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METHODS FOR THE EVALUATION OF HYDROELECTRIC POTENTIAL

by the Energy Division of the Economic Commission for Europe

NOTE: This text is subject to editorial revision.

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Introduction

Up to the beginning of the last decade it was a commonplace - in Europe as elsewhere - that estimates of total hydro-electric resources tended to be incomplete, often subjective in character and frequently out-of-date. During the post-war period a high rate of growth in demand for electric power has been maintained and this has promoted great advances in design and construction technique for hydro-electric schemes - where resources are in course of full development - and has encouraged every effort to increase the economic size of projects and equipment. A rapid harnessing of resources has, in turn, encouraged the making of far more complete surveys of river basins both near and remote, and at the same time has led to improved stream-flow recording and a more adequate coverage of gauging records. These tendencies have also emphasized the need for comprehensive assessment of total hydro potential in countries where water power resources offer a significant source of primary energy. Essentially, any such comprehensive approach must depend on two principles - first that the natural or theoretical potential of a river basin is easier to assess than ever changing conceptions of the power that it is economically feasible to harness; and second that the former, which is fixed, offers a datum against which changes in the latter can be compared. It is on these and certain other associated concepts of duration that the overall study of hydro-electric resources has come to be built up.

A methodology of this kind has been worked out and applied in Europe during the last ten years. The work entailed has fallen more particularly within the terms of reference of the Group of Experts for the Study of Hydro-electric Resources of the Committee on Electric Power of the Economic Commission for Europe. The results obtained from the use of this type of approach have - for different reasons - proved of interest in highly electrified and less electrified countries alike. The same basic mode of analysis has lately been adopted by countries co-operating through the Economic Commission for Asia and the Far East (ECAFE, for use under the somewhat different conditions existing in that region.

/The present

The present paper is divided in two main parts. The first consists of a general review of some of the economic and technical conditions which influence the part played by hydro resources in different countries and thereby pose problems of evaluation; and the second discusses some of the more important methods which may be applied to study such resources comprehensively within a given country or region, or to compare their characteristics over a wider area.

1. Objects of a comprehensive approach

Until very recent times the normal method of exploiting water resources for hydro production was mainly empirical and piecemeal. Sites generally tend to be harnessed roughly in the order of their more obvious economic attractiveness, projects offering low cost per kW at the time of study and the highest degree of accessibility being the first to be built. Estimates of total possibilities thus tend to include only the projects studied, and such estimates are modified from time to time as development progresses. Very broadly this procedure was the one applied in most European countries which possess important hydro potential during the earlier stages of their electrification programmes. In part this was a consequence of incomplete knowledge of the characteristics of different river basins and particularly of their stream-flow conditions.

During the post-war period the information required for hydro-electric and multi-purpose development has become more detailed and exacting. Improved methods of survey have made possible a more thorough examination of river basins and their geological and site conditions. Higher densities of precipitation and flow-gauging stations have become the rule and longer series of records have been accumulated. It is in part due to these trends that estimates of total hydro potential in many European countries have been considerably extended within the last few years. Exploitable hydro resources in Sweden, for example (where electric power consumption in 1959 was 4,220 kWh/per head) were in 1923 set at 32 milliard kWh. By 1938 the total had been increased to 40 milliard kWh and by 1955 this figure had been doubled. Following a recent re-assessment of the gross or natural potential made according to methods discussed later in this

/paper, usable

paper, usable resources in Sweden are currently put in the region of 85×10^9 kWh, or 11,400 kWh/inhabitant. Similar tendencies have occurred in Switzerland (consumption 3,110 kWh/head in 1959). Here the known resources of hydro-electric power, which are virtually the country's sole internal source of energy, were estimated at 14 milliard kWh in 1914 and 27 milliard kWh in 1946. At present they are put at 33×10^9 kWh (6,300 kWh/inhabitant). Similar trends have occurred in other countries.

A second group of factors contributing to the expansion of usable possibilities arises from technical progress and economic change. The effects on costs per hydro kW of higher interest rates and price inflation have been largely cancelled out of late by a variety of technical advances in methods of plant construction; by greatly enlarged perspectives of design; and by increased economies of scale made possible by larger schemes and components, larger generating units and the possibility of utilising very low heads. Very large run-of-stream plants on the lower reaches of important rivers have thus become practicable, as in Europe on the Rhine, Lower Rhône and Middle Danube. Concentrations of head and flow due to the linking up of several distinct catchments have made some large seasonal storage installations more economic. Improvements in the economic prospects of pumping and pumped storage schemes have further extended the range of application of natural hydro potential. Finally, resources in remote areas, which are commonly the most highly concentrated, have been brought into economic range. Development of very high-voltage transmission systems has allowed large concentrations of hydro power in remote areas to be brought into the inventory of exploitable potential where loads are sufficiently high to justify bulk transmission to consuming centres. New automatic control devices have made possible the integrated working of smaller plants in remote situations.

These tendencies, working jointly in opposition to cost-raising influences in the post-war period, have sufficed to bring a larger proportion of the natural hydro potential of Europe within the economic range. Requirements for electric power growing exponentially at 7-8 per cent annually have already led to the harnessing of a large part of this

/potential in

potential in some countries lacking other large-scale resources, while in others the tempo of exploitation is still rising. As development of water resources proceeds and the more attractive sites (particularly for storage) are used up, average construction costs/kW tend to rise - a trend that in certain countries is already well advanced. There is thus at any time an optimum percentage of hydro power in a given supply system. This percentage will commonly tend to rise during the earlier stages of electrification towards a maximum and thereafter to decline somewhat until harnessing of water resources is complete. The different stages of such a process can in fact be distinguished among various European countries at the present time.

At present the main general objectives influencing the rate of exploitation of hydro power in Europe tend to be to use all remaining unused reserves to the best advantage by realising their maximum potentialities for supplying power of high value on the load diagram; and to secure adequate protection for supply systems against capacity and energy shortages during dry periods. One means of attaining the second of these objects, where countries with contrasting types of hydro, thermal or mixed system adjoin one another, is by the judicious growth of mutually advantageous contractual, occasional and emergency transfers and exchanges of electric power across frontiers. Some overall reduction in plant or fuel requirements is then possible where there are contrasts or diversity in time in the normal seasonal supply characteristics. Any differences which may be found in the occurrence of unpredictable departures from average flow conditions in adjoining regions can similarly be turned to account.

What, then, is the proper role of a comprehensive study of hydro resources? It is clear that reasonably full knowledge at the earliest possible stage of ultimate limits to their exploitation is useful in planning the long-term perspective of power supply in time and in deciding the general balance between hydro and thermal plant. For newly developing countries in particular knowledge of the distribution of resources allows the location of industries to be envisaged. The same applies to possible high-voltage transmission requirements.

/In this

In this respect reserves of hydro power are more amenable to measurement than most fuel reserves. The basic reason for this is that the geographical distribution of the natural or physical hydro potential usually corresponds pretty closely to that of the portion which can be harnessed. This relationship, which depends on the interaction of a variety of physiographic factors, is one of the reasons why a comprehensive approach is possible. It is found in practice therefore that exploitable and theoretical levels of resources are fairly consistently correlated with one another. Moreover, not only the average distribution of power in different basins, but those of its fluctuations in time which affect operation, are in principle almost equally amenable to a comparative approach.

If it is true that natural water power potential can be measured consistently, (as also can maximum levels of power considered technically exploitable) it is clear from the foregoing discussion that there can be no "economic potential" that is universally definable in any strict sense. Exploitable power can be evaluated according to agreed assumptions which apply to a particular point in time and to conditions within a single country. Under the influence of technical progress as outlined above it is also true that the proportion of the natural power resources that can usefully be harnessed has consistently been found to rise. Allowing as necessary for geological and hydrological differences in site conditions, overall relationships between physically available and usable power do tend to remain remarkably constant as between different countries, at least under conditions met with throughout Europe.

One of the main conclusions which follow from a study of resource appraisal and hydro power development in countries of Europe with different economic characteristics is that the newer comprehensive approach, involving common evaluation of water power potential ever an entire country or group of countries, is particularly fruitful in allowing results in areas with adequate stream flow and other necessary data, and a long history of hydro plant construction, to be used by analogy to assist the rapid survey of power resources in less electrified countries where the basic

/information required

information required for a full and detailed investigation is still lacking.

Comprehensive surveys of water power resources thus seek to establish first the theoretical or gross physical potential in an average year or season and to use it as a yardstick to compare successive lower levels of producibility, defined on a common basis. Surveys of this gross or theoretical potential, which is constant, thus measure the total production possibilities of each area of watercourse concerned and show how they vary in density from point to point. They show the geographical distribution of water power as well as its amount and thereby offer a broad basis for studying the best location of plants and transmission lines and - in newly developing countries - the possible location of new industries. Recent experience in Europe has, however, shown that such appraisals, or re-appraisals, equally can throw new light on the hydro-electric resources of countries already highly electrified.

A second aspect of hydro-electric resources that has been found to justify comprehensive treatment is that of duration. This covers, on the one hand, the degree of availability of hydro power within an average year; and on the other, the sequence of relative conditions for production from one year to another and the comparison of their simultaneity of occurrence in different basins over a wider area -i.e. variation from region to region in the sequence of departures from a long-term mean.

2. Methods of evaluation

The methods of investigating hydro-electric resources discussed below are, in general, those which have been applied within the work programme of the Committee on Electric Power of the Economic Commission for Europe. They are thus methods found useful for evaluating and comparing the fundamental hydro-electric resources of different countries and regions on a common basis. Additional modes of analysis are necessarily employed within the various contries - i.e. to explore operational questions involved in the use of water resources to meet the needs of national power supply systems; to study the integrated harnessing of a succession of sites along

/a given

a given watercourse or the characteristics of a given project; and for various other matters of detail. These latter questions are not generally discussed in the present paper. Principles and methods of investigation similar to those described below have also been adopted recently by the Sub-Committee on Electric Power of the Economic Commission for Asia and the Far East as a basic methodology for resource appraisal in that region. References are given as necessary to various sources of more detailed information on the matters treated.

Three main types of investigation are discussed below:

- surveys of the physical upper limit to hydro power represented by gross surface and river hydro-electric potentials, and of the relationships to such limits of the power capable of being harnessed;
- analyses of special regional characteristics of such resources due to differences in succession and amplitude of year-to-year flow fluctuations;
- recording of short-term changes in hydraulic conditions on a common basis.

(a) Gross hydro-electric potential and the relationship to it of exploitable resources

Two main types of comprehensive assessment of hydro resources can be distinguished:

(i) theoretical potentials, defining objectively the natural power and energy resources of a river basin without reference to practical use; and (ii) exploitable potentials, defining an aggregate producibility of all schemes, including those in service and those capable of being harnessed at a given date with prevailing technique or with current technique and defined construction cost/kW.

Theoretical potentials include gross surface potentials, giving data in kWh for each small catchment area and specific values in kWh/km^2; and gross river potentials, giving power and energy values (actual and specific) along the course of each individual stream. Exploitable potentials too are sometimes sub-divided into technical and economic potentials.

/Gross hydro

Gross hydro potentials exclude any deduction for irreducible losses of head, flow and power. An average multiplying coefficient to allow for deductions from 100 per cent generating efficiency such as occur in practice may be put at 0.75-0.80. Gross potentials also assume 100 per cent utilization of capacity throughout the year rather than the 40-60 per cent more likely to be attained in practice.

For a rapid general appraisal of national hydro-electric potential and its distribution, it is found useful first to determine and map the gross surface potential for an average year and, if possible, for the winter and summer periods of the hydrological year beginning 1 October. This entails dividing up the total area concerned into the maximum number of small catchments for which mean runoff values are available or can be estimated, and for which median elevation above sea level can be determined from contoured maps. The simplest assessment of gross surface potential for each unit area is then given in millions of kWh by the formula: $\frac{FH}{367}$ where F = mean flow originating in the catchment, in $10^6 m^3$; and H = median elevation (m = above mean sea level).

To map the distribution of available gross resources it is then necessary only to plot each value obtained (expressed in $10^6 kWh/km^2$) at the centre of its unit of area and to interpolate isopleths at a convenient interval (see Figure 1). The amount of detail that it is possible to show will thus depend on the number of unit catchments employed. It should also be noted that such a map, while giving a complete portrayal of the maximum theoretical hydro potential, does not necessarily indicate where such potential can in fact be harnessed.

This method has been adopted as standard within ECE for determining gross surface hydro-electric potential. From the results obtained in the various countries a European map of gross surface hydro-electric potential is being prepared at a scale of 1:2,500.000.

Two questions of method remain to be discussed. In many countries suitable flow data for some areas will not be fully available and it is then necessary to calculate values in order to fill in any gaps. This may sometimes be done by correlation through study of specific hydrological

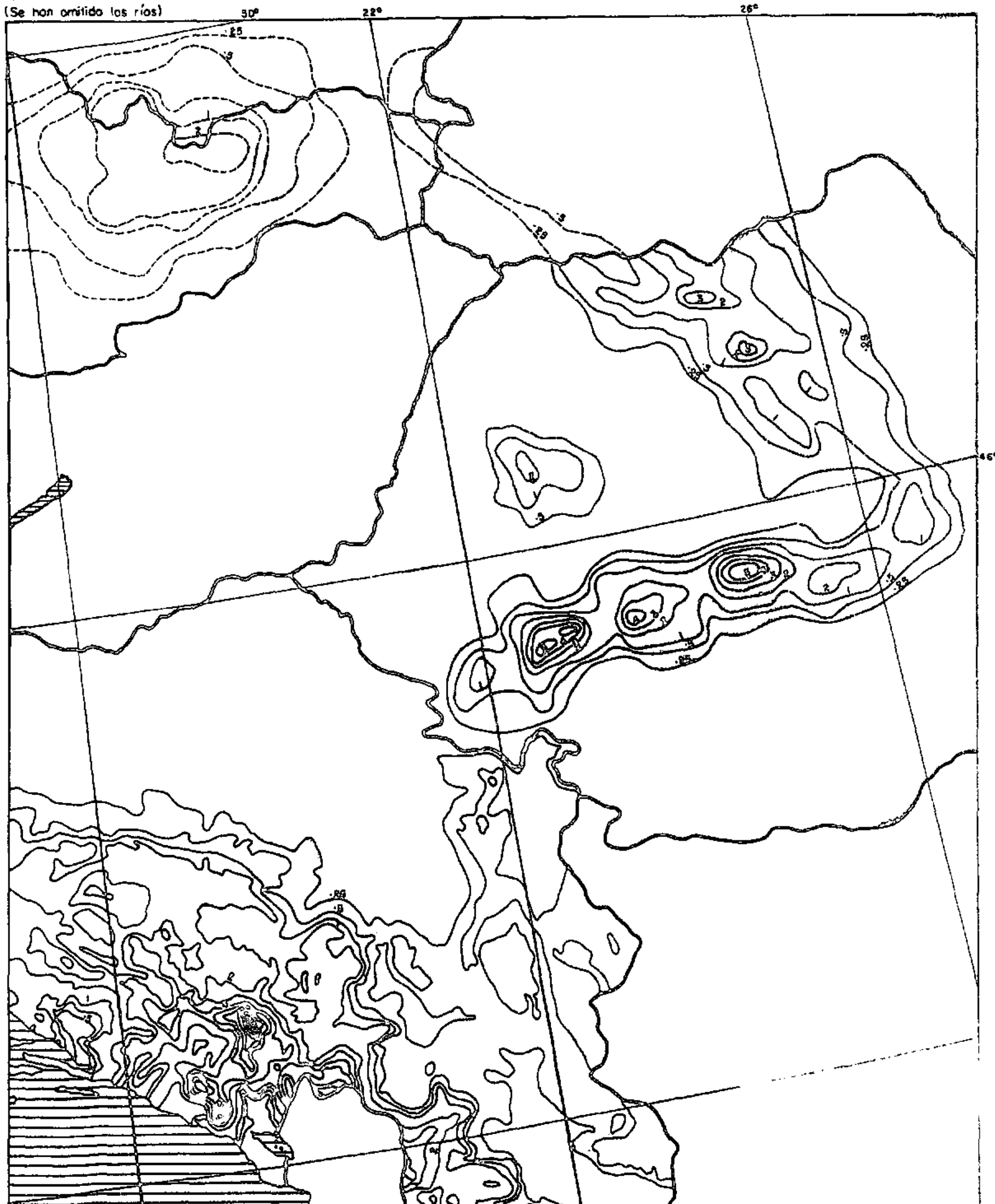
/data for

FIGURE I

EXAMPLE OF MAP SHOWING DISTRIBUTION OF GROSS SURFACE HIDRO-ELECTRIC POTENCIAL IN 10^6 KWH/Km^2
(Rivers omitted)

GRAFICO I

MAPA QUE MUESTRA LA DISTRIBUCION DEL POTENCIAL HIDROELECTRICO BRUTO DE SUPERFICIE EXPRESADO EN 10^6 KWH/Km^2
(Se han omitido los ríos)



The boundaries shown on this map do not imply endorsement or acceptance by the United Nations.
Prepared by United Nations Economic Commission for Europe.

Los límites que aparecen en este mapa no han sido necesariamente reconocidos o aceptados por las Naciones Unidas
Preparado por la Comisión Económica para Europa de las Naciones Unidas.

data for adjoining basins of a similar character. In other cases it is necessary to determine precipitation-runoff relationships in different catchments and to derive a probable runoff value for the area concerned from mean precipitation and the calculated precipitation loss[1/].

A second question concerns countries whose outflowing rivers are terminated not at sea level but by a frontier crossing. If the survey is to cover more than one country the method of calculation to sea level must be retained for mapping purposes. Coefficients may be applied to the calculation for certain basins in order to arrive at a true value for the part of the potential falling within the countries concerned. In a case of this kind where a determination is purely a national one, the catchment areas, and their base levels, may be selected in such a way as to allow the resources of each river basin to be determined in the most appropriate manner. It is possible also to distinguish between the flow originating within a catchment area and that passing through it from a higher level. Such a procedure, which requires more work, may thus allow some account to be taken of the location as well as the amount of resources available[2/].

Gross surface hydro potential (which we may call "S") represents the maximum theoretical energy equivalent of total runoff. It may thus be compared with the aggregate potential found to be economically exploitable ("R"). Where up-to-date information for the latter has been available in Europe for fully electrified countries of similar physical character the ratio R : S has commonly approximated to an overall value of around 20 per cent. Under the influence of technical and economic factors operating during the last few years this ratio has, however, tended to rise. Any generalization must take account of the physiographic,

1/ See for example the method used in respective Secretariat studies of Turkey and Greece (E/ECE/EP/131/Add. 1 and ST/ECE/EP/6), United Nations, Geneva, 1956 and 1960.

2/ The two methods outlined give the same total result. An annual and seasonal re-assessment of gross surface potential made recently in Sweden employed both methods.

/geological, and

geological, and economic conditions of different countries and river basins, since the proportion of usable sites is in some degree related to such factors as well as to density of surface potential.

The following figures give some average indications for entire European countries with different degrees of electrification and different climatic and site conditions. Conditions in Sweden may be taken to be exceptional economically and to give a maximum ratio owing to favourable geological structure and related topography :

Country	Gross surface hydro potential		Exploitable as percentage of gross potential
	Yearly total (10^9 kWh)	Density (10^6 kWh/km^2)	
Italy	318.0	1.02	19.7
Sweden	196.1	0.44	43.4
Switzerland	144.0	3.49	22.9
Turkey	536.5	0.70	19.9

Specifications have also been adopted within ECE for determining gross river potential. Surveys of this type evaluate the separate unit potentials of successive short stretches of watercourse along each stream within a river basin. Basic formulae employed are consistent with the long-standing recommendations of the World Power Conference. If such a survey is made comprehensively, it will give data for the investigation of hydro-electric development possibilities in different river basins. The total gross river potential for an entire area thus surveyed will however give a lower result than that furnished by gross surface potential, since every affluent will not in general be completely covered.

Detailed specifications for preparing surveys and maps of river hydro-electric potential are contained in document E/ECE/EP/204. It may be noted that the application of a coefficient to give net river potential defines an upper limit to the hydro resources that may be exploited without reference to economic considerations - i.e. the "maximum technical potential".

/Somewhere below

Somewhere below that limit lies the total of resources found to be economically usable at a given time. This "economic potential", which has for some time been tending slowly to rise, can either be arrived at from an appraisal of all foreseeable projects on the basis of partially comparable criteria; or it can be determined in such a way as to include all projects whose unit costs fall within an acceptable upper limit. This limit may be a given multiple of the specific cost of providing power of equivalent value on the load diagram from an accepted alternative source of supply 3/.

(b) Irregularity of hydro resources

Methods for comparing fluctuations in hydro-potential rely largely on the principle of the flow duration curve 4/. If successive rates of flow for a given stream in m^3/s and over a given interval of time - such as one year or a thirty-year period - are arranged in order of magnitude as ordinates with the highest at the left, the curve which results has many comparative uses. In the first place the values may be expressed as indices (modular coefficients) relative to the average value as 100. If the abscissae are subdivisions of one year and the ordinate scale of 100 is equivalent, say, to the half-year distance as abscissa, various characteristics of different river basins with respect to duration of power potential can be compared when their respective curves are plotted on the same diagram. This applies to such characteristics as the ratio of mean and extreme discharges, the deficiency in the volume of flow below the average, and so on.

The flow duration curve can also be used as the basis for a classification of wet, dry and normal hydrological years or half-years, as in fact it is within ECE. For this purpose the yearly (or half-yearly) average rates of flow over a period of years are arranged in the form of a flow-duration curve. The years with the highest and lowest 15 per cent of values are

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3/ Some articles dealing with this question are given in the list of references.

4/ Coefficients of hydraulicity, which are prepared in some countries, express the effect of departures from average flow in terms of the relative producibility of existing hydro-electric equipment.

then classified as very wet and very dry respectively; the next 20 per cent as wet or dry; and the middle 30 per cent as normal years (Figure 2).

This system can further be applied to analyse regional differences in the sequence of dry and wet periods, i.e. their lack of simultaneity from region to region. There is evidence that such diversity is worthy of further study in Europe and to this end the system of classification already mentioned is being applied to a representative series of data for river basins very widely distributed geographically, the basis of comparison being a standard 30-year period (1920/21 - 1949/50). Various types of analysis and comparison of sequence and diversity are possible when this method is used. In particular its application to a common period of reference means that the rank-order of all flow values, and their classification as representing wet or dry years, has a common significance which is independent of the actual range of departures from average conditions. The importance of this arises from the fact that the actual coefficients representing this range may be influenced by basin size and other physical factors.

Another useful indicator of hydro resource fluctuations is the index of stream-flow irregularity, i.e. the ratio of the reservoir volume which would be needed in theory to regularize a river's annual flow to the actual volume of that annual flow. To calculate a mean value for such an index the average of a series of actual yearly values must be used. It is possible to map the distribution of this characteristic of within-year irregularity by means of isopleths interpolated between index values plotted at the centres of each unit of catchment over a wide area[5/].

The purpose of any such broad analysis of sequence and regional diversity of year-to-year fluctuations in hydro-electric resources over an area which may embrace a number of countries is, first, to allow development possibilities to be used in the most economic way; and, second, to throw light on the conditions to be satisfied in order to ensure maximum security of supply

5/ Specifications for constructing an index of this kind have been drawn up by the Committee on Electric Power of ECE and issued as document E/ECE/EP/205 (United Nations, Geneva, 1959)

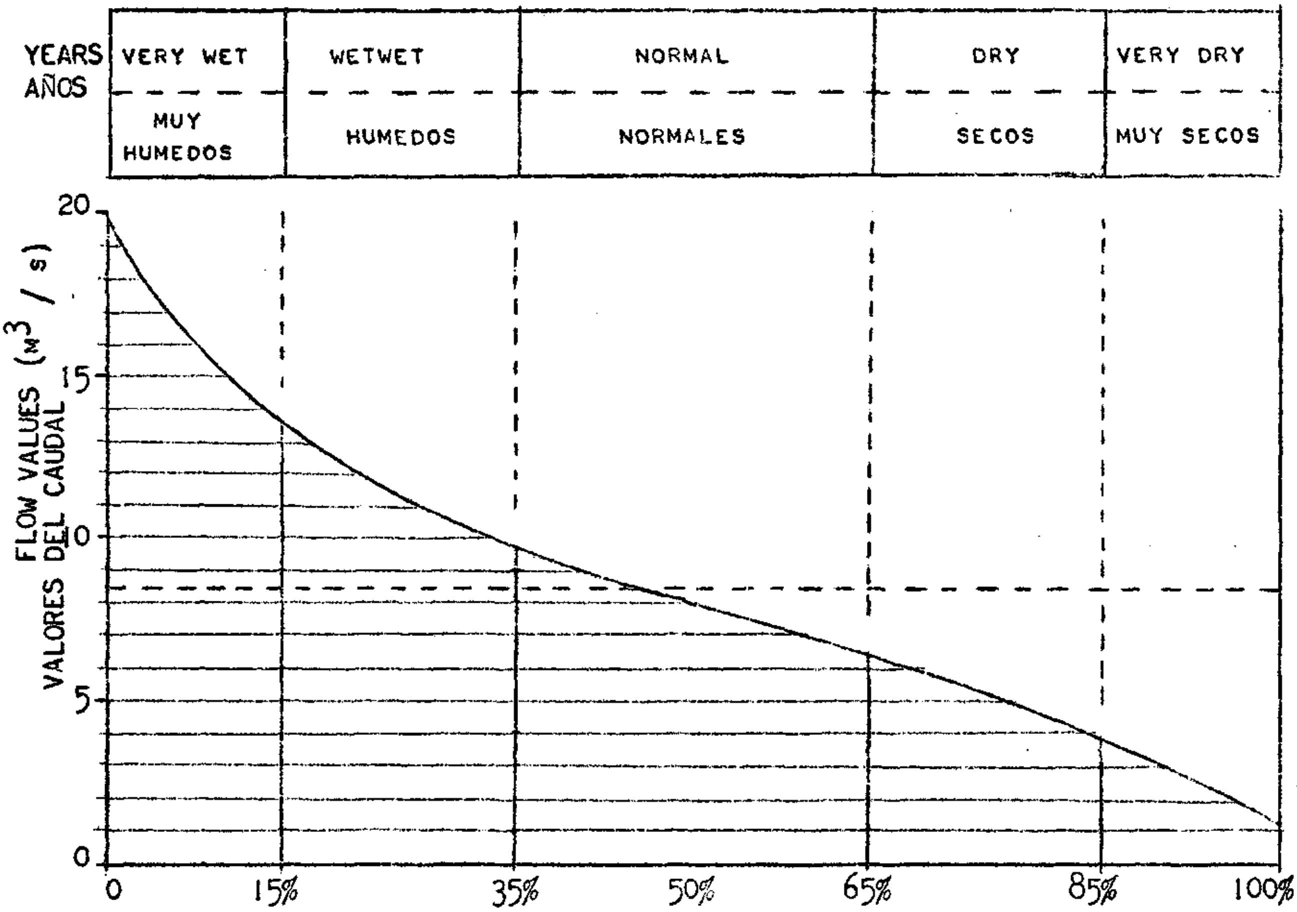
/from hydro-

FIGURE II

METHOD OF CLASSIFYING FLOW CONDITIONS

GRAFICO II

METODO PARA CLASIFICAR LAS CONDICIONES DEL CAUDAL



DURATION AS A PERCENTAGE OF TOTAL PERIOD

LA DURACION EXPRESADA COMO PORCENTAJE DEL PERIODO TOTAL