HYDROPOWER

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Contents

Summary

This article deals with all significant theoretical, technological, environmental, and economic aspects of sustainable utilization of the mechanical energy inherent in surface waters. Named briefly, this is *hydropower*, which is and probably will remain for decades, the *most important renewable source* for electric power production in most countries of the world. The physical principles of hydropower utilization and the various levels of the terrestrial hydropower potential are explained. The historical progress and the participation of hydropower plants in the world's electric power production are reviewed.

Presentation of the commonly well-known terrestrial plants, named conventional hydropower plants, is made. These are grouped according to the main physical properties of the project sites on the one hand, and according to the type and size of the structures and their arrangement on the other. The civil engineering works and the

mechanical equipment, especially the turbines, are discussed in detail. The electrical machines and appurtenances are only briefly outlined, because their design and functioning show small differences from the electrical equipment of thermal power plants, and, consequently, they cannot be regarded as exclusively belonging to hydropower plants.

Extraordinary achievements of plants and turbines, concerning the maximum value of head, size, and output, are noted. Establishment of small plants in remote rural areas and mountainous regions deserve special attention, on account of their social and cultural benefits. The turbine types usually applied in small developments are listed. The several possible objectives of multipurpose projects are enumerated.

The usual methods for assessing the economic feasibility of a hydropower project are presented and commented on. Procedures for calculating the benefits of multipurpose projects are referred to.

The presentation of pumped-storage schemes proves their great and steadily growing importance in peak power production, and especially, in increasing power-supply network stability. The various maritime developments are outlined only, because their participation in electric power production, from a global point of view, is not significant up to the present.

The need for refurbishment of old plants will be of growing importance in the future. Restored and upgraded plants in their "second life" usually produce electric power at a lower cost than during their first lifetime. Types of refurbishment are outlined.

A conscientious analysis of the positive and negative environmental impacts of hydropower projects deserves special attention. Balancing out the equation of these impacts generally proves that in cases of careful design, construction, and operation, *hydropower plants preserve the environment and especially the atmosphere*. In addition, they contribute to savings in fossil fuels.

Political implications, and legal and bureaucratic regulations, can largely influence the progress of hydropower development.

A detailed historical survey demonstrates that the evolution of hydropower utilization has been closely connected with the invention of newer and more efficient turbine types. The final concluding section presents the author's vision of hydropower development for the decades of the third millennium.

1. Introduction

Hydropower is a method for producing usable power from moving waters on our Earth. Hydropower (waterpower) plants (projects, schemes) are established for realizing this aim.

Hydropower utilization is a wide multidisciplinary subject. In addition, numerous phases of planning actions have to be effected for the complete implementation and operation of hydropower plants. For the realization of large projects, special research studies, exploration, and physical model tests precede the planning phase. Obsolete and old plants can generally be refurbished, or sometimes even upgraded. According to the individual natural situation, the participation of various specialists is, in particular during the first phases of planning, indispensable. Expert advisers are needed, for example, in the following fields: meteorology, hydrology, geodesy, geology, soil-mechanics and rock-mechanics, seismology, ecology, economy including marketing, and so on. Nevertheless, the bulk of the planning, construction, and operation phases pertains to the disciplines of civil, mechanical, and electrical engineering (see *Hydraulic Structures in Water Resources Development*).

This article concentrates on a description of the general arrangement, and on those structures and installations that are exclusive components, of hydroelectric projects. On the other hand, a detailed presentation of hydraulic structures and associated equipment, which are adapted to various other purposes, is obviously beyond the scope of this treatise, e.g., canals, tunnels, weirs, fish passages, ship locks, dams, pressure pipes, electrical equipment, and so on (see *Design of Sustainable Life-Supporting Hydraulic Structures and Equipment*).

1.1. Historical Review

The primitive and ancient forms of hydropower installations (known as *water wheels*) converted the kinetic energy of flowing waters in creeks and rivers into mechanical energy. Various kinds of simple waterpower-operated machines were used for grinding grain, breaking stones, lifting water for irrigation, and for several other purposes, including industry (see *Uses of Water from Rivers and Streams and Impacts*).

The utilization of hydraulic energy for producing electrical current dates back to the third quarter of the nineteenth century, and since that time the electrical type of power conversion became the general procedure for utilizing hydropower resources. Thus, hydropower plants are also named *hydroelectric plants*. There is more detailed information later in this essay (see *Historical Survey*).

1.2. Hydropower as a Renewable Energy Source

The natural hydropower potential is, due to the permanent hydrological cycle between Earth's surface and atmosphere, a *renewable energy resource*, thus an indirect harnessing of solar radiation (see *Hydrologic Cycle*).

When realized by environmentally *sustainable projects*, hydropower reveals two global advantages over other sources of power generation, which are of paramount importance:

- Hydropower plants do not produce detrimental gas emissions, and therefore this type of electrical power production considerably contributes to *reducing the greenhouse effect* and, consequently, to protecting the atmosphere of our wonderful blue Planet Earth.
- The worldwide utilization of waterpower potentials significantly contributes to *savings in fossil fuels,* namely coal, oil, and gas, which have to be

preserved for the coming generations. It has to be borne in mind that our Earth with its well-defined dimensions cannot have infinite quantities of fuels, and so it can be anticipated that, when taking into account the enormous, progressively growing, and in some regions even prodigal consumption of fossil fuels, the clear signals of "running out" will be detectable not later than at the end of the twenty-first century.

1.3. Further Benefits of Hydropower Development

In the following section are listed the principal additional benefits of hydropower, in addition to its advantages of being a renewable energy source, clean in the absence of emissions, and a saving in fossil fuel exploitation:

- The *participating* generation of hydroelectricity *in multipurpose projects* can contribute to environmental, social, and cultural development of the relevant region.
- The capability of hydroelectric plants to react with *fast response* to the rapid changes in the network load increases the stability and availability of the complete electrical power system

The two main *technological realization* categories of hydropower conversion are:

- Terrestrial developments, including conventional hydropower plants and pumped-storage plants
- Maritime developments

2. Terrestrial Hydropower Developments

In the following sections the *physical explanation of hydropower resources*, the *terrestrial hydropower potential*, and *world hydropower potential and utilization* will be considered.

2.1. Physical Explanation of Utilization of Natural Hydropower Resources

The radiation of the sun permanently evaporates tremendous water masses from the surface of all waters on the globe, most of them from the oceans. The evaporated water masses return to the earth's surface as rain or snow. This is known as the hydrologic cycle (see *Hydrologic Cycle; Hydroinformatics;* and *Hydrological Data Acquisition Systems*).

Through ascension, that is while evaporating from the seas into the atmosphere, the water masses gather potential energy, a portion of which is wasted in the process of precipitation from the clouds, while the remainder is dissipated in the course of flowing as brooks, rivers, and streams down into the seas. Accordingly, every particle of water that appears either as precipitation—snow or rain—on the earth's surface or infiltrates into the ground—disposes of a definite potential energy, the magnitude of which depends upon the elevation (above the sea level), where the precipitation reaches the earth's surface, or where the infiltrated part of the precipitation emerges from the groundwater and feeds a water course (see *Hydrologic Cycle*).

Considering the fact that the energy accumulated during the ascending phase of the hydrological cycle, that is the potential energy carried by (inherent in) the terrestrial flows, is supplied by the sun, the utilization of waterpower (hydro-energy) can be regarded as virtually an indirect harnessing of the permanent solar radiation. Accordingly, hydropower is a renewable power resource.

The question can be raised: *What becomes of the potential energy of the water masses of the terrestrial flows when they travel from the mountains down to the seas?*

The particle of water starting from a hillside and running toward the sea possesses more or less kinetic energy depending on the changes in the velocity of the flow. Although the kinetic energy of descending waters is created at the expense of the potential energy, the amount of the former is insignificant as compared to that of the dissipating potential energy, so that, from the energy point of view, the changes in kinetic energy are altogether negligible. Accordingly, only the dissipation of potential energy of runoff has to be examined (see *Fluids at Rest and in Motion*).

The answer to the above question is simple: *While the water is descending, the potential energy is dissipated to overcome internal friction of turbulent flow, to supply energy to whirls, eddies, and spiral flows, to scour the material of the riverbed and to transport sediment*. The mechanical work, wasted in overcoming frictional resistance in free-surface water courses, which is termed “bed resistance,” and the head losses in conduits, termed “pipe friction,” is converted entirely into heat, and, due to radiation, is lost forever (see *Hydraulics of Two-Phase Flow: Sediment and Water*, and *Fluid Mechanics in Pipelines*).

The fundamental principle of waterpower development is to reduce the amount of energy dissipated by friction and converted into radiation of heat into the environment. Friction losses can be diminished, in principle, by means of two methods:

- In any arbitrary L_o stretch of the river, the hydraulic gradient I required for the conveyance of water can be diminished by decreasing the velocity of flow. This can be achieved by impounding the water through building a low-head barrage (weir) in the riverbed or a higher dam blocking even the valley, where the water discharges from the upper reach into the lower reach (see *The Construction of Small Earthfill Dams*).

Thus, at the dam, between the backwater level and the natural surface of the stream a certain concentrated head H is created. The major part of this head can be directly utilized by hydraulic and electrical machines, as shown in Figure 1.

By impounding the water course, a headwater pond or a reservoir is formed, and the flow is decelerated on a section of length L_o, called the backwater reach. Out of the total water level difference H_o, on a river section of length L_o, with a hydraulic gradient I, the head available for utilization is H, while the potential energy represented by the difference in elevation H_1 is inevitably dissipated in overcoming the reduced frictional resistance in the backwater reach.

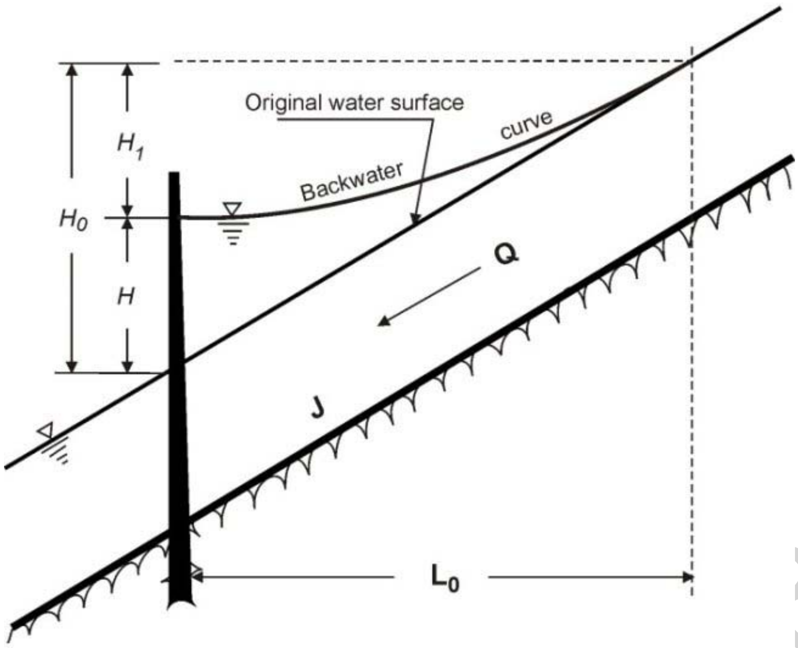

Figure 1. Profile of the riverbed arrangement

- Another fundamental method for reducing the head required for the conveyance of water is to divert the whole or one part of the flow into an artificial bypass, which is either a power canal or a pressure tunnel. In the case of a free-surface power canal, the powerhouse can be situated at its most suitable site, thus dividing the canal into two sections: the headrace and the tailrace, as shown in Figure 2. The head available for power generation is the difference between the headwater level and the tailwater level. In case of a pressure tunnel, supplied in mountainous regions from a reservoir, a high head is usually created for utilization.

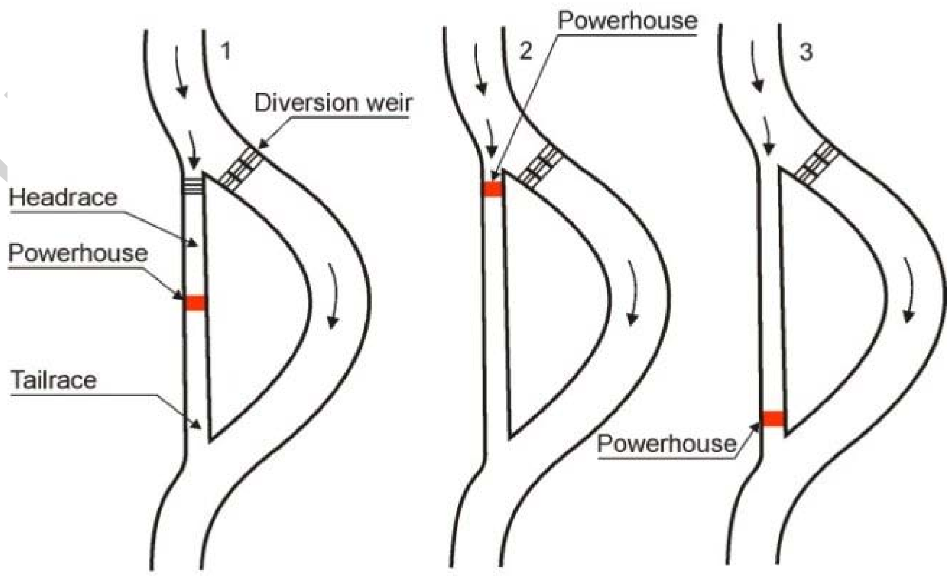

Figure 2. Location of the power station in the diversion canal

Again, the physical explanation of this so-called diversion-type development is: the concentrated head available for power generation that can be regained from the nature. With the canal-type solution, two measures provide for diminishing the friction. On the one hand, the canal, with a sufficiently large cross-section and usually lined, conveys the power flow at a smaller head loss, that is at a lower gradient than the riverbed, and, on the other hand, the canal is, in general, shorter than the bypassed river stretch (see *Dependable Civil, Mechanical and Electrical Engineering Structures and Equipment* and *Hydraulic Structures in Water Resources Development: Water Collection, Water Transfer and Conveyance Systems*).

Furthermore, the impounding effect by the diversion weir contributes, even if slightly, to the utilizable head, as shown in Figure 3. In the case of a pressure tunnel, the head resulting from the above two factors is in most cases significantly increased by the head created by the dam, as discussed later in this essay (see *Diversion Projects*).

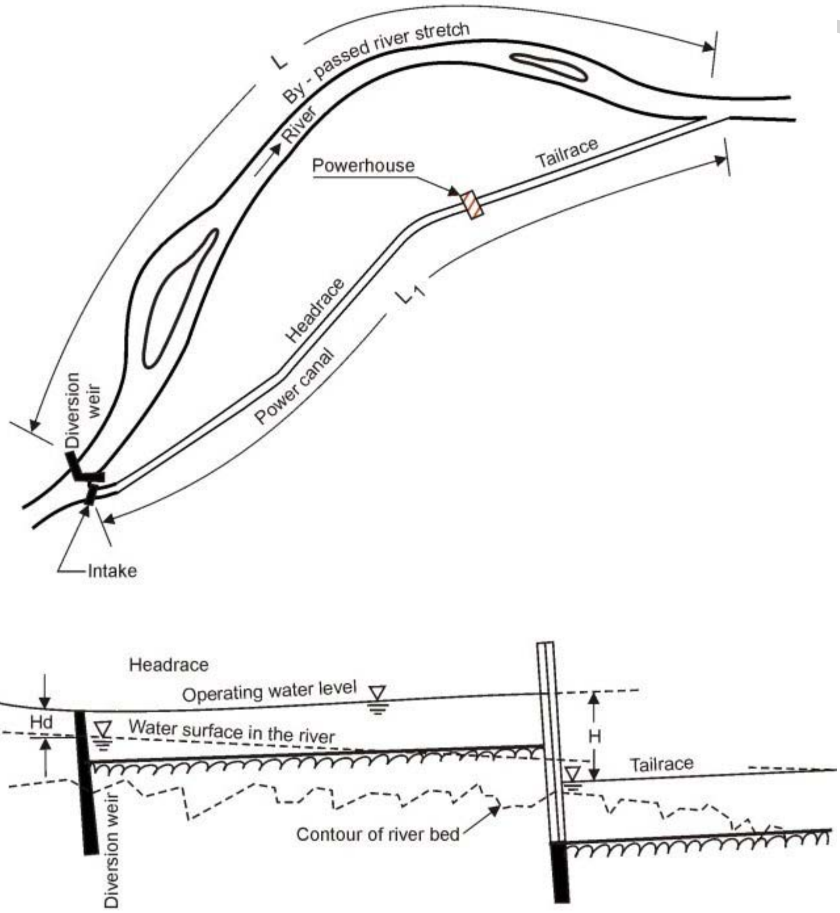

Figure 3. Profile of the diversion-type arrangement

2.2. Terrestrial Hydropower Potential

Because the rate of flow, or discharge, in a water course changes and consequently the utilizable power increases along its way from the mountains down to the sea, the so-called theoretical, or physical, power can be estimated. This is done by the addition of the power components calculated for river stretches where an approximately constant rate of flow can be assumed. Thus, for a section of a river, as between two confluences, the discharge Q [m^3s^{-1}], being the assured volumetric rate of flow in cubic meters per second, or the volume of water flowing through the river stretch during the time of one second, has to be established (see *Probabilistic Methods and Stochastic Hydrology*).

The theoretical waterpower potential can then simply be evaluated when the elevation difference H in meters between the upper and lower end of the stretch, called the hydraulic head, is measured, as shown in Figure 4. According to the relevant law of physics, the sectional potential P_{pot} pertaining to the stretch A-B can be gained in newton-meter per second units, by the multiplication of three quantities listed below as expressed in Eq. (1), (see *Fluid Mechanics*):

- γ = specific weight of the water, approximately 9810 newton weight per cubic-meter [Nm^{-3}]
- Q = discharge in cubic-meter per second [m^3s^{-1}]
- H = hydraulic head in meters

Therefore:

$$P_{pot} = \gamma\, QH = 9810\, QH \left[\text{Nm s}^{-1}\right] \qquad (1)$$

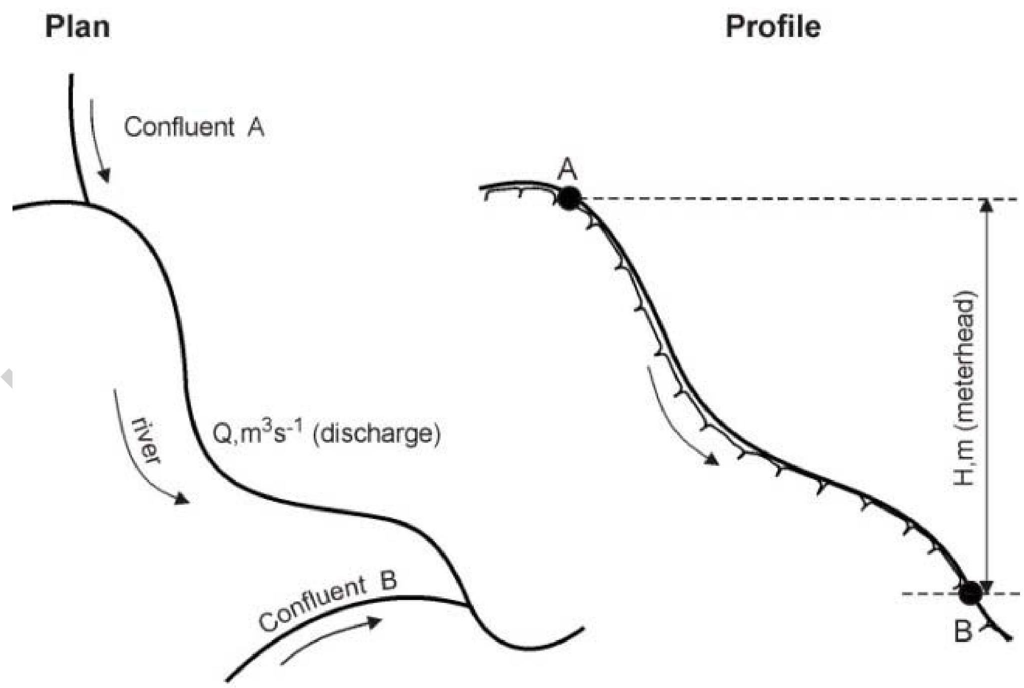

Figure 4. The river is divided into sections for calculating the power potential.

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Biographical Sketch

Professor Emil Francis Mosonyi was born in November 1910 in Budapest, Hungary. He received a Civil Engineering Diploma at the Budapest Technical University (1934). His further academic degrees are Certificate from the Hungarian Academy for Agriculture (1939), Dr. Techn. in Hydraulic Engineering, Aerophotography, and Geology (1947), and Habilitation at the Budapest Technical University (1950), where he had been a Research Assistant (1934–1936). Afterward he was employed at the Hungarian National Authority for Irrigation as Design Engineer, Head of the Research Division. He served as Chief of the Hungarian National Bureau for Water Power Development (1942–1948), and between 1948 and 1964 he held various leading positions with the Hungarian National Authority for Water Management. Also in 1948 he became a Lecturer at the Technical University in Budapest, advancing to Full Professor from 1953 to 1957. He was a resident of Budapest until February 1965, when he left for the German Federal Republic. He received a nomination from the University of Karlsruhe and a personal invitation by the Minister of Education of the Federal State of Baden-Wurttemberg to take the Chair of Hydraulic Structures and Agricultural Engineering and the Directorship of the Theodor-Rehbock Hydraulic Laboratory. His further teaching activities have been: Visiting Professor at the University of Wisconsin, Milwaukee, WI, US; Lecturer at the International Institute for Hydraulic and Environmental Engineering in Delft, Holland; and instructor at the NORAD Course on Water Power Development in Trondheim, Norway. He served as temporary Senior Consultant at the Food and Agriculture Organization of the UN

(1958–1963), and as Adviser on the Maine-Danube Canal and on various dam, flood control, irrigation, inland navigation, hydropower, and pumped-storage projects in Germany and several countries in Europe, Asia, Africa, South and Central America, New Zealand, and Australia. For more than 15 years, Dr. Mosonyi was Chairman of the Senior Advisory Board dealing with several hydropower projects in Pakistan. He is a past President of the Hungarian Hydrological Society, Full Member of the Hungarian Academy of Sciences, Honorary Member of the Scientific Society of Argentina, and Corresponding Member of L'Academie des Sciences, Inscriptions et Belles Lettres de Toulouse.

With the International Commission on Irrigation and Drainage (ICID), he has been Vice-President and is Honorary Vice-President. He is Honorary Member of several German, Austrian, Hungarian, and international associations. Dr. Mosonyi is author of nineteen books in three languages, co-author and editor of four books in the fields of water resources management, hydropower, hydraulic structures, engineering geology, and hydrology. His main works are textbooks on *Water Power Development*, published in two volumes in Hungarian, German, and English. He has written more than two hundred professional articles. In addition to being named an Honorary Professor of the University of Lahore, he has received honorary doctorate degrees from the University of Wisconsin, Milwaukee, 1975; Munich Technical University, 1976; University of Liège, 1980; Northwestern University, US, 1982; and Technical University of Budapest, 1995. In 1953 he was awarded the Kossuth Prize of the Hungarian Academy of Sciences, then the Médaille de Vermeil, Paris, 1973, and also the Ritter von Prechtl Medal from the Technical University of Vienna. He is recipient of the Golden Needle of the Austrian Association for Water Resources Management. He was initiated into the Flag Order by the President of the Republic of Hungary. Some further distinctions have been conferred upon Dr. Mosonyi in his mother country. The University of Auckland (New Zealand) established a MOSONYI PRIZE (1993), which is, since that time, annually given to a student who presents the best study on sustainable hydropower development. He was Founding Member and Executive Vice-President of the International Water Resources Association (IWRA). He founded the International Hydropower Association (IHA) in 1995, was its first President (1995–1997), and is Honorary President for life. Dr. Mosonyi, an Emeritus Professor since 1982, takes part as Scientific Adviser in the work of his former Institute.