV and solar thermal (water heaters) are harnessed at either the same power flux density of the incident solar radiation at that site, or at slightly higher concentration through built-in optical concentration (e.g. Fresnel lenses) and this low power flux density form is then compatible with ambient environmental conditions on building surfaces. These types of technology produce few hazards or noise, or emissions, as the power ranges in terms of voltages, currents or temperatures and pressures are relatively low per m^2.

This points to the significance of the type of technology used for harnessing renewable energy, as a determinant in the overall resulting environmental impact. Therefore it suggests that the direct conversion of the low power flux density by these technologies (solar PV and solar water heating), could result in lower impacts, in terms of land requirement, and possibly in other respects too. Large scale focussed solar (CSP, CPV) may be a different issue, as is discussed later.

Resource Variation

In a rather more obvious respect power flux density variations might be seen to relate to environmental impact resulting from differences in the overall resource distribution across the globe. The total annual solar radiation flux to earth varies by a factor of about two (WEC 2004 p297) or perhaps three. The highest values experienced in e.g. the Red Sea, Sahara desert, at ~300 W/m^2 annual mean, vary to some of the lowest values in e.g. Northern European regions such as the UK at ~100 W/m^2 or ~1000 kWh/m^2 per annum or parts of Scandinavia and the Arctic, down to about 800 kWh/m^2 (WEC 2007 p383). This variation results from of differences in latitude, affecting the angle of the suns rays to the surface, and in climate, i.e. cloud cover in particular. Even southern parts of Europe have almost twice the solar resource as the regions of the lowest amount (Boyle 1996).

Areas with high solar resource totals, for the same area of collector, could harness roughly twice the energy or alternatively require half the collector area. If the solar collector area is translated into impact in terms of manufacture and disposal, as well as use of (some) space there could be half the impact per kWh. It could then be stated that solar could produce up to twice the impact in terms of land use, per kW hour in lower solar flux regions.

This can be translated into power flux density in terms of the reduced maximum kW per square metre experienced in e.g. the UK compared to the tropics; around 80% of the 1kW per square metre with the sun directly overhead, and the reduced time spans that higher solar flux occurs, with long periods of low power flux density. E.g. in winter the highest values at the solstice will be in the region of 20% or less.

However, this relationship to power flux density is somewhat tenuous, as it concerns the distribution and frequency of the solar flux peaks and higher values, rather than the values of the maxima, which only vary by ~20%. The impacts of manufacturing and disposal of collectors and the ancillary system components, although they are the main ones cited for PV and solar thermal, are considered to be relatively minor (ExternE 1995).

A.2.2.2 Concentrating Solar Thermal Technologies

The low power flux densities of solar energy, even in desert areas, have led to the development of concentrating technologies for thermal energy conversion which relies on high temperature difference for efficient thermodynamic conversion. The main types are parabolic mirrors concentrating solar radiation on a pipe in series, or alternatively, tracking mirrors reflecting on to a central "power tower" point, to achieve the desired concentration (Boyle 1996).

The Nevada Solar 1 Parabolic CSP plant in Nevada USA near Boulder City has collectors occupying 1.42 km^2 area to provide continuous power of 22MW, or a maximum of 64MW (US DoE 2008). The actual "Solar field" mirror area is cited at 357,200 m^2. At average output, the power flux density would be 22MW/ 1.42km^2 = 15.5Wm^{-2}, and a maximum of 45Wm^{-2}, for the whole plant.

The peak power fluxes for the collector area could be expected to be close to 1 kWm^{-2}, with the losses accounted for by the conversions from electro magnetic radiation to heat in the form of the synthetic oil, then the conversion of this heat through a heat exchanger to raise steam, followed by thermodynamic conversion to rotational shaft power by the turbine, and then finally to electricity.

The maximum theoretical efficiency ε for thermodynamic conversion is given by:

$$\varepsilon = \frac{Tin - Tout}{Tin}$$

Where T is in kelvin

T_{in} = inflow temperature

T_{out} = outflow temperature (Boyle 1996 p75)

At the design temperature of 371 °C, field inlet temperature is 350 °C and field outlet temperature is 395 °C (NREL 2008). The concentration ratio is 71 and the optical efficiency is cited as 0.77 (NREL 2008). The turbine steam pressure is 102 bar and 371 °C inlet temperature, the reheat pressure being at 17.5 bar, steam outlet temperature is not given. The steam turbine generator's gross output is 75 MWe, and the net output to the grid network is 70 MWe. Plant parasitic energy requirements, such as for pumping the circulant and steam condenser, plus reflector tracking, account for the remaining 5 MWe. Annual electricity production is estimated to be 140-150 GWh.

Therefore the average power produced would be 145GWh / 8760 = 16.6 MW.
The average solar irradiation is 6.75 to 8-8.25 kWh/m^2 per day, in the vicinity of this area of Nevada (NREL 2008). An average solar radiation power flux density per 24 hr day is then 7.5/24 = 313 W per m^2.

This produces an overall efficiency of:

$$357200\ \mathrm{m}^2 \times 313\ \mathrm{W} = 111.8\ \mathrm{MW}\ \text{average solar energy input}$$

$$16.6 / 111.8 \ = \ 0.14\ \text{overall efficiency}$$

Power Flux Density, proportion and efficiency

In terms of the hypothesis, the power flux density is a maximum of almost 1 kW/m^2, and an average of 313 W m^{-2}. The concentration is then 71 times, giving a maximum power flux density of 54 kWm^{-2} at the heated pipe taking into account the optical efficiency, and an average there of 17 kWm^{-2}.

The proportion of the solar radiation intercepted is unknown, but likely to be ~35% taking into account reflector spacing, though the energy extracted will be 0.77 of this (optical efficiency), together with any other losses.

The efficiency of conversion is 0.14 overall, being optically 0.77, Hang et al (2007) cite overall annual efficiencies of 10-15% for parabolic trough systems, which is in agreement with the figures above. They cite land use at 6-8m^2 / MWh a (or 16.3Wm^{-2}, though this value cannot be a whole plant one) and a thermal cycle efficiency of 30-40% (Hang et al 2007 p258).

The number of conversion processes is four or five including the reflection and concentration. Firstly solar radiation is reflected and concentrated by 71 times, secondly conversion to heating the circulant, thirdly conversion to steam, and fourthly steam to mechanical shaft power, and finally to electricity at the generator.

Impacts as related to parameters

Land use should be inversely proportional to power flux density. Unlike wind energy, incompatibilities with other land uses such as farming at the plant site and the requirement to avoid over-shading require an almost complete occupation of the site.

However, since the required insolation rates of 6.75 kWh m^{-2} per day, (281 W /m^2 average) are largely only found in desert areas, the need for large areas is less likely to be a problem; there are few if any competing land uses due to the dry conditions, which cause the high insolation rates (together with low latitudes).

Visual impacts are relatively high, though since population densities are very low in such regions, there could be lower sensitivity to this. The optical efficiency, of 0.77 cited will cause some reflection and so glare. Some noise may result from the steam turbine and circulating pumps. Safety is unlikely to be an issue except in relation to the extensive heated circulant pipes, steam boiler and turbines and condenser. However, this affects mainly only on-site staff and possibly wildlife.

Impacts of Solar CSP and opposition

Although wildlife effects may be assumed to be small, due to the low density of life in such arid regions, there have been protests against CSP Solar developments. In California a sudden increase in CSP Solar scheme applications from none two years ago to one hundred and twenty five in 2008, for 70 GW total capacity resulting from the 20% renewables target, and high energy prices, has led to protests which resulted in a moratorium on further applications (New York Times 2008).

This was itself subsequently reversed. Impacts cited by the opponents (mainly local residents) include the large area occupied, water consumption for cleaning mirrors, chemicals used to clear undergrowth below the panels / reflectors, as well as loss of habitat for endangered species such as the ground squirrel, the desert tortoise and the burrowing owl. In the Nevada desert the endangered species and habitats are desert tortoise (Beacon Solar 2008). Opponents to CSP schemes propose use of dispersed roof mounted PV as an alternative.

On the one hand, the high ratio of coverage required for Concentrating Solar Power Plants and their large area, results in an intrusive development, which would appear to be incompatible with any other land uses in the same area. On the other hand, there may even be positive effects, in the shade created below solar reflectors, where dew and soil moisture is more likely to be retained, as suggested by a study of microclimatic responses to solar collectors or mirrors in a Sonoran desert (Smith 1981). Although shading levels and panel /

mirror coverage in this case was high, resulting in a 91% midday reduction of the midday solar irradiance, there was a net gain in photosynthesis due to increased plant cover from reduced soil temperatures, increased moisture retention in the dry season, and reduced wind. However, the practice of using herbicide to clear the ground cover below panels and reflectors, to avoid accumulation of dust and organic detritus, will negate any gains in photosynthetic activity.

Power Tower

The second type of CSP Solar energy technology uses tracking mirrors to reflect sunlight and concentrate it on a heat exchanger on a tower, which then heats synthetic oil to high temperature, to raise steam, and so turn a turbine generator unit (Boyle 1996).

Concentrating solar power technologies clearly can result in impacts deriving from the high interception rate, i.e. proportion of flow intercepted and extracted, as well as the concentration -in terms of glare, and conversion processes. This points to the relevance of the parameters used in the hypothesis.

A.2.2.3 Photovoltaic Solar

Photovoltaic solar energy conversion uses semi-conductors materials to allow photons to release electrons giving rise to a voltage difference which can be used to create a current (Boyle 1996). The semi-conductor materials consist of p-n junctions, where the doped p material contains an excess of electrons, and the doped n material has a deficiency of electrons. Silicon solar cells use high purity silicon doped with small amounts of boron in the p layer and phosphorous in the n layer. Photons have an energy of ~2eV and electromagnetic wave particle radiation is a highly organised form of energy. Mono crystalline silicon solar PV cells have attained an efficiency of about 16% (Boyle 1996 p101) though up to 22% is claimed (Sunpower 2008) and a typical cell produces about 1.25 W, with a voltage of about 0.5V and a current of about 2.5 amperes (Boyle 1996).

Generally solar cells are assembled into large flat panels to provide useful amounts of power. Such panels, having no moving parts and requiring only electrical connections and secure mountings, can be installed on buildings' roofs or walls or alternatively on frames on the ground. In higher latitudes the panel will need to be tilted to be normal to the solar beam, e.g. ~30° in the UK as a compromise between seasonal variations.

Solar PV will only incur extra land use when placed in solar array fields, as has been done for example in Germany at the Muhlhausen Solarpark 10.08 MW capacity (TDW 2004).

PV power stations in terms of the hypothesis

The solar irradiance energy density at Muhlhausen is ~1350 kWh/m^2 pa. (Suri et al 2006), or an average power flux density of 154 W/m^2. Here solar PV panels with an area of 250,000m^2 are used in the solarpark, which occupies a total area of 400,000m^2 (Sunpower Corp 2008). Output is expected to be 6.8GWh pa, giving an average output of 0.776 MW, resulting in a land use of 58.82 km^2/ TWh pa.

Therefore the overall efficiency of energy capture for the total flow is

$$0.776\text{MW} / (154\text{W} \times 250000) = 2\%.$$

The flow interception rate would then be 250,000/ 400,000 = 62.5%.

A typical interception rate would be ~33% for the 400,000 m^2 collector / 110ha total area PV solarpark, e.g. Brandis / Bolanden near Leipzig (Juwi 2008).

A feasibility study by the ACT government in Australia Capital Territory for a solar power station to supply 10,000 homes (ACT 2008), identified solar PV as more efficient in land use requirement than Solar Concentrated Thermal, at 75 ha of land for 57 MW (76 W/ m^2) capacity as opposed to 120ha (47.5 W/m^2) for the SCT plant.

This latter example illustrates how power flux density can be used to compare and assess land use impact of different technologies, showing the value of a common parameter that can be applied to compare impacts of different schemes, together with the factors of efficiency, interception and energy extraction ratio as well as number of conversions.

A.2. 3 Biomass

The case of biomass renewable energy is more complex than some of the other sources since it is in effect stored solar energy in a chemical form. But its use as a fuel does allow us to produce a power flux density figure based on output per unit land use requirement. Moreover, it is both a low power flux density source, derived from sunlight, and, as the carbon and carbohydrate materials themselves flow through the natural environment, a higher power flux density source.

Furthermore since biomass sources involve carbon compounds, carbohydrates (CH_2O compounds), the building blocks of life, there are additional environmental issues such as biodiversity, as well as competition with food production to consider in their use.

Moreover the storage capability of biomass energy sources introduces still further complications. However, despite this complexity the environmental effects of biomass sources can still be assessed in terms of the hypothesis described in this thesis.

Biomass Energy Sources

Biomass energy refers to the use of dead plant and animal matter for energy (Hall 1991). Biomass is derived from a large number of diverse sources as shown in Table A.2.4 below.

-Urban Domestic Wastes,
-Urban Industrial Wastes
-Food Processing Wastes,
-Sewage Wastes
-Forestry Wastes,
-Energy Forestry,
-Fuel Crops, (for e.g. Biodiesel)
-Landfill Gas
-Energy Coppicing (SRC)
-Agricultural Wastes

Table A.2.4 List of biomass energy sources.

(Ramage & Scurlock 1996)

Biomass energy can be divided into two parts: -production of the fuel material and secondly -conversion into useful energy. The first part is the growing of plant matter, or collection of wastes, and the second can include the conversion to fuels with a higher energy density (kWm^{-3}). The definition of a fuel is a store of energy (Boyle 1996).

Biomass energy sources are the traditional supplies of energy used by humans ever since the use of fire was discovered. Such sources are still important in global total primary energy supply, estimated at 8% (IEA 2006) or more, since much of traditional use is in the informal sector. Traditional use is the burning of wood and plant or animal matter for cooking, lighting and heating. Although this source has declined with the increasing use of fossil fuels and other energy sources, the modern use of biofuels is expanding in many countries with the development of more efficient and clean technologies for production and conversion. In the UK e.g. ~50% of the renewable electricity supplied was derived from biomass sources (DUKES 2008).

A.2.3.1 Environmental Impacts of Biomass Energy

Because biomass energy is comprised of biomatter, the substance of living matter, its use has considerable environmental implications. Production issues concern the land area required and the substitution of natural vegetation by the biomass crop, which will have biodiversity consequences, depending on the former crop. Visual impact can be a concern from stands of crops. Wildlife can be affected due to habitat changes. Soil quality can be an issue depending on the rate of harvesting, and water and fertilizer requirements are important considerations. Biomass crops can have incompatibilities with some other land uses; -for example Short Rotation Coppicing (SRC) may preclude simultaneous wind energy use due to increased surface roughness. Land use incompatibilities will be similar to those of arable farming use. Biomass fuel crops compete for land use with food production and in recent times this has become a more contentious issue (Srinivasan 2008). In addition, biomass energy use is rarely entirely CO_2 neutral, that is, cultivation and harvesting as well as fertilizer inputs all require an energy input, usually in the form of carbon (fossil) fuels. The ratio of carbon saved can very widely with biofuel crop, e.g. ethanol produced from maize can result in savings of only ~33%, compared to ethanol produced from sugar cane which can produce 71% savings (Gallagher 2008 p26).

Conversion of biomass into fuels and energy constitutes a very diverse topic with many varieties of processes and technologies. This author has reviewed many of these at length in previous publications, especially Clarke (1995) (2000), as well as other authors (Hall 1991, Ramage & Scurlock 1996). It is beyond the scope of this thesis to consider all the different means of biomass production and conversion. Here, the general principles of applying the hypothesis to some selected examples will suffice. A summary of the environmental impacts of biomass energy is shown in table A.2.5 below.

Production	Conversion
Visual	Visual
	Noise
	Safety
Wildlife	
Soil Effects	
Water Requirements	
Fertilizer	
Land-use	Land-use
Incompatibilities	Incompatibilities
	Emissions: gas, liquid, solid
Competition with Food	
Degree of CO_2 neutrality	
Waste processing	

Table A.2.5 Environmental impacts from Biomass energy.

Biomass Power Flux Density

Biomass energy sources have the lowest overall power flux, ranging from a maximum of 320W m^{-2} absorbed at the leaf surface to just $16Wm^{-2}$ actually available as biomatter after the plant has used the energy required for respiration (Ramage & Scurlock 1996). This can be seen from Figure 3.3 in Chapter 3, page 76.

The reasons for this very low power density flux are that solar light radiation, already the most diffuse of the primary renewable energy flows, is then converted by photosynthesis by plants at low efficiency, and only a proportion of this energy is actually used for plant growth, so forming biomass materials for use as a fuel. The overall efficiency has been estimated at as low as ~0.5% of the original solar input (Ramage & Scurlock 1996 p154).

Power flux density and land area required for biomass energy

As a consequence biomass energy primary production requires very large amounts of land area. See also the Figure 3.5 (Gagnon et al 2002 *a* Fig 4 p1274), in Ch3, p 89, confirming this.

Therefore the production of biomass energy can be expected to have a large environmental impact in terms of land use, directly related to the low power flux density of the source production. E.g., short rotation willow coppicing (SRC) can produce ~10t / hectare per year in the UK (Ramage & Scurlock 1996), which provides 150 GJ pa or $0.48Wm^{-2}$.

Conversion of the biomass materials to more concentrated forms, results in much higher power flux density (in terms of carbon material flows). Table A.2.6 below shows that the energy density for some typical biomass materials used for fuels is between a quarter and half (or lower) than that of fossil fuels. Fossil fuels are of course derived from biomass stock, compressed and chemically processed, i.e. converted into the more energy dense forms that currently provide ~80% of human use of energy worldwide (IEA 2006).

Low energy density biomass materials are inconvenient to handle and transport, as well as being prone to decay (Ramage & Scurlock 1996). The low value materials are uneconomic to transport and utilise in solid forms such as logs or grass, and therefore are converted to higher energy density forms such as the more familiar fuels such as alcohols and methane, which can have environmental implications.

Average Energy Content of Fuels

Fuel	*Energy Density*	
	GJ t^{-1}	*GJ m^{-3}*
Wood	15	10
Paper	17	9
Dung	16	4
Straw	14	1.4
Sugar Cane	14	10
Domestic Refuse (as collected)	9	1.5
Commercial wastes (UK average)	16	*
Grass	4	3
Oil	42	34
Coal	28	50
Natural Gas	55	0.04

Table A.2.6 Average energy density of biomass and fossil fuel stock.

(Ramage & Scurlock 1996)

Carbon flow and other cycles

Carbon flows are also important to fundamental life processes, such as the cycling of soil nutrients and the organic carbon compounds which are cycled by fungi and saprophytic organisms (Nasholm & Ekblad 1998), as well as the storage of carbon in the soil. Carbon flows through soils are to be understood as comprising both inorganic and organic carbon, with the inorganic carbon in solution being much more readily available, and the organic CH_2O compounds having greater permanence.

The soil stores about twice the carbon that the atmosphere does (IPCC 2007) and the importance of carbon stores in soil, as a sink for carbon sequestration, has been acknowledged (IPCC 2007) by many commentators. Abstracting from these carbon flows in order to extract energy could result in greater cycling of the carbon via the atmosphere.

Figure A.2.2 below shows a simple biomass combustion cycle which assumes that all of the carbon is cycled via the atmosphere. One of the major impacts of using fossil fuels has been the rise in atmospheric carbon from ~280 parts per million in 1800 to a 365 ppm in 2003 (Blackmore & Barrett 2003), leading to average global warming of at least 0.5° C so far (Blackmore & Barrett 2003). This results in changing of climates, and so further cycling of carbon via the atmosphere needs to be undertaken only in a sustainable controlled manner. That means ensuring that carbon neutrality or near neutrality is achieved; measuring of net carbon flows from the soil stores is required.

Simple Biomass Combustion Cycle

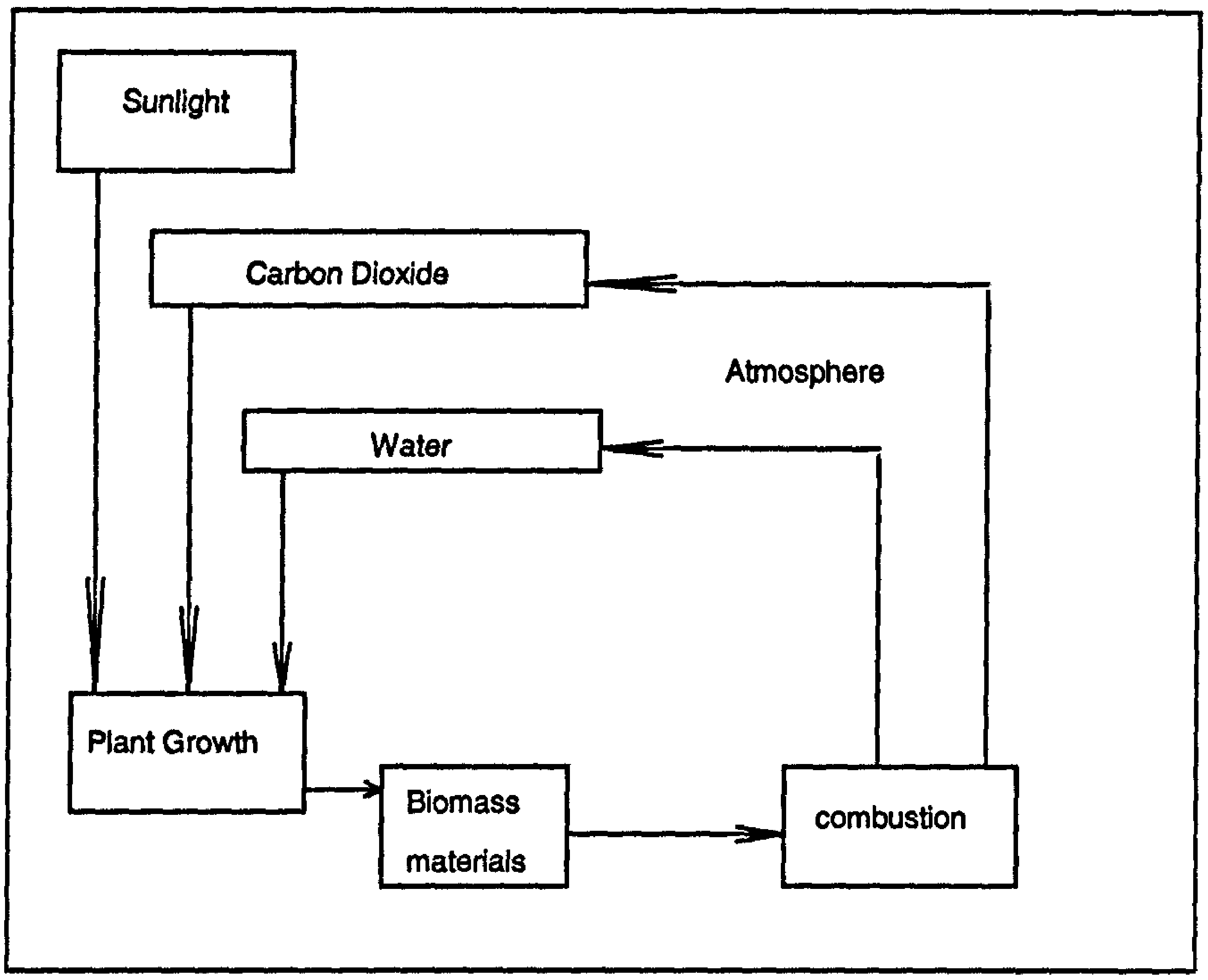


Figure A.2.2 Simple Biomass Combustion Cycle.

(Clarke 2000)

In practice it is difficult to accurately measure soil carbon, due to the dynamic nature of the flows; as inorganic solutions, and organic compounds much of which may be in flux being processed by micro organisms, bacteria and fungi, at any one time. Figure A.2.3 below shows a more developed cycle for natural plant carbon, nitrogen, water and minerals cycle, with cycling of organic compounds via the soil and fungi or microrhyzal organisms on plant roots (Nasholm et al 1998). Despite the difficulties in obtaining accurate soil carbon content figures, the importance of knowing the size of the store, as well as what the flows are, is evident.

Natural Plant, Carbon, Nitrogen, Water and Minerals cycle

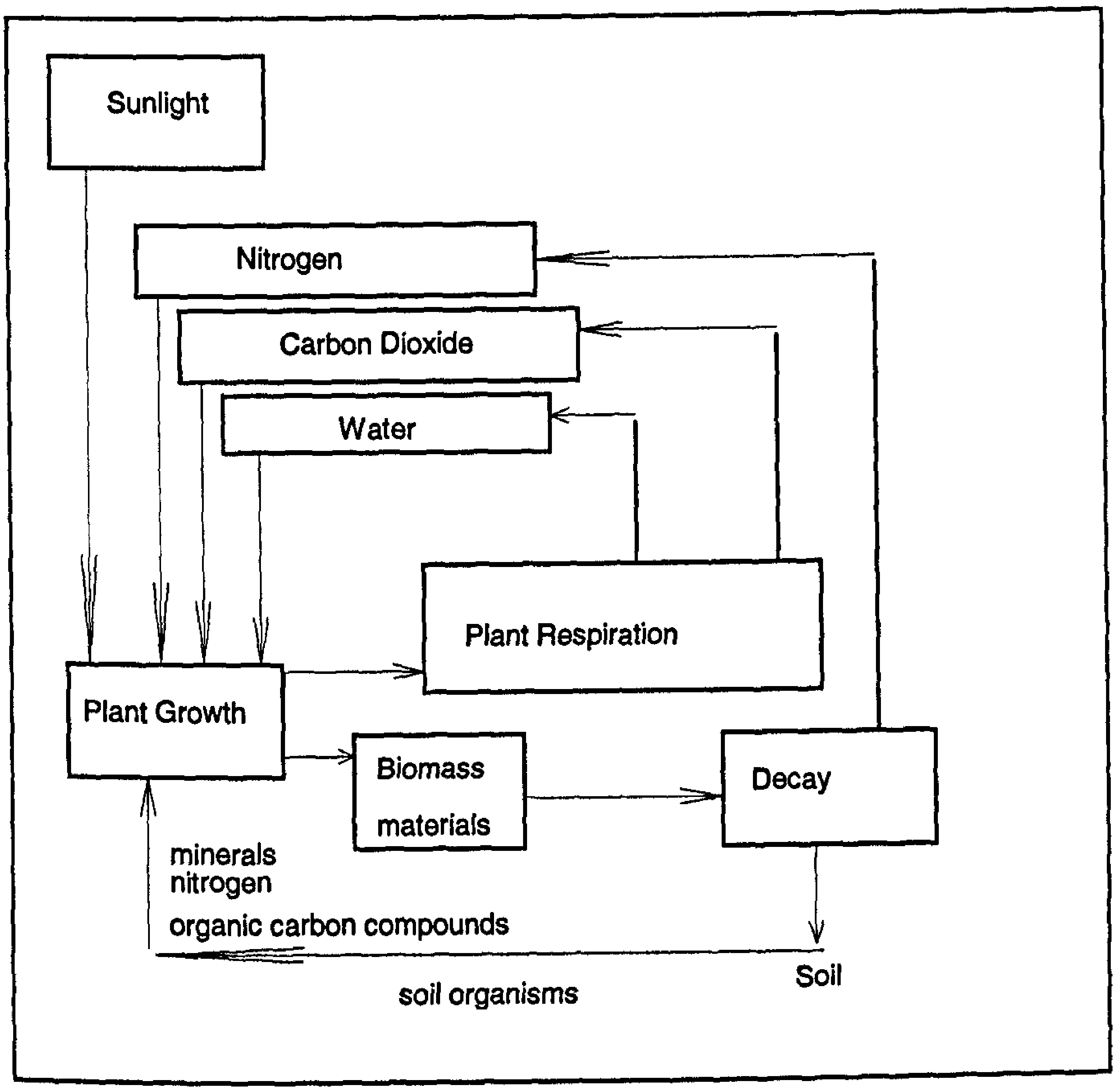


Figure A.2.3 More developed biomass cycle taking account of soil flows of organic carbon. (Clarke 2000)

Conversion of Biomass fuels

There is a wide diversity of methods for biomass energy conversion. The different conversion methods:-

-Direct combustion, to produce heat for direct use in external combustion engine.

-Thermochemical processing such as pyrolysis, gasification, and liquefaction.

-Biological Processing such as anaerobic digestion to produce CH_4, and fermentation to produce alcohols such as ethanol C_2H_5OH (Ramage & Scurlock 1996).

A.2.3.2 Biomass energy in terms of the hypothesis parameters

In terms of the hypothesis:-

-the power flux density (at the primary production stage) is very low at 16W/m^2, or less depending on the biome (climatic conditions) in question. This leads to high land use per unit of energy obtained.

The proportion of the energy flow that is extracted needs to be no more than the plant can replace on a long term basis, while not depleting existing stores of organic carbon in the soil.

The efficiency of the initial energy conversion from solar radiation to organic compounds by plants, i.e. photosynthesis and plant growth is very low at ~0.5% (Ramage & Scurlock 1996 p145). Utilising biomass fuels for energy by combustion limits efficiencies to those determined by the laws of thermodynamics, which will rarely exceed 50% energy conversion, and often lower efficiencies of ~30%. Harvesting, processing, transport and conversion involve further efficiency losses.

The number of conversions involved will be relatively high since firstly there is conversion of solar radiation to chemical potential energy by the plant (although this is a natural process and therefore could be considered a positive impact), secondly there may be conversion of the biomass fuel stock to a more energy dense form, such as an alcohol or gas (or at the least harvesting involves some forms of processing), thirdly a conversion from potential chemical energy to heat energy or rotational shaft energy by combustion in a heat engine and fourthly, to electricity in a generator.

These multiple conversions can each lead to further impacts, as the efficiency losses at each stage lead to waste energy forming unwanted by-products such as gaseous chemical compounds of unburnt hydro carbons, e.g. CO, particulates, or NOx, or other residues.

Biomass Energy Conclusions

Applying the hypothesis could help identify how impacts can arise from the use of biomass energy sources. The low power flux densities lead to large use of land per unit of energy, which can compete with food cultivation, and also to the need to convert the fuel stock so that high energy density useful and economic forms can be employed. The proportion of the energy flow that is extracted could be crucial to long term performance of soils and also to the net carbon neutrality. Conversion efficiency is low and multiple conversions are required -all of which can lead to further impacts. However, biomass energy flows are an integral part of the natural environment, and there are many waste streams from human food production and economic activity that can be effectively utilised. The primary production of biofuels for fuels needs greatest scrutiny to ensure that overall gains are worthwhile, both in energy and carbon terms, as well as other mineral cycles. Using biomass energy sources can produce environmental gains, e.g. for wildlife, for carbon sequestration in soils, or through treatment of wastes, provided that the overall processes are carefully identified, assessed and managed. Nevertheless, biomass energy utilisation also has the potential to be unsustainable and environmentally damaging.

A.2. 4 Geothermal energy

Geothermal energy is the use of the decay heat from radioactive isotopes, such as Uranium $_{238}$, Thorium $_{232}$, and Potassium $_{40}$, and heat from the formation of the earth in the earth's crust and core (Brown 1996). It is one of the older renewable energy sources, dating from about the turn of the nineteenth and twentieth century (Brown in Boyle 1996). It produced 54,941 TWh pa globally, about 0.4% of world primary energy in 2004 (IEA 2006), mainly in volcanic or plate margin areas. Two types of geothermal energy exist potentially; wet aquifer, (current geothermal energy) and Hot Dry Rock (HDR), which has only been proven in prototypes so far. While wet aquifer geothermal is a relatively limited resource, HDR potentially has much greater total heat capacity. Geothermal energy is only partly renewable in that it represents a store of heat, albeit one which is replenished, but not over the lifetime of a development, rather over tens or hundreds of years (Brown 1996).

Approximately 10GW of geothermal electricity generation capacity is installed worldwide (IEA 2006), plus ~15GW thermal in use. Enhanced geothermal systems are now being developed which use improved drilling technology e.g. in Germany and in the UK.

Environmental Impacts of Geothermal Energy

This author has reviewed impacts of geothermal energy usage in Clarke (1995). Below is a summary of the impacts in Table A.2.7.

Land use / use of space
Incompatibilities
Planning
Noise
Visual
Safety
Wildlife
Gaseous emissions
Liquid Emissions
Subsidence possible
Minor earth movements

Table A.2.7 Summary of environmental impacts from geothermal energy.

(Clarke 1995)

It is not proposed here to go into great detail, applying the hypothesis to geothermal energy, as this is outside the scope of this study. Rather the method of applying the hypothesis is briefly outlined.

In terms of the hypothesis, the power flux density of the average background heat radiated from the earth's surface is very low at 0.06W/m^2 (Brown 1996 in Boyle 1996 p358). However, the total flow amounts to 10^{21}Jpa^{-1} which is ~21 times world total primary energy use so the resource is potentially large. Despite the low average power flux density, it is concentrated at certain points to an average of ~300mW/m^2, in the form of aquifers due to suitable geological conditions, i.e. permeable rocks, and a syncline with a cap of non permeable rock, insulating rocks and a suitable energy gradient per depth (Brown

1996). Such aquifers can be natural features, breaking to the surface as geysers or hot springs. At such points high power flux densities, of for example tens or hundreds of watts per m^2 can be found, but they are relatively rare.

In terms of the function in nature of this energy flow, it is part of the geological and lithosphere evolution of the planet that the rocks gradually cool and change chemically in so doing, at least near the surface. Extracting this heat may not be significant environmentally, provided that it is the existing flow which is exploited. However, exploratory boreholes are drilled to find new resources of wet aquifers, and possibly in the future for HDR wells, which could accelerate the rate of cooling that would have occurred naturally. A possible result of this is the minor earthquakes and seismic events which often accompany geothermal exploitation.

Geothermal energy in terms of the hypothesis

In terms of the hypothesis, the increase in power flux density over that which would have occurred naturally, produced by e.g. HDR or wet aquifer extension, could have the potential to result in environmental impact, in that changes might be accelerated. Whether the greater cooling rate will cause contractions of the rocks which result in significantly increased seismic events is a question that could be posed. Some accelerated rock reservoir cooling could possibly occur almost without impact on the surface, provided that the hot rock reservoirs are not cooled too rapidly or extensively, depending on heat conductivity of the surrounding rocks and recharge rates. However, this topic must remain largely speculative here, though not outside the bounds of feasibility.

The proportion of the flow intercepted, as a parameter, could be applied to geothermal and HDR sources, although data is lacking in this study.

The efficiency of conversion -as related to impacts could also be a relevant parameter for geothermal. Some of the lower temperature and enthalpy (total heat content of the system) geothermal developments have lower conversion efficiencies, due to the Second Law of Thermodynamics limitations of thermal energy conversion from lower temperature resources. This can result in the requirement for more plant equipment, such as condensers, piping per unit of electricity produced (Brown 1996).

The number of energy conversions is four. Firstly hot steam or water under pressure, which for the lower temperature and enthalpy developments may require "flashing over" to steam, the heat being passed to a heat exchanger. Hot dry steam of a quality to turn turbines directly, is rare except in the highest temperature geothermal regions (Brown 1996). Secondly the steam is converted to rotational shaft power and thirdly to electrical form in the generator. A fourth stage is required, re-injecting condensed steam into the borehole preventing the aquifer running dry, and since the minerals in solution and chemicals such as CO_2, HCO_3, H_2S and dissolved salts, are highly corrosive and potentially polluting (Brown 1996).

It is tentatively suggested therefore that the hypothesis parameters for evaluating the impacts of renewable energy sources could be applied meaningfully to geothermal energy too.

A.2. 5 Conclusions to appendix 2.

The parameters identified in the hypothesis could be applied to the lower power flux density sources of renewable energy to help identify, analyse and explain environmental impacts. The lower power flux densities can result in greater land use per unit of energy, as can be seen especially in the case of solar power stations and biomass production. Higher power flux densities, as achieved by larger wind turbines and windier locations, or areas of high solar energy, e.g. above 1600kWh /m^2 pa, or biomass production from more productive biomes and species, conversely appear to use less land area. However, the sensitivities of other impacts to variations in power flux density are perhaps lower, given the smaller variations in power flux densities, e.g. solar energy fluxes vary by a factor of only ~2.5 - 3 (Boyle 1996) across the globe.

Low power flux density could result in compatibility with human habitation, since solar PV can be incorporated into dwellings. Where the energy conversion technologies are direct, i.e. involving only one conversion, and with little further concentration, e.g. photovoltaics, impacts could be minimised, with the result that panels can be placed on roofs of buildings which are already occupying land. Solar PV generation need then require little extra land. Biomass sources from wastes streams can also result in minimal further land use, too.

The concept of proportion of energy flow extracted is harder to define for the low power flux sources, although still apparently valid, because the flow itself is much less defined than those of e.g. water flowing in a river. The air currents of winds occur as broad flows, while those of solar are universal across the globe, though varying by latitude, and diurnally, seasonally and climatically. Biomass energy depends crucially on the productivity of biomes, particularly the availability of water and temperature. As a result of this difficulty in defining these flows, the notion of local flows has been proposed, and so the proportion of energy flux intercepted and extracted could then be determined locally. This would appear to apply to wind or central solar power stations or even biomass.

The nature of wind energy generally as broad and high air currents, together with the Betz limit and the need to disperse turbines, could result in only a small proportion of the energy being extracted, unless the flow is of limited cross section and volume. Solar energy conversion technologies cannot yet achieve very much more than ~30-40% maximum efficiencies and the proportion extractable is limited by this, although the proportion intercepted is often about ~33% at the plant, for central solar plants, whether PV or Concentrating Solar Thermal type.

The parameter efficiency of conversion could be applied to these renewable energy sources to help determine their environmental impacts, particularly in the case of biomass where very low overall energy conversion efficiency is often found from solar to biomass energy end use, e.g. about 0.5% (Boyle 1996) to 2% (Tan et al 2009). As yet solar electric conversion rarely achieves efficiencies of 30% and generally ~<15% is more likely for CSP or PV. Wind energy conversion efficiency is limited by the theoretical Betz limit turbine coefficient-which would need to be optimised for the range of wind speeds found at the site.

The number of energy conversions as a parameter of impact might be relevant for solar, biomass and wind, though maybe to a lesser degree. For biomass, where a large number of conversions are carried out this parameter could also be informative of impacts.

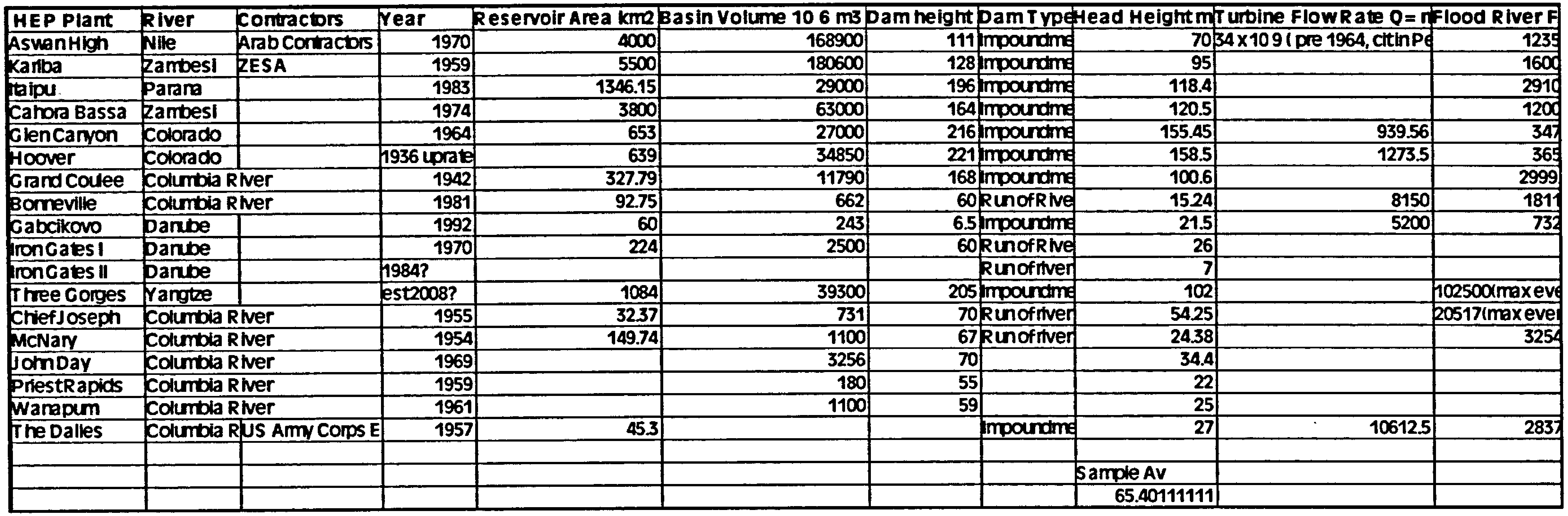
Appendices 3

A.3 Spreadsheets and Data Sources

The HEP Scheme reservoir and dam parameters spreadsheet is shown below in figures A.3.1.1 to A.3.1.5. This shows the full set of parameters used as well as the data values. The river gradient profile and modeled TSP spreadsheets are also shown below in section A.3 2.1.

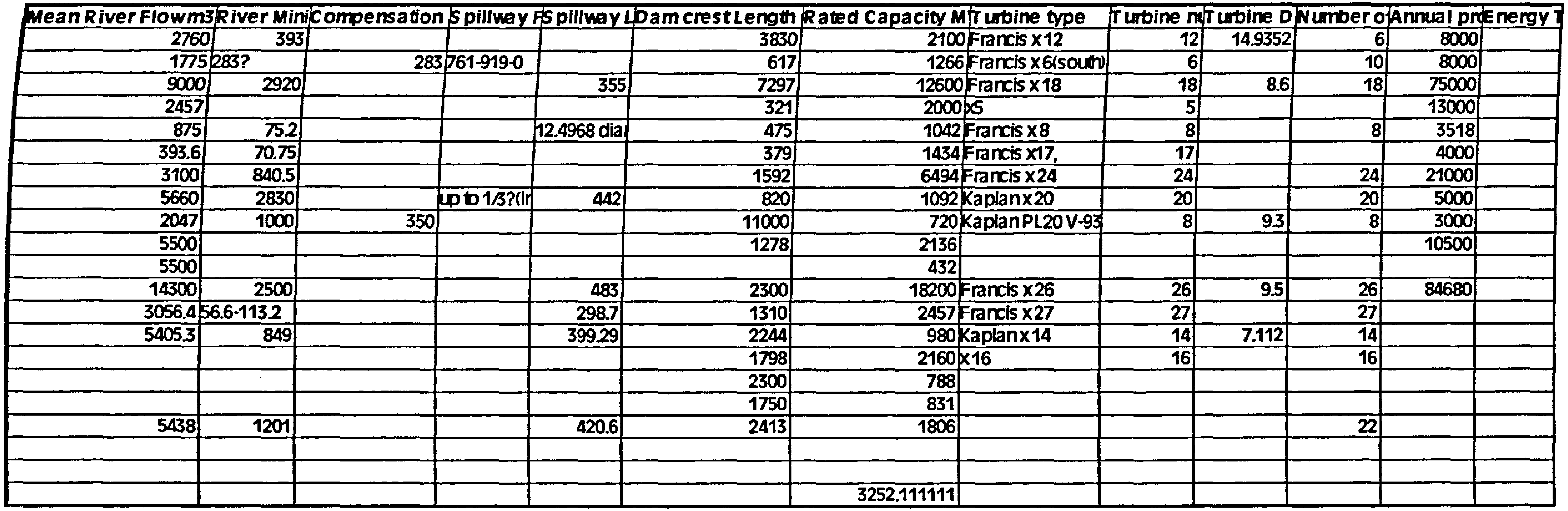
Data Sources

Data for the HEP scheme reservoirs and dam parameters were obtained from either sources listed in the references, or from additional sources listed below in section A.3.1.2 .



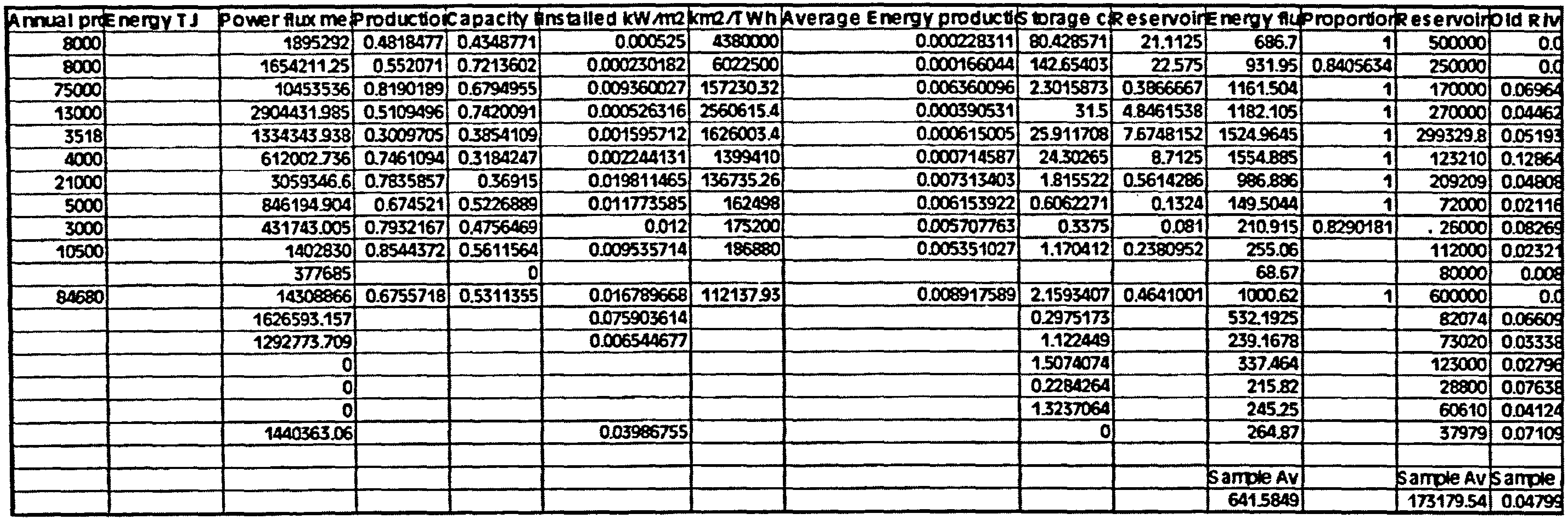
HEP Plant	River	Contractors	Year	Reservoir Area km2	Basin Volume 10 6 m3	Dam height	Dam Type	Head Height m	Turbine Flow Rate Q= m	Flood River F
Aswan High	Nile	Arab Contractors	1970	4000	168900	111	Impoundme	70	34 x 10 9 (pre 1964, cit in Pe	1235
Kariba	Zambesi	ZESA	1959	5500	180600	128	Impoundme	95		1600
Itaipu	Parana		1983	1346.15	29000	196	Impoundme	118.4		2910
Cahora Bassa	Zambesi		1974	3800	63000	164	Impoundme	120.5		1200
Glen Canyon	Colorado		1964	653	27000	216	Impoundme	155.45	939.56	347
Hoover	Colorado		1936 uprate	639	34850	221	Impoundme	158.5	1273.5	365
Grand Coulee	Columbia River		1942	327.79	11790	168	Impoundme	100.6		2999
Bonneville	Columbia River		1981	92.75	662	60	Run of Rive	15.24	8150	1811
Gabcikovo	Danube		1992	60	243	6.5	Impoundme	21.5	5200	732
Iron Gates I	Danube		1970	224	2500	60	Run of Rive	26		
Iron Gates II	Danube		1984?				Run of river	7		
Three Gorges	Yangtze		est2008?	1084	39300	205	Impoundme	102		102500(max eve
Chief Joseph	Columbia River		1955	32.37	731	70	Run of river	54.25		20517(max ever
McNary	Columbia River		1954	149.74	1100	67	Run of river	24.38		3254
John Day	Columbia River		1969		3256	70		34.4		
Priest Rapids	Columbia River		1959		180	55		22		
Wanapum	Columbia River		1961		1100	59		25		
The Dalles	Columbia R	US Army Corps E	1957	45.3			Impoundme	27	10612.5	2837
								Sample Av		
								65.40111111		

Figure A.3.1.1 HEP Scheme Reservoir and Dam parameters spreadsheet.



Mean River Flowm3	River Mini	Compensation	Spillway F	Spillway L	Dam crest Length	Rated Capacity M	Turbine type	Turbine n	Turbine D	Number o	Annual pr	Energy T
2760	393				3830	2100	Francis x12	12	14.9352	6	8000	
1775	283?	283	761-919-0		617	1266	Francis x6(south)	6		10	8000	
9000	2920			355	7297	12600	Francis x18	18	8.6	18	75000	
2457					321	2000	x5	5			13000	
875	75.2			12.4968 dia	475	1042	Francis x8	8		8	3518	
393.6	70.75				379	1434	Francis x17,	17			4000	
3100	840.5				1592	6494	Francis x24	24		24	21000	
5660	2830		up to 1/3?(ir	442	820	1092	Kaplan x20	20		20	5000	
2047	1000	350			11000	720	Kaplan PL20 V-93	8	9.3	8	3000	
5500					1278	2136					10500	
5500						432						
14300	2500			483	2300	18200	Francis x26	26	9.5	26	84680	
3056.4	56.6-113.2			298.7	1310	2457	Francis x27	27		27		
5405.3	849			399.29	2244	980	Kaplan x14	14	7.112	14		
					1798	2160	x16	16		16		
					2300	788						
					1750	831						
5438	1201			420.6	2413	1806				22		
						3252.111111						

Figure A.3.1.2 HEP Scheme Reservoir and Dam parameters spreadsheet.

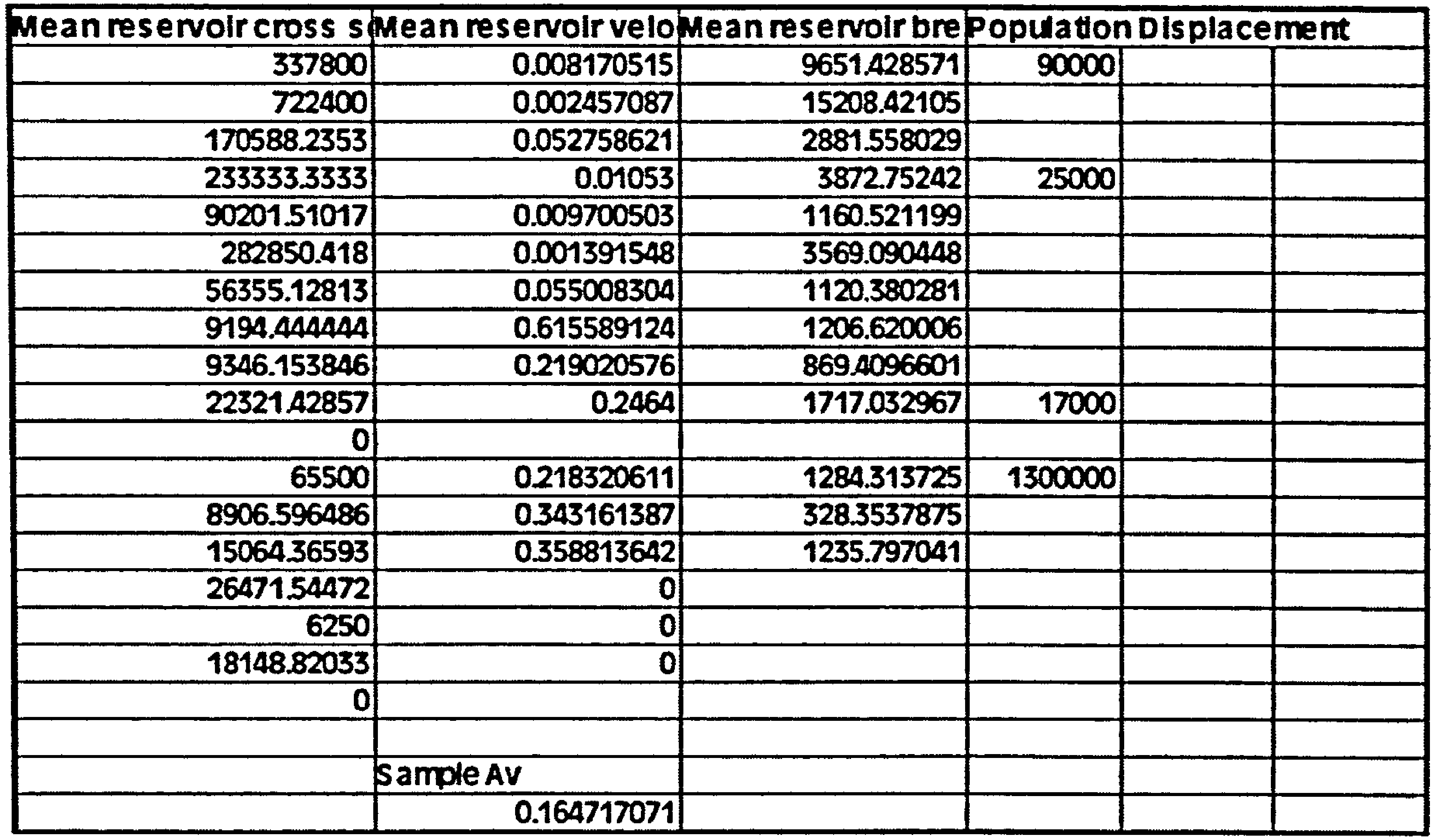


Annual pr	Energy TJ	Power flux me	Productio	Capacity f	Installed kW/m2	km2/TWh	Average Energy producti	Storage c	Reservoir	Energy flu	Proportion	Reservoir	Old Riv
8000		1895292	0.4818477	0.4348771	0.000525	4380000	0.000228311	80.428571	21.1125	686.7	1	500000	0.0
8000		1654211.25	0.552071	0.7213602	0.000230182	6022500	0.000166044	142.65403	22.575	931.95	0.8405634	250000	0.0
75000		10453536	0.8190189	0.6794955	0.009360027	157230.32	0.006360096	2.3015873	0.3866667	1161.504	1	170000	0.06964
13000		2904431.985	0.5109496	0.7420091	0.000526316	2560615.4	0.000390531	31.5	4.8461538	1182.105	1	270000	0.04462
3518		1334343.938	0.3009705	0.3854109	0.001595712	1626003.4	0.000615005	25.911708	7.6748152	1524.9645	1	299329.8	0.05193
4000		612002.736	0.7461094	0.3184247	0.002244131	1399410	0.000714587	24.30265	8.7125	1554.885	1	123210	0.12864
21000		3059346.6	0.7835857	0.36915	0.019811465	136735.26	0.007313403	1.815522	0.5614286	986.886	1	209209	0.04808
5000		846194.904	0.674521	0.5226889	0.011773585	162498	0.006153922	0.6062271	0.1324	149.5044	1	72000	0.02116
3000		431743.005	0.7932167	0.4756469	0.012	175200	0.005707763	0.3375	0.081	210.915	0.8290181	. 26000	0.08269
10500		1402830	0.8544372	0.5611564	0.009535714	186880	0.005351027	1.170412	0.2380952	255.06		112000	0.02321
		377685		0						68.67		80000	0.008
84680		14308866	0.6755718	0.5311355	0.016789668	112137.93	0.008917589	2.1593407	0.4641001	1000.62	1	600000	0.0
		1626593.157			0.075903614			0.2975173		532.1925		82074	0.06609
		1292773.709			0.006544677			1.122449		239.1678		73020	0.03338
		0						1.5074074		337.464		123000	0.02796
		0						0.2284264		215.82		28800	0.07638
		0						1.3237064		245.25		60610	0.04124
		1440363.06			0.03986755			0		264.87		37979	0.07109
										Sample Av		Sample Av	Sample
										641.5849		173179.54	0.04799

Figure A.3 1.3 HEP Scheme Reservoir and Dam parameters spreadsheet.

Reservoir	Old River	River Gra	Average V	Catchmen	Sediment	% efficien	% effic Brov	% effic Chu	Streampo	Total Stre	Mean reservoir cross s	Mean reservoir velo	Mean reser
500000	0.014		1.9405014	3612000	125	98.129456	91.34865	99.99251	379058.4	1895292	337800	0.008170515	965
250000	0.038		3.2263597	663840		98.699912	98.398243	99.958591	661684.5	1654211.3	722400	0.002457087	152
170000	0.0696471		0.102176	2172009	45	85.398483	75.092771	99.999939	6149138.8	10453536	170588.2353	0.052758621	288
270000	0.0446296		0.8130716			96.525585		99.997565	1075715.6	2904432	233333.3333	0.01053	38
299329.8	0.0519327		0.9784736			96.953273		99.996819	445777.18	1334343.9	90201.51017	0.009700503	116
123210	0.1286422		2.8076378			98.563794		99.936372	496715.15	612002.74	282850.418	0.001391548	356
209209	0.0480859		0.1205995			86.931148		99.999931	1462339.9	3059346.6	56355.12813	0.055008304	112
72000	0.0211667		0.0037088			17.809519		100	1175270.7	846194.9	9194.444444	0.615589124	120
26000	0.0826923	0.43	0.0037643	131486		18.139792	29.444012	99.999999	8634860.1	431743.01	9346.153846	0.219020576	869
112000	0.0232143	0.04	0.0144135		20	52.299445		99.999998	2158200	1402830	22321.42857	0.2464	171
80000	0.00875		0								0		
600000	0.017		0.0871465		541.16	83.775033		99.999987	2384811	14308866	65500	0.218320611	128
82074	0.0660989		0.007584			35.701082		99.999999	1981861.7	1626593.2	8906.596486	0.343161387	328
73020	0.0333881		0.0064531			31.435817		99.999999	1770437.8	1292773.7	15064.36593	0.358813642	123
123000	0.0279675								0	0	26471.54472	0	
28800	0.0763889								0	0	6250	0	
60610	0.0412473								0	0	18148.82033	0	
37979	0.0710919		0	656568			0	100	3792525	1440363.1	0		
Sample Av	Sample Av		Sample Av									Sample Av	
173179.54	0.0479968		0.7778377									0.164717071	

Figure A.3.1.4 HEP Scheme Reservoir and Dam parameters spreadsheet.



Mean reservoir cross s	Mean reservoir velo	Mean reservoir bre	Population	Displacement	
337800	0.008170515	9651.428571	90000		
722400	0.002457087	15208.42105			
170588.2353	0.052758621	2881.558029			
233333.3333	0.01053	3872.75242	25000		
90201.51017	0.009700503	1160.521199			
282850.418	0.001391548	3569.090448			
56355.12813	0.055008304	1120.380281			
9194.444444	0.615589124	1206.620006			
9346.153846	0.219020576	869.4096601			
22321.42857	0.2464	1717.032967	17000		
0					
65500	0.218320611	1284.313725	1300000		
8906.596486	0.343161387	328.3537875			
15064.36593	0.358813642	1235.797041			
26471.54472	0				
6250	0				
18148.82033	0				
0					
	Sample Av				
	0.164717071				

Figure A.3.1.5 HEP Scheme Reservoir and Dam parameters spreadsheet.

A.3 1.2 HEP Reservoir and Dam Parameters Data Sources

A.3. 1.2.1 Aswan High

Nile

Flow Rates

Water Flow figures from UNH GRDC Aswan Dam Flow measuring station website, (www.grdc.sr.unh.edu/html/Polygons/P1362600.html) for period year 1869 to end 1984.

.

Catchment Area 3612000 km^2 from (online UNH GRDC resources 2002)UNH GRDC Aswan Dam Flow measuring station website, (www.grdc.sr.unh.edu/html/Polygons/

Population Displacement Over 90,000 Nubians reportedly displaced, with Egyptian Nubians relocated to 28 miles distance, but Sudanese Nubians relocated to 370 miles away from their homes, (Freeservers Geography 'The Aswan Dam').

A.3. 1.2 .2 Kariba Dam

River Zambesi

Figures from International Water Power & Dam Construction Year Book '96,

Figure for reservoir area from Kariba Dam Case Study, Final Draft, WCD, Sept 2000,

Working Paper for the World Commission on Dams, from

http://www.damsreport.org/docs/kbase/studies/drafts/zzdraftx.pdf (30/210/02).

Minimum Flow Rate Requirement of 283m³/s set in 1964 (?) by Zambesi River Authority, (cit above). Power station turbine type from Zambezi River Authority, Technical Data Web Site, http://www.zaroho.org.zm/kariba_technical.htm (14/01/03).

Power output ~8000 GWh pa, reservoir length 250km, inflow rates 57-35 x 10^9 m^3 per year, turbine flow 18-30 x 10^9 m^3 per year, spillway flow rates 29 x 10^9 m^3 per year, peak flood rate discharge 16000 m^3/s, minimum discharge rate 21 x 10^9 m^3 per year, (Goguel & Mpala, 1992).

A.3. 1.2.3 Cabora Bassa Dam

River Zambezi

Installed capacity currently 800MW, designed capacity is 2000MW.(or even 4000MW?)

Reservoir area 2700 -3000 km2 figure from Fisheries Article .. 3800 cited(?)

http://www.sifar.org/SIFR%20study/149%20Fisheries%20&%20Aquac.%20Research%20Capabilities%20in%20Africa-Part%202html (8/11/02)

-

Production cited as 13,000 GWhr (Sebitosi & da Graca 2008) source cited World Bank.

Also 380,000 hectares reservoir area is cited in Bujagali Hydro Project Technical Resources table. Head height figures from private communication, with Henrique Silva, Hydro Resources & Environment Manager, typical reservoir level 323m, downstream river level 203m.

Reservoir level, 320-326m,downstream level, 201.45-203.28m. (private communication Henrique Silva, Hidroelectric De Cahora Bassa (HCB) Mozambique, 08/01/03).

http://www.bujagali.com/technical_resources/table.html (11/11/02)

Annual mean river flow from estimated 77.5km^3 inflow into Lake Cahorra, cited in FAO Documment on Zambezi Basin. http://www.fao.org/docrep/W4347E/w4347e0o.htm (accessed 8/11/02)

Flood flow from US Geological Survey USAID (Zambesi Basin Flood Risk Map http:/.../8728FA9A956F024485256A730051B393?Opendocumen (accessed 11/11/02).

Population displacement 25,000, cited by Petts 1984, from Jackson (1975, cit in Petts 1984).

Catchment Area 663840 km^2 (on-line resources Zambezi River Authority 2003)

A.3. 1.2.4 Itaipu

Parana

Power output 75 TWh per annum, from http://www.solar.coppe.ufrj.br/itaipu.html. (accessed 19/07/04).

Catchment Area 2172009 km^2 (on-line UNGRDC resources 2002, Corrientes measuring station 2002)

Turbine diameter data from Moraes, J., Rodriguez, J., Gummer, J., del Brenna, F., 'Turbines for Itaipu Pt 2', Water Power and Dam Construction, January 1982, p28-33.

A.3. 1.2.5 Hoover Dam

River Colorado

Head Height 590-420ft, 510-530 mean, and annual production figures (4bn kWh [10.3-2.6]), also turbine max flow rate (45,000ft3/s) from Hoover Dam website 'Power Development' http://www.hooverdam.usbr.gov/History/powerfaq.html (accessed 15/11/02)

River Flow rate figure from below Hoover Dam, 13900 ft /s mean, from US NASQAN Programme http://water.usgs.gov/nasqan/progdocs/factsheets/clrdfact/clrdfact.htm (accessed 17/7/02, also 23/11/04).

River Flood rate figure of ~129,000 cubic ft/s, or 3653 m^3/s, of flow below Hoover Dam, pre dam flow in ~1922, cited in http://www.usbr.gov/lc/region/g4000/tbhd.xls (accessed 23/11/04).

Minimum Flow rate of ~2500 cubic ft /s, or 70.75$m^3/$ s, cited in US Bureau of Reclamation, 'Flow below Hoover Dam' graph, covering period 1905-2005; also shows exceptional low flow in 1993, of 14 $m^3/$ s, but normal flow minima are of ~ 70-85 $m^3/$ s . http://www.usbr.gov/lc/region/g4000/tbhd.xls (accessed 23/11/04).

Lake Mead dam length measured as 123.21 km from map, http://www.nps.gov/lame/lmnra.pdf (accessed 25/11/04).

A.3. 1.2.6 Glen Canyon

River Colorado

Head height from (US) National Bureau of Reclamation hydropower Program, http://www.usbr.gov/power/data/sites/glencany/glencany.htm (accessed 11/11/02)

Maximum Turbine Flow rate 33200 cu ft /s, or 939.56 m^3/s, cited in http://walrus.wr.usgs.gov/grandcan/dam.html (accessed 30/10/04).

Flood Flows of 122,739 cfs, or 3473 m^3/s are cited for 'Inflow', presumably including all tributaries, for 1/7/1983., http://www.usbr.gov/uc/crsp/download/cubic%20feet%20per%20second%20(cfs)-110054098 1301.1st (accessed on 15/11/04).

Flood Flows of ~100,000 cfs, or 2830 m^3/s, are cited for 1983 spring flows, and 40,000 cfs, & 50,000 cfs flows maintained for about a month in 1984, '5 and '6, cited http://walrus.wr.usgs.gov/grandcan/floodflows.html.

Mean Flows of 30,900 cu ft/s or 875 m^3/s are cited for Lees Ferry monitoring station, just below Glen Canyon Dam, (recording period 1895-2004).

http://water.usgs.gov/nasqan/progdocs/factsheets/clrdfact/clrdfact.htm (accessed 23/11/04).

Average annual electricity generation 3518,296,940kWh, or 3518 GWh generated in 2003, from http://www.usbr.gov/power/data/site/glencany.html (accessed on 1/11/04). Total rating of power plant 1.296 GW, previously 1024 GW, uprated 1984 and 1997. Source above cit.

Lake Powell reservoir length 186 miles or 299.3298 km, cit in http://www.powellguide.comlakepowell.html (accessed 2/11/04)

A.3. 1.2.7 Bonneville Dam

Columbia River

Turbine figures from http:/www.nwp.usace.army.mil/hdc/projects/bonneville.htm (accessed 24/10/02).

Power house and turbine flow figures from http:/www.cbr.washington.edu/crisp/hydro/bon.html (accessed 24/10/02)

Flow rate figures from 'Recorded Outflow and Spill Rates 1998, from http://www.nwd-wc.usace.army.mil/TMT/1998/curre.../BON.htm (accessed 24/10/02), mean flow rate estimated from 1998 flow data above cit, at ~ 5660 m^3/s.

Reservoir Length figures and total annual production from 'Bonneville dam celebrates 50 years', Water Power and Dam Construction', September 1987.

Reservoir surface area figures from Fish Mortality Models, School of Aquatic and Fishery Sciences, University of Washington, Wa, USA, at http://www.cbr.washington.edu/crisp/models/crisp1manual/theory16/TCVchp25a.html (

A.3.1.2.8 Grand Coulee

Columbia River

Figures from International Water Power & Dam Construction Year Book '96,

Turbine figures

Flow rate figures from http://www.usbr.gov/power/data/sites/grandcou/grandcou.htm (accessed 29/10/02)

Lake Roosevelt reservoir area cited as 81,000 acres, or 327.79 km^2, http://www.travel-in-wa.com/travel/roosevelt.html, (accessed on 1/12/04).

Average flow rate discharge of 3100 m^3/s cited in source. Mean flow rate figure from USGS website data, at US/Canadian border, i.e. reservoir entrance, of 66,110 cubic ft/s, or 1870.9 m^3/s. http://waterdata.usgs.gov/nwis/uv?12399500 (accessed 30/11/04).

Minimum flow rate figure from USGS website data, at US/Canadian border, i.e. reservoir entrance, of 29700 cubic ft/s, or 840.5 m^3/s, daily mean flow over 65 years, http://waterdata.usgs.gov/nwis/uv?12399500 (accessed 30/11/04).

Maximum flow rate figure of 106,000 cubic ft/s or 2999.8 m^3/s, at US/Canadian border, ie reservoir entrance, from USGS website data.

Reservoir elevation 1200ft above NGVD, or 365.76m.

http://waterdata.usgs.gov/nwis/uv?12399500 (accessed 30/11/04).

River Mile 745 above confluence (http://waterdata.usgs.gov/nwis/uv?12399500, accessed 30/11/04).

Average output figures from Bureau of Reclamation

http://www.usbr.gov/power/data/sites/grandcou/grandcou.htm (accessed 29/10/02)

A.3. 1.2.9 Gabickovo

River Danube

Figures taken from Lovenc & Santo (1986)

Turbine designed for maximum flow of 5200 m^3/s, as is the canal, (leat).

Flood flow rate cited is designed for 10,000 year event, at 15,000 m^3/s.

Low flow rate 1000 m^3/s cited from Gabcikovo Part of the Hydroelectric Power Review Environmental Impact , Faculty of Natural Sciences Comenius University Bratislava, Slovakia, 'River Morphology' Jana Topolska & Jelika Klucovska, Ground Water Consulting Ltd, Bratislava. 1995.

'Ecological Flow', (i.e. compensation flow?) cited as $50m^3/s$ in winter and up to $200m^3/s$ in growing season, in 1977 Treaty, which specifies exact flows, (cited in 'Gabcikovo-Nagymaros: a review of its significance and impacts', (Liska 1993).
Also in Liska (1993), dam crest length 11km cited for Temporary solution (to scheme) on Slovakian territory.

Head 16-21.5m variable.

Continuous Operation in an average year would produce 2980 GWh per year.

Continuous Operation at maximum flow would produce 6307 GWh per year.

Continuous operation in an average year is about 0.47 of max possible, ie flood.

Flow Rates: Figures taken from UNH GRDC Station Information - Bratislava

www.grdc.sr.unh.edu/html/Polygons/P6142200 (accessed 22/10/02)

Bratislava Station

Flow Rate Mean Discharge 2047 m^3/s

Min. Discharge 633 m^3/s

Max Discharge 7324 m^3/s

Catchment Area 131486 km^2

Figures from UNH GRDC Station Information -Nagymaros

www.grdc.sr.unh.edu/html/Polygons/P6442500 (accessed 22/10/02)

Nagymaros Station

Flow Rate Mean Discharge 2346 m^3/s

Min. Discharge 628 m^3/s

Max Discharge 7056 m^3/s

A.3. 1.2.10 Iron Gates I & II

River Danube

Figures (installed capacity, total head head height, total reservoir volume, reservoir lengths, annual average output, sediment trapped) from Joint Danube Survey http://www.icpdr.org/icpdr-pages/dams structures.htm (19/06/06), and International Water Power and Dam Construction year Book 1996}. Some discrepancy exists in the reservoir volume which is cited in Water Power and Dam Construction as $2400 \times 10^6 m^3$,

though in the Joint Danube Survey (2005), Ch5 the volume is cited as $3.2 \times 10^9 m^3$. Also whereas the dam effects on flow and depth reach back 270km to Belgrade, the "reservoir" in effect is only 85km long , if deduced from the gradient data given by the JDS, 0.04%, and the head height of 34m. However, this is presumed to be the total head height of I & II schemes, as other sources indicate a head height of 26m for the Iron Gates I scheme. Reservoir length quoted as 112km (Cioranescu, 1980). Also annual mean output cited as 10500 GWh in same source, but elsewhere as 13140 GWh. The higher figure may include the Iron Gates II scheme.

Flow Rate: Mean Discharge 5500 m^3/s

A.3. 1.2.11 Three Gorges

River Yangtze

Figures (head height, installed capacity, turbine diameter, reservoir volume) Qing (1994).

Figures for reservoir area, annual average output, (Jiazhu,1994). Average Annual Flow derived from figure given for annual volume of water flowing in Yangtze of 453 billion m^3 at Yichang (Qing 1994 p219).

Average Flow rate at Three Gorges site 14300 m^3 / s, from (Yonfu, 1994).

Designed for 100 Year Flood Flow 83700 m^3 / s, (Freer, 2001), with max spillway flood flow of 102500 m^3 / s, and 20 year flood of 72300 m^3 / s. 'Average' flood flow 35000 m^3 / s, (Freer 2001).Max spillway flood flow cited as 116000 m^3 / s in Greeman (1996).

Flood Control strategy is to open bottom gates and lower the reservoir during summer flood season. 22.2 x 10^9 m^3 out of reservoir capacity of 39 x 10^9 m^3 is available for flood control, which is only 4.3% of yearly runoff at the dam (Freer 2001).

Water residence time is cited as 2 months in (Greeman 1999).

Average sediment Load is cited as 1.2kg per m^3, ('The Three Gorges Project on the Yangtze River in China', (Freer, 2001), and annual silt sediment load is calculated at 541.16 million tons, on basis of average flow of 14300 m^3/s.

Permanent gates in spillway section 23 bottom outlet gates 7 x 9 m at 90m inlet level, and 22 surface sluice gates 8m wide with a cill level at 158m. Also 22 bottom outlet gates in the base of the dam which will be used during the construction phase.

A.3. 1.2.12 Dalles Dam

Columbia River

Flow rates, from GRDC Station Information, The Dalles Station, www.grdc.sr.unh.edu/html/Polygons/P4115200.html (accessed 30/10/ 02). Head height from

lock height from US Army Corps of Engineers, Portland District, 'The Dalles/ John Day / Willow Creek Project', www.nwp.usace.army.mil/op/D/standard/td/td.htm (accessed 08/ 06 /04).

Reservoir surface area and length from Fish Mortality Models, School of Aquatic and Fishery Sciences, University of Washington, Wa, USA, at http://www.cbr.washington.edu/crisp/models/crisp1manual/theory16/TCVchp25a.html

Catchment Area: 656568 km^2 (on-line resources UN GRDC 2002)

A.3. 1.2.13 John Day

Columbia River

Figures from International Water Power & Dam Construction Year Book '96,

Reservoir surface area and length from Fish Mortality Models, School of Aquatic and Fishery Sciences, University of Washington, Wa, USA, at http://www.cbr.washington.edu/crisp/models/crisp1manual/theory16/TCVchp25a.html

A.3. 1.2.14 McNary

Columbia River

Figures from International Water Power & Dam Construction Year Book '96, Reservoir surface area and length from Fish Mortality Models, School of Aquatic and Fishery Sciences, University of Washington, Wa, USA, at http://www.cbr.washington.edu/crisp/models/crisp1manual/theory16/TCVchp25a.html

Normal operating pool height:109m, and Reservoir area from McNary Master Plan, supporting Data, http://www.nww.usace.army.mil/plamming/er/mcnary/sptdata/mcnspt5.htm accessed 18/10/07.

A.3. 1.2.15 Priest Rapids

Columbia River

Figures from International Water Power & Dam Construction Year Book '96,

Reservoir surface area and length from Fish Mortality Models, School of Aquatic and Fishery Sciences, University of Washington, Wa, USA, at http://www.cbr.washington.edu/crisp/models/crisp1manual/theory16/TCVchp25a.html

A.3. 1.2.16 Wanapum

Columbia River

Figures from International Water Power & Dam Construction Year Book '96,

Reservoir surface area and length from Fish Mortality Models, School of Aquatic and Fishery Sciences, University of Washington, Wa, USA, at http://www.cbr.washington.edu/crisp/models/crisp1manual/theory16/TCVchp25a.html

A.3. 1.2.17 Rock Island Dam

Columbia River

Flow rates of 3305 m3/s cited from article (accessed 4/11/07).

Average output of 2600 GWh per annum for past 10 years. (4/11/07).

A.3. 1.2.18 Chief Joseph

Columbia River

Figures from International Water Power & Dam Construction Year Book '96,

Mean annual flow rate of 108,000cfs or 3056.4 m^3/s from USACE site:

http://www.nws.usace.army.mil/PublicMenu/Menu.cfm?sitename=cjdam & pagename=hydropower#facts

Head height of 178ft or 54.25m, no of penstock units 27 -one for each generator, (plus two small ones for small generators for dam operation), from

http://www.nws.usace.army.mil/PublicMenu/Menu.cfm?sitename=cjdam & pagename=hydropower#facts

Spillway length of 980ft or 298.7m and reservoir length of 51 miles or 82km, from

http://www.cbr.washington.edu/crisp/hdro/chj.html .

Reservoir area of 8000 acres or 32375200 m^2 , 32.375 km^2, from USACE website

http://www.nws.usace.army.mil/PublicMenu.cfm?sitename=waterres&pagename=uppercolumbia

Reservoir area cited as 8400 acres on USACE Dam Details data site, (accessed 14/12/04).

Maximum flow rate 725000 cfs, or 20517.5 m^3/s, in 1894, cited in 'Chief Joseph Dam Dissolved Gas Abatement Project, Final Environmental Impact Statement', United States Army Corps of Engineers, June 2000. Also minimum flow rates of 2000-4000 cfs, or 56.6-113.2 m^3/s cited.

2nd Tranche of Dams

-Columbia River

Going upstream from the Bonneville Dam:

-The Dalles Dam, 2080MW constructed 1957, Federal Project, Oregon / Washington

-The John Day Dam, 2480 MW, constructed 1968, Federal Project, Oregon / Washington

-McNary Dam, 1120 MW or 980 MW cit (International Water Power and Dam construction Yearbook, 1996), constructed 1953, Federal Project, Oregon / Washington

-Priest Rapids Dam, 907 MW or 788 MW (Internat Water Power and Dam construction Yearbook, 1996), constructed 1961, Grant County, PUD.

-Wanapum Dam, 985 MW, constructed 1964, Grant County, PUD.

-Rock Island Dam, 660 MW constructed 1979, Chelan County, PUD

-Rocky Reach Dam, 1287 MW, constructed 1961, Chelan County, PUD.

-Wells Dam 840 MW, constructed 1967, Douglas County,

-Chief Joseph, 2614 MW, constructed 1955, Federal project, Washington.

-Grand Coulee Dam, 6494 MW or 7141 MW, constructed 1941, Federal Project, Washington

Further upstream though not included in this study:-

-Keenleyside Dam, No power production, British Columbia Canada.

-Revelstoke Dam, 1843 MW, constructed 1984, British Columbia, Canada.

-Mica Dam, 1736 MW, constructed 1976, British Columbia, Canada.

A.3. 2.1 River gradient profile and modeled TSP spreadsheets.

In order to apply TSP to river reaches downstream of the HEP plant, monthly average flow data from flow monitoring stations was sourced from the Ground Run-off Data Centre (GRDC), for as long periods as was available. It was then retabulated into a form so that this could be represented as a monthly hydrograph. From this the average flow rates per month over a specified period could be ascertained. This was carried out for a total of 34 flow stations on four rivers. Any longer term trends and changes could then be observed from the monthly hydrograph, and the data could be tested statistically.

The gradient profiles of the four rivers tested, had been plotted into a spreadsheet, an example of which is shown below, for the Danube below Nussdorf. This shows the river flow station, river kilometre from the mouth, elevation in metres, gradient, average flow rate, and the TSP as calculated from the formula:

$$TSP = \rho g Q S L,$$

where

ρ = density of water in kgs, (1000)

g = acceleration due to gravity, ($9.81 ms^{-2}$)

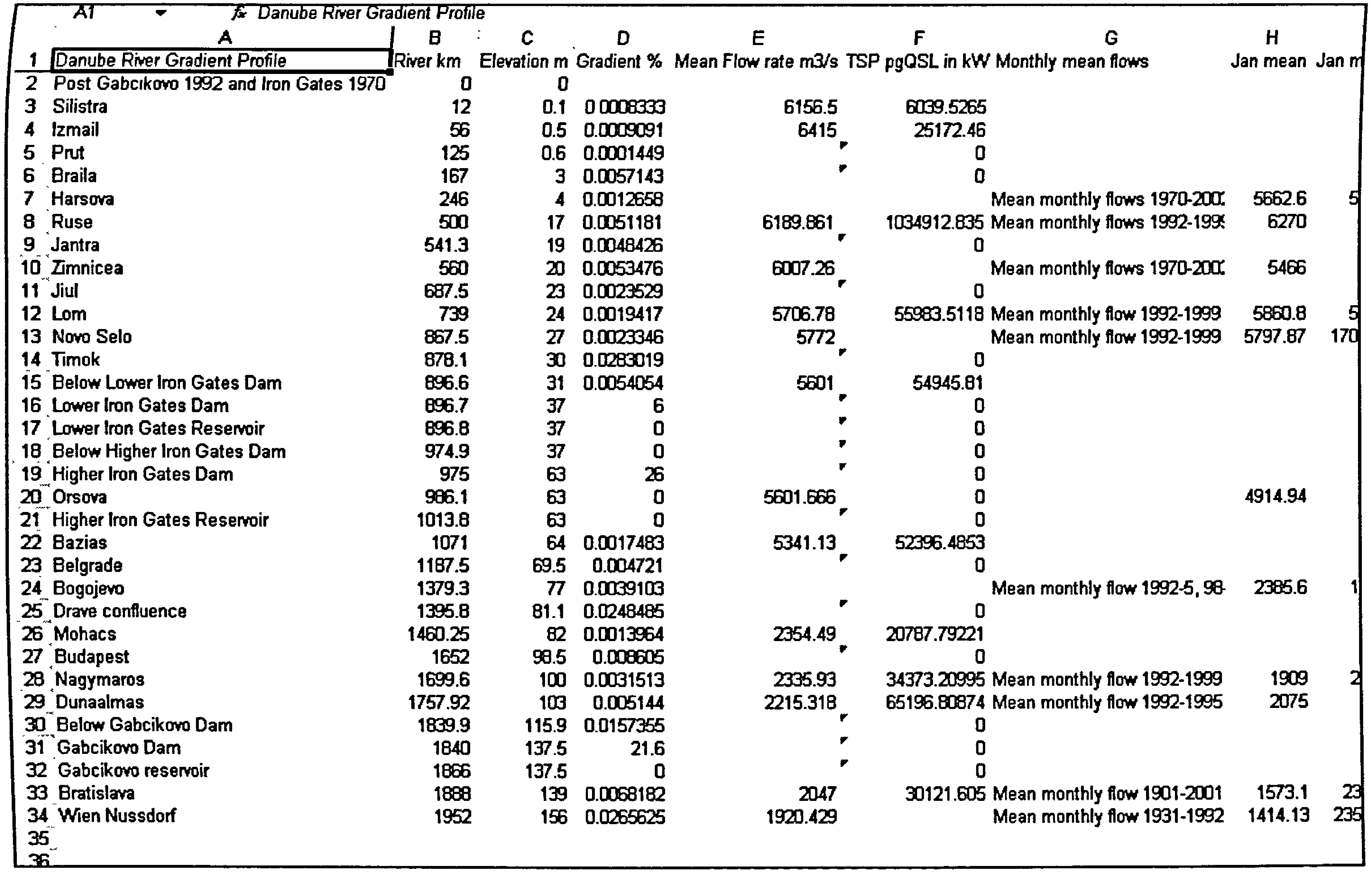
Q = flow rate (m^3/s),

S = slope, (height difference / horizontal distance)

L = length in metres

.The monthly mean flow rates were then plotted into this spreadsheet from the hydrographs and alongside the TSP was calculated. This was then carried out for periods before the construction of the HEP and dam in question, and then afterwards, subject to data availability.

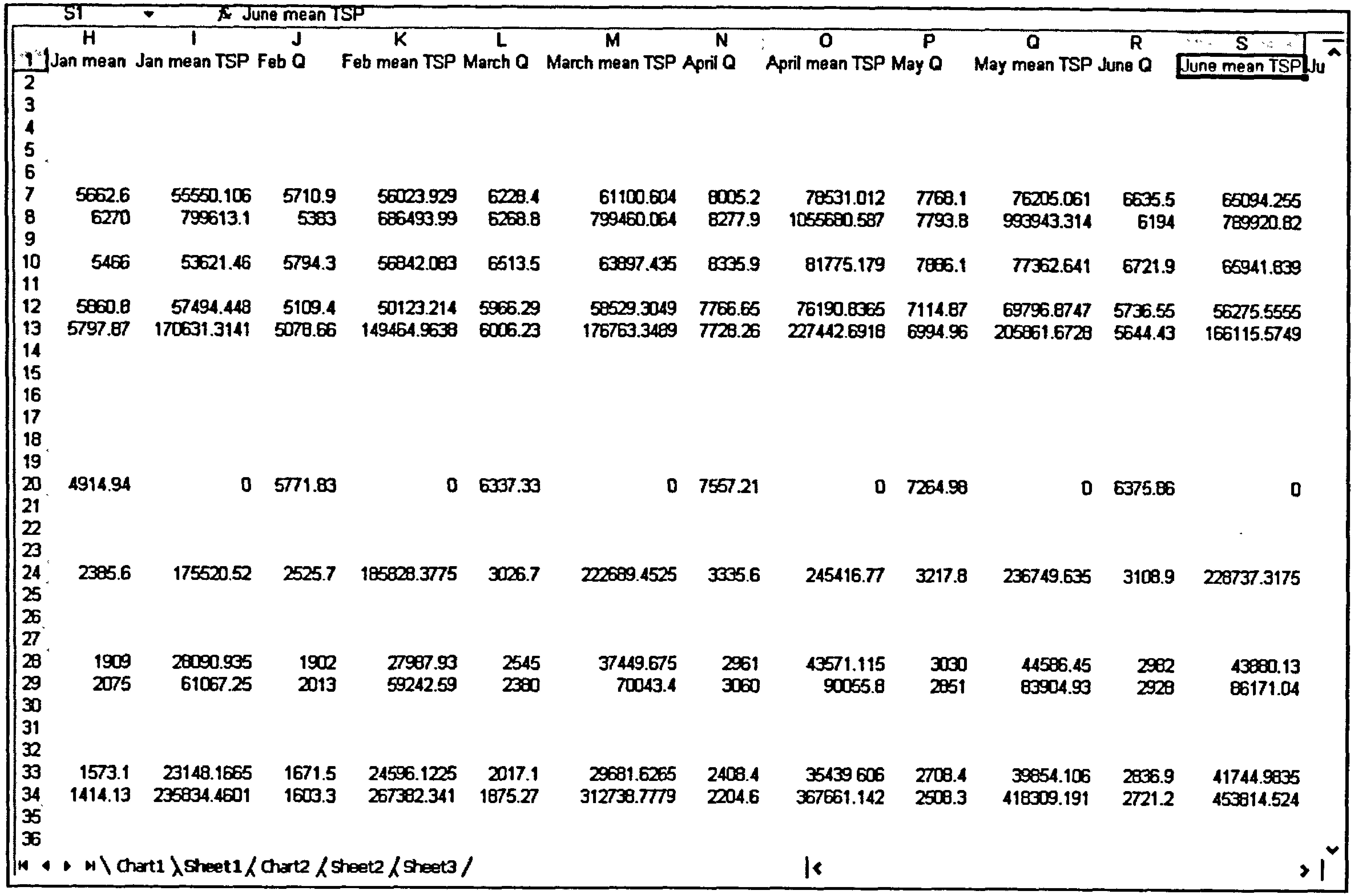
A.3. 2.1 Example Danube River Gradient Profile and monthly TSP spreadsheet.



A1 ▾ fx Danube River Gradient Profile

	A	B	C	D	E	F	G	H	
1	Danube River Gradient Profile	River km	Elevation m	Gradient %	Mean Flow rate m3/s	TSP pgQSL in kW	Monthly mean flows	Jan mean	Jan m
2	Post Gabcikovo 1992 and Iron Gates 1970	0	0						
3	Silistra	12	0.1	0 0008333	6156.5	6039.5265			
4	Izmail	56	0.5	0.0009091	6415	25172.46			
5	Prut	125	0.6	0.0001449		0			
6	Braila	167	3	0.0057143		0			
7	Harsova	246	4	0.0012658			Mean monthly flows 1970-200	5662.6	5
8	Ruse	500	17	0.0051181	6189.861	1034912.835	Mean monthly flows 1992-199	6270	
9	Jantra	541.3	19	0.0048426		0			
10	Zimnicea	560	20	0.0053476	6007.26		Mean monthly flows 1970-200	5466	
11	Jiul	687.5	23	0.0023529		0			
12	Lom	739	24	0.0019417	5706.78	55983.5118	Mean monthly flow 1992-1999	5860.8	5
13	Novo Selo	867.5	27	0.0023346	5772		Mean monthly flow 1992-1999	5797.87	170
14	Timok	878.1	30	0.0283019		0			
15	Below Lower Iron Gates Dam	896.6	31	0.0054054	5601	54945.81			
16	Lower Iron Gates Dam	896.7	37	6		0			
17	Lower Iron Gates Reservoir	896.8	37	0		0			
18	Below Higher Iron Gates Dam	974.9	37	0		0			
19	Higher Iron Gates Dam	975	63	26		0			
20	Orsova	986.1	63	0	5601.666	0		4914.94	
21	Higher Iron Gates Reservoir	1013.8	63	0		0			
22	Bazias	1071	64	0.0017483	5341.13	52396.4853			
23	Belgrade	1187.5	69.5	0.004721		0			
24	Bogojevo	1379.3	77	0.0039103			Mean monthly flow 1992-5, 98-	2385.6	1
25	Drave confluence	1395.8	81.1	0.0248485		0			
26	Mohacs	1460.25	82	0.0013964	2354.49	20787.79221			
27	Budapest	1652	98.5	0.008605		0			
28	Nagymaros	1699.6	100	0.0031513	2335.93	34373.20995	Mean monthly flow 1992-1999	1909	2
29	Dunaalmas	1757.92	103	0.005144	2215.318	65196.80874	Mean monthly flow 1992-1995	2075	
30	Below Gabcikovo Dam	1839.9	115.9	0.0157355		0			
31	Gabcikovo Dam	1840	137.5	21.6		0			
32	Gabcikovo reservoir	1866	137.5	0		0			
33	Bratislava	1888	139	0.0068182	2047	30121.605	Mean monthly flow 1901-2001	1573.1	23
34	Wien Nussdorf	1952	156	0.0265625	1920.429		Mean monthly flow 1931-1992	1414.13	235
35									
36									

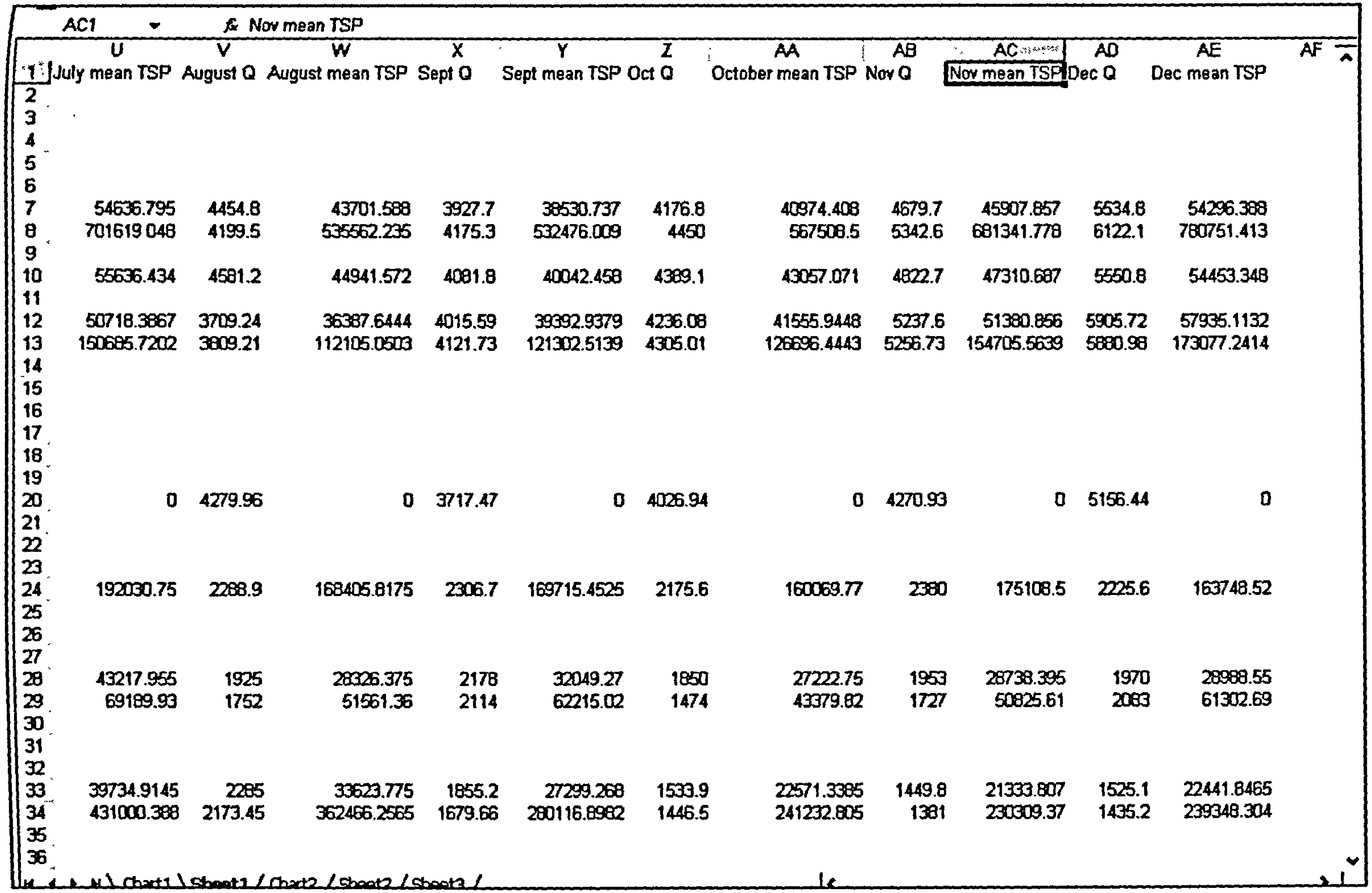
Figure A.3.2.1 Danube River Gradient Profile and monthly TSP spreadsheet, for periods post Iron Gates I HEP scheme, 1970-2000, and post Gabcikovo HEP scheme 1992-1999, as well as longer periods for upstream stations.



S1 June mean TSP

	H	I	J	K	L	M	N	O	P	Q	R	S
1	Jan mean	Jan mean TSP	Feb Q	Feb mean TSP	March Q	March mean TSP	April Q	April mean TSP	May Q	May mean TSP	June Q	June mean TSP
2												
3												
4												
5												
6												
7	5662.6	55550.106	5710.9	56023.929	6228.4	61100.604	8005.2	78531.012	7768.1	76205.061	6635.5	65094.255
8	6270	799613.1	5383	686493.99	6268.8	799460.064	8277.9	1055680.587	7793.8	993943.314	6194	789920.82
9												
10	5466	53621.46	5794.3	56842.083	6513.5	63897.435	8335.9	81775.179	7886.1	77362.641	6721.9	65941.839
11												
12	5860.8	57494.448	5109.4	50123.214	5966.29	58529.3049	7766.65	76190.8365	7114.87	69796.8747	5736.55	56275.5555
13	5797.87	170631.3141	5078.66	149464.9638	6006.23	176763.3489	7728.26	227442.6918	6994.96	205861.6728	5644.43	166115.5749
14												
15												
16												
17												
18												
19												
20	4914.94	0	5771.83	0	6337.33	0	7557.21	0	7264.98	0	6375.86	0
21												
22												
23												
24	2385.6	175520.52	2525.7	185828.3775	3026.7	222689.4525	3335.6	245416.77	3217.8	236749.635	3108.9	228737.3175
25												
26												
27												
28	1909	28090.935	1902	27987.93	2545	37449.675	2961	43571.115	3030	44586.45	2982	43880.13
29	2075	61067.25	2013	59242.59	2380	70043.4	3060	90055.8	2851	83904.93	2928	86171.04
30												
31												
32												
33	1573.1	23148.1665	1671.5	24596.1225	2017.1	29681.6265	2408.4	35439 606	2708.4	39854.106	2836.9	41744.9835
34	1414.13	235834.4601	1603.3	267382.341	1875.27	312738.7779	2204.6	367661.142	2508.3	418309.191	2721.2	453814.524
35												
36												

Figure A.3.2.2 Danube River Gradient Profile and monthly TSP spreadsheet, for periods post Iron Gates I HEP scheme, and post Gabcikovo HEP scheme, as well as longer periods for upstream stations.



	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF
1	July mean TSP	August Q	August mean TSP	Sept Q	Sept mean TSP	Oct Q	October mean TSP	Nov Q	Nov mean TSP	Dec Q	Dec mean TSP	
2												
3												
4												
5												
6												
7	54636.795	4454.8	43701.588	3927.7	38530.737	4176.8	40974.408	4679.7	45907.857	5534.8	54296.388	
8	701619 048	4199.5	535562.235	4175.3	532476.009	4450	567508.5	5342.6	681341.778	6122.1	780751.413	
9												
10	55636.434	4581.2	44941.572	4081.8	40042.458	4389.1	43057.071	4822.7	47310.687	5550.8	54453.348	
11												
12	50718.3867	3709.24	36387.6444	4015.59	39392.9379	4236.08	41555.9448	5237.6	51380.856	5905.72	57935.1132	
13	150685.7202	3809.21	112105.0503	4121.73	121302.5139	4305.01	126696.4443	5256.73	154705.5639	5880.98	173077.2414	
14												
15												
16												
17												
18												
19												
20	0	4279.96	0	3717.47	0	4026.94	0	4270.93	0	5156.44	0	
21												
22												
23												
24	192030.75	2288.9	168405.8175	2306.7	169715.4525	2175.6	160069.77	2380	175108.5	2225.6	163748.52	
25												
26												
27												
28	43217.955	1925	28326.375	2178	32049.27	1850	27222.75	1953	28738.395	1970	28988.55	
29	69189.93	1752	51561.36	2114	62215.02	1474	43379.82	1727	50825.61	2083	61302.69	
30												
31												
32												
33	39734.9145	2285	33623.775	1855.2	27299.268	1533.9	22571.3385	1449.8	21333.807	1525.1	22441.8465	
34	431000.388	2173.45	362466.2565	1679.66	280116.8982	1446.5	241232.805	1381	230309.37	1435.2	239348.304	
35												
36												

Figure A.3.2.3 Danube River Gradient Profile and monthly TSP spreadsheet, for periods post Iron Gates I HEP scheme, and post Gabcikovo HEP scheme as well as longer periods for upstream stations.