小規模 水力發電 開發을 위한 스크린 方法

A Screening Procedure for the Development of Small-Scale Hydropower

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要　旨

小規模 水力發電 시스템은 주요 에너지源으로써 여러 가지 利點을 가지고 있다.

本 研究는 小規模 水力發電의 計劃 및 開發을 위한 豫備調査로서, 체계적인 基準 및 節次를 提案한다. 이러한 調査方法은 候補地의 工學的 特性은 물론, 社會·環境·經濟的인 면도 초기단계에서 考慮되어야 한다.

本 論文에서 槪略的으로 소개된 方法은 不充分한 資料에도 適用할 수 있고, 결과적으로 막대한 時間과 費用을 節減할 수 있다.

Abstract

Small-scale hydropower systems offer several advantages compared to other alternatives as an important source of energy in both developed and developing countries.

This study proposes systematic criteria for screening of small-scale hydropower sites to determine their potential for further study, and demonstrates the general procedure. These criteria are based on the physical characteristics of the sites and their social, environmental and economic aspects.

The procedure presented shows great flexibility for screening based on the availability of information and situation at the site.

1. Introduction

Hydropower is one of the most important aspects of water resources development and an essential part of comprehensive planning for conservation and use of river basins for the greatest public good.

After years of neglect, small-scale hydropower (SSH) is becoming an interesting source of energy with favorable economics in both developed and developing countries. SSH projects usually include installations that have 15,000 kilowatts or less of capacity to distinguish between major and minor projects[(8)].

SSH systems offer several advantages com-

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pared to other alternatives(1,5,7). A recent development that improves the economics of SSH projects is the availability of standardized units with potential for mass production. Its relatively simple technology is well-established and proven with efficiencies of turbine now as high as 95 percent(2). Operation and maintenance costs for SSH facilities have been proved very low, and once completed, the plant's costs are largely unaffected by inflation. In addition, the lifespan normally exceeds its projected economic life with no significant change in efficiency.

A number of studies exist on SSH development. The three primary study types are reconnaissance, feasibility and design studies(9). The screening criteria presented in this paper are especially useful at the early stage of reconnaissance study.

This paper is intended to proivde a systematic technique for screening of SSH sites to be used by the planners or developers with a minimal amount of data. This provides a basic understanding of the planning process of SSH projects before a more detailed study is conducted. The procedure developed in this paper will reduce the number of candidates for hydrosites and minimize the amount of study cost and time.

2. Development of Criteria

The procedure identifies two levels of screening based upon the availability and reliability of information. Level one is based on office work from readily obtainable data without visiting site. Level two is a quick site reconnaissance based on inexpensive and easily measurable data from a field visit.

The indices suggested in this paper were divided into four "Feasibility Groups":

(1) Physical or technical criteria including streamflow, geology, slopes, etc.;
(2) Economic criteria which include distances of waterways, transmission lines, etc.;
(3) Social criteria including land use and recreation, etc.; and
(4) Environmental criteria including change of species and inundation by impoundment, etc.

The numbers in the indices may be either cardinal or ordinal numbers, but the criteria finally show the feasible or unfeasible region which means the desirability of the project on the basis of qualitative measurement.

2.1 Availability of Energy

For the first step, potential of site can be determined from the average annual flow and gross head available for the stream.

The power capacity can be computed by using the basic power equation as follows.

$$P=9.8Q\cdot H_e\cdot\eta \qquad (1)$$

in which P=power capacity in KW; Q=flow rate in m^3/sec; H_e=hydraulic net head in meters; and η=plant capacity. To determine a rough approximation of potential power capacity for screening study, Eq. (1) can be modified as follows.

$$P_{ds}=7.50Q_{ds}\cdot H \qquad (2)$$

in which P_{ds}=design capacity of turbine in KW; Q_{ds}=design flow rate in m^3/sec; H=gross head in meters, assumed that $0.9H=H_e$; and 7.50=constant, includes units conversion and system efficiency of 85%, i.e., $7.50=9.8\times0.9\times0.85$.

If this power capacity is constant, the discharge Q increases as the gross head H decreases. Therefore, there is a certain limit of H which has unlikely potential for the sites because the cost of the turbine depends also on the magnitude of discharge. In equaion form, this can be stated as

$$I_{T1}=H<V_{T1} \tag{3}$$

in which I_{T1}=index which shows that it should be screened out when its magnitude is less than a certain number, i.e., V_{T1}; H=difference of elevation between two points on the topographic map; and V_{T1}=critical value of index I_{T1} for screening.

For the same reason as mentioned above, there is a limit of discharge because high head with very low discharge results in high costs in the size and length of waterways. This can be expressed as

$$I_{T2}=\bar{Q}_a<V_{T2} \tag{4}$$

in which I_{T2}, V_{T1}=index and its critical value; and $\bar{Q}_a$=mean of average annual flows.

The installed capacity can be an index for the limitation of minimum capacity corresponding to the appropriate purpose of the particular project. This capacity is a function of the product of discharge and gross head. Then the mean of average annual flow can be used for the index as follows:

$$I_{T3}=\bar{Q}_a \cdot H<V_{T3} \tag{5}$$

in which I_{T3}, V_{T3}=index and its critical value.

The shaded area in Fig. 1 shows the concept for the unfeasible area which should be screened out on the basis of the values of indices: I_{T1}, I_{T2} and I_{T3}.

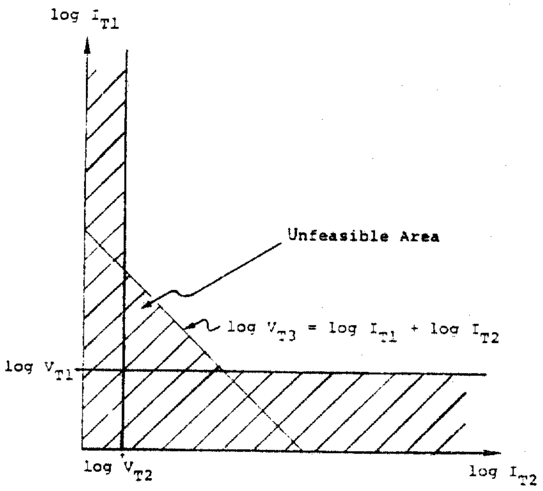


Fig. 1. Unfeasible area on the basis of I_{T1}, I_{T2} and I_{T3}

2.2 Reliability of Energy

The coefficient of variation is very useful for determining the reliability of energy potential for the proposed site.

This coefficient of variation for annual flow is the ratio of standard deviation to mean of annual flow as follows.

$$C_V=\frac{s_a}{\bar{Q}_a} \tag{6}$$

in which C_V=coefficient of variation; and s_a=standard deviation of average annual flows.

When the ratio is low, it means more uniform flow through the year on a year-to-year basis. If the ratio is a relatively high number, it means large variability of flows. However, this ratio cannot be applied by itself because the project with low value of this ratio may still have high probability of uniform flow by catching relatively low flow discharge. Therefore, the index for this effect should be a function of the coefficient of variation and power potential as follows.

$$I_{T4}=\frac{\bar{Q}_a \cdot H}{C_V} \tag{7}$$

in which I_{T4}=index for coefficient of variation and power potential.

2.3 Estimation of Energy Output

The flow duration curve is a graphic representation of streamflows in descending order of magnitude, simply plotted against the percent of time that particular flow is either equalled or exceeded. The flow duration curve as shown in Fig. 2, is very important in hydropower studies because the area under the curve represents the total volume of water available at a particular site after application of a conversion factor.

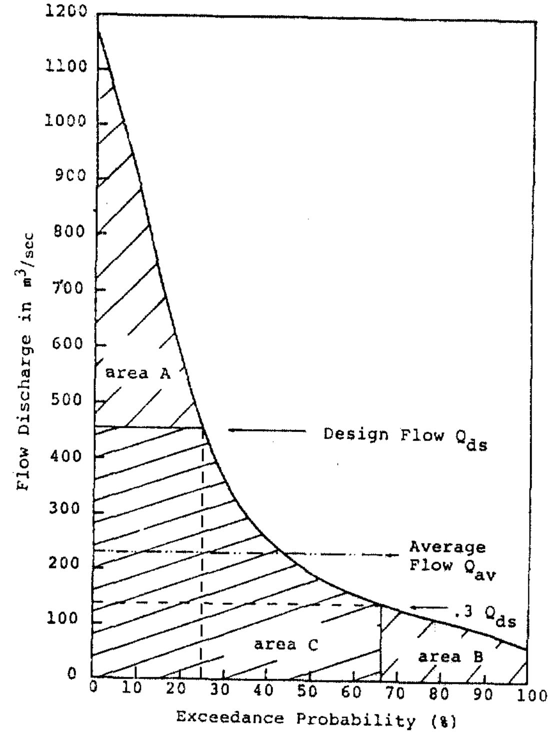


Fig. 2. Typical Flow Duration Curve

The installed capacity is determined on the basis of the available flow below a specified percent value from the flow duration curve. Most of the studies suggested the 25% exceedance flow (Q_{25}) as design flow (Q_{ds}) for the installed capacity.

For the estimation of the amount of energy production, the average flow Q_{av}, which actually can be utilized for power generation, could be used with a few assumptions. First, it is assumed that the turbine installed is capable of operating under all flow conditions represented by the flow duration curve and still maintain a constant efficiency over the flow range. Another assumption is that the tailrace elevation does not change at high flows. In the absence of the operating range of the project's turbine, flows in excess of design flow which corresponds to the area A in Fig. 2 are assumed to be lost over the spillway. In addition, it can be assumed that the turbine will not operate when flows are less than 30 percent of the design flow which corresponds to the area B in Fig. 2. The remaining area under the curve, area C in Fig. 2, represents the available energy output. Average flow is computed on the basis of dividing of the area C by 100 percent with a corresponding conversion. This average flow is the average unregulated flow for run-of-river plants. If a reservoir storage exists, the average flow may be adjusted upward to take account of this storage. The average flow with the option of storage capacity is derived from Eq. (8)⁽⁴⁾.

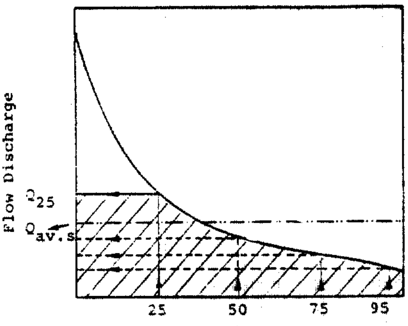
$$Q_{av.s}=0.1316(3Q_{25}+2Q_{50}+1.8Q_{75}+0.8Q_{95}) \qquad (8)$$

in which $Q_{av.s}$=average flow with storage; and Q_{25}, Q_{50}, Q_{75} and Q_{95} indicate the magnitude of flow at the exceedance percent with corresponding number respectively. This average flow $Q_{av.s}$ corresponds to the whole area under the 25 percent of exceedance probability on the flow duration curve as shown in Fig. 3(a). Then the index for the potential of total developable energy production with storage capacity is

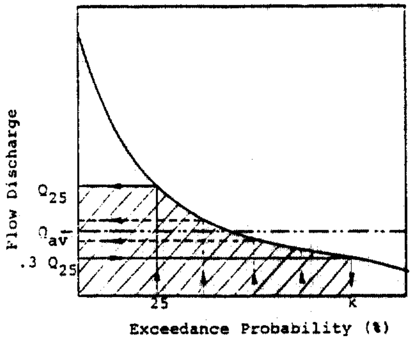
$$I_{T5}=Q_{av.s}\cdot H \qquad (9)$$

in which I_{T5}=index for the potential of energy production. Figure 3(a) shows that the amount of energy production may be higher with regulation of stream flow than the case without storage.

The average flow with a run-of-river type project can be estimated with a similar procedure. Figure 3(b) shows a simple procedure for estimating the area under the flow duration curve with 25 percent of exceedance probability in the case of a run-of-river type by using the basic concept of Simpson's rule. Then the average flow Q_{av} and the index I_{T6} for the potential of total amount of energy



(a) Total Developable Energy



(b) Developable Energy without Storage

Fig. 3. Estimation of average Flow

with a run-of-river type project are as follows.

$$Q_{av}=0.01\left[25\cdot Q_{25}+\frac{\Delta k}{3}\left\{Q_{25}+4Q_{(25+\Delta k)}+2Q_{(25+2\Delta k)}+4Q_{(25+3\Delta k)}+Q_k\right\}\right] \qquad (10)$$

$$I_{T6}=Q_{av}\cdot H \qquad (11)$$

in which k is the value of exceedance probability corresponding to the value of $0.3Q_{25}$; and $\Delta k=1/4(k-25)$. All values of Q used in the above equations are based on average monthly flows.

2.4 Storage Capacity

In this screening study, a few types of storage as well as run-of-river project are considered at up and downstream reservoir sites. Downstream storage may require less capacity than upstream storage for the purpose of mandatory flow and erosion control. Figure 4 shows the possible types of storage and their combinations at up and downstream reservoir sites.

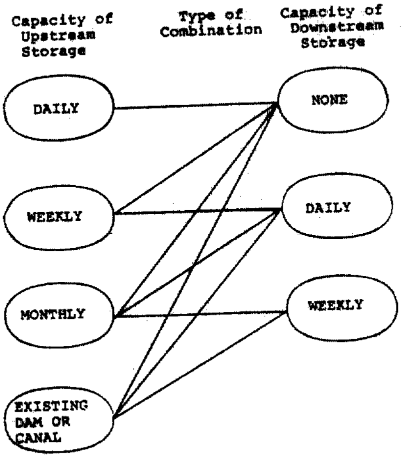


Fig. 4. Possible Types and Combinations of Storage Capacity

Necessity for storage capacity can be estimated from the shape and slope of the monthly flow duration curve. Storage of water can modify the curve and produce more energy output. However, in the case of fairly flat curves, the site does not need storage capacity. For determining storage capacity, the flow duration curve provides an easy and efficient method as follows.

$$I_{T7}=\frac{Q_{75}}{Q_{25}} \qquad (12)$$

in which I_{T7}=index for necessity of storage capacity.

2.5 Indirect Estimation of Flows

Where flow records are not available at or near the proposed site, flows can be indirectly estimated from the drainage areas, annual precipitations, and known gaging station records which have similar watershed characteristics as follows[3,6,9].

$$Q_p = DR \times Q_g \tag{13}$$

$$DR = \left(\frac{\sum_{i=1}^{p} P_i \cdot A_i}{\sum_{i=1}^{g} P_i \cdot A_i} \right)^C \tag{14}$$

in which Q_p=flow values at the proposed site; DR=coefficient of transfer ratio; Q_g=flow values at the gaging station; P_i=average annual precipitation at the i^{th} section; A_i=area between isohyetal lines at the i^{th} section; p= number of sections to the proposed site; g= number of sections to the gaging station; and C=regional constant.

The first step is to obtain the value of the regional constant C, from the flow records at the known gaging stations, i.e., site #1 and #2 as an example. Then, the equation for C is modified from the above equations as follows:

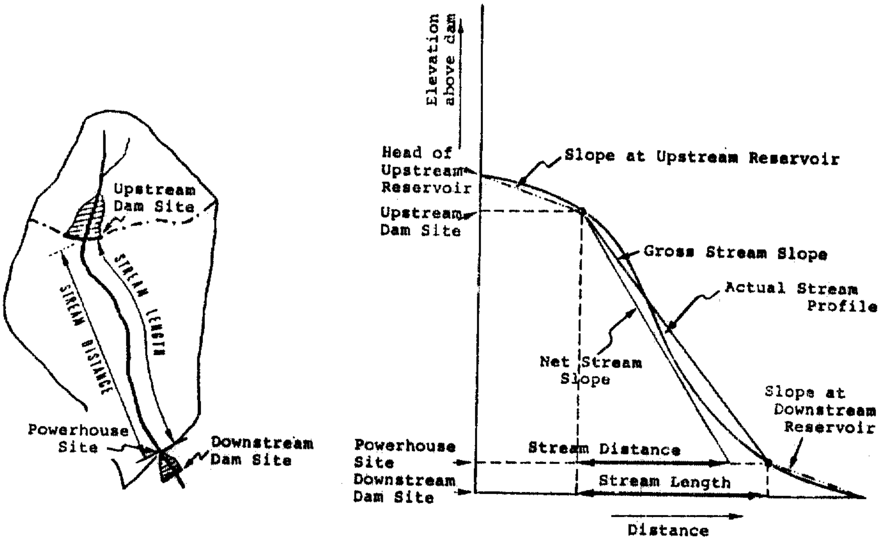
$$C = \frac{\log \dfrac{(Q_g)_{\#2}}{(Q_g)_{\#1}}}{\log \dfrac{(\sum_{i=1}^{g} P_i \cdot A_i)_{\#2}}{(\sum_{i=1}^{g} P_i \cdot A_i)_{\#1}}} \tag{15}$$

in which subscript #1 and #2 in variables mean the corresponding values at the known gaging stations, site #1 and #2 respectively.

Each of the flows or flow duration values at the proposed site can be estimated by multiplying DR by the appropriate values obtained from the gaging stations such as Eq. (15).

2.6 Stream Topography

Stream length is the distance along the stream between the dam site and power house to obtain a potential head, while stream distance is the straight distance between those two sites. Topographic maps are useful for obtaining such measurements. Fig. 5 illustrates the relation among stream length, distance and slopes. Stream slopes at up- and downstream sites are also important factors in hydropower potential. They might influence the amount of storage available, erosion on the stream and sedimentation at reservoir sites.



(a) Relation between Stream Length and Distance

(b) Stream Slopes

Fig. 5. Typical Stream Profile

2.7 Economic Analysis

Benefit/cost analysis is perhaps the most widely used economic analysis. In this screening study, some economic indices are proposed for the screening process with some indirect relation to the concept of benefit/cost analysis. However, these indices include two different points of view from the B/C ratio. First, the components of these indices are not real benefits and costs, but factors which can affect the important economic aspects of the projects. Second, these indices don't need to put all factors relating to benefit and cost categories into one term. Therefore, the indices are very flexible because some of them are related to other aspects and some of them may be better placed in other categories.

Net stream slope, as defined in Fig. 5, is the first economic factor because it affects necessary length and cost of waterways. The capacity factor which is the ratio of average to design flow shows the effectiveness of energy production. Other indices in this category are the length of transmission line which is distance between powerhouse and load center, cost index for waterways, and ratio of volume of water storage to dam.

2.8 Environmental Criteria

The rating scales such as 0 to 10 can be used to know undesirability of projects from the viewpoint of environmental impacts. Low numbers mean that the project will have low possibilities of adverse impacts, high numbers mean the likelihood of severe impacts. The overall impacts can be rated by using weighting factors for each item. In some items, the rating decision can be based on not only

Table 1. Criteria for Evaluation of Environmental Impacts

Item	Rating Scale 0 to 10	Weighting Factor 0 to 10	Products
Change of Species			
Fishery habitat	—	—	—
Aquatic & terrestrial wildlife	—	—	—
Endangered species, plant and animal	—	—	—
Inundation by Impoundment*			
Historical sites	—	—	—
Archaeological sites	—	—	—
Structures & residential properties	—	—	—
Agricultural & important lands	—	—	—
Geological resources	—	—	—
Changes in Water Quality			
Sediment conditions	—	—	—
Flow distruption	—	—	—
Total Points		A_E	B_E

* For storage type project only

Environmental Overall Impacts for Run-of-River

$$I_{EV1}=\frac{B_E}{A_E}$$

Overall Impacts with Storage

$$I_{EV2}=\frac{B_E}{A_E}$$

Table 2. Criteria for Evaluation of Social Aspects

Items	Rating Scale 0 to 10	Weighting Factor 0 to 10	Products
Land use & development	—	—	—
Recreation(Flat water and running water recreation)	—	—	—
Community organization	—	—	—
Rural electrification, population benefited and rate of population	—	—	—
Local interest & employment	—	—	—
Local industry by electrification	—	—	—
Total points		A_S	B_S

Social overall aspects $I_{SC}=\frac{B_S}{A_S}$

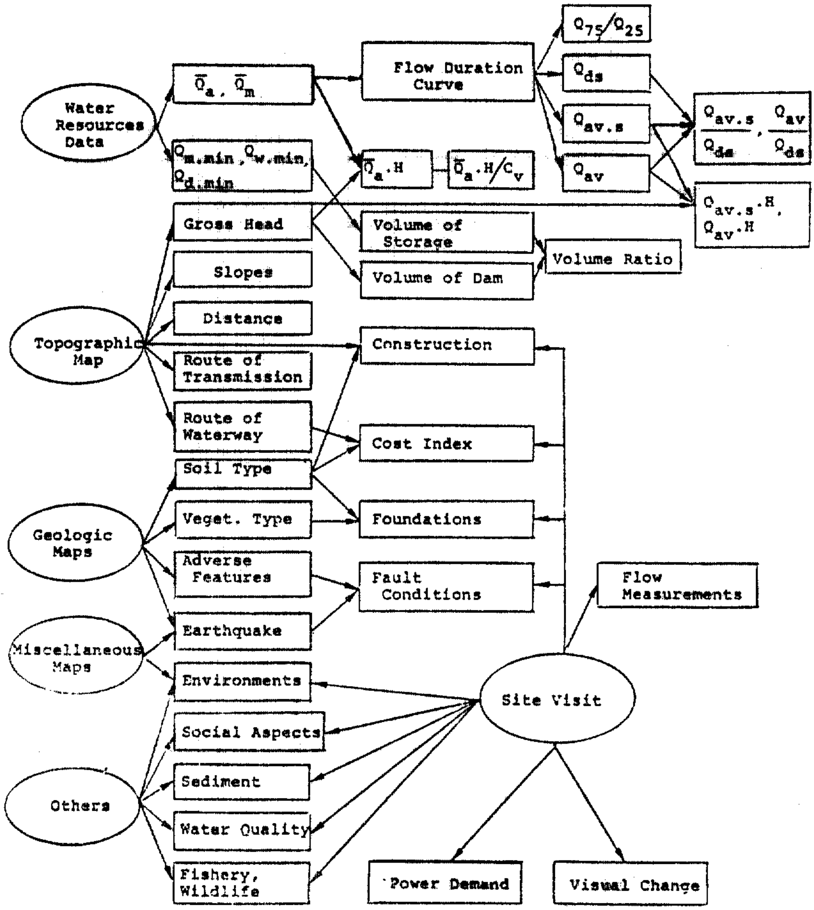


Fig. 6. Data Sources and Relationships with Criteria

adverse impacts but also the required cost for the protection facilities.

Table 1 is the list of criteria for the evaluation of the environmental impacts. When information is not available for a certain item, it can be left as a blank.

2.9 Social Criteria

Desirability of social aspects can be rated in the same manner as environmental feasibility. Low numbers mean most desirable and high numbers mean no potential benefits. Table 2 is the list of criteria for social aspects.

3. General Procedure

Figure 6 shows the data sources and relationships with criteria for the derivation of them as an example.

The initial activity in the screening process is selecting a number of sites which might have some potential for development of hydropower, and preferably marked on the topographic maps.

After selecting the potential sites, screening can proceed in the direction as shown in Fig. 7. The sites remaining after the screening at each stage should go to the next stage. The critical values or ordinal numbers of the indices for the screening can be decided by judgement of the planner as the situation requires on the site specific basis. The process can be done hierarchially with a combination of some indices. This process can be explained in five steps.

The first step of the procedure is to start with the most basic data of the physical features of the sites. These are the gross heads and mean of average annual flows which

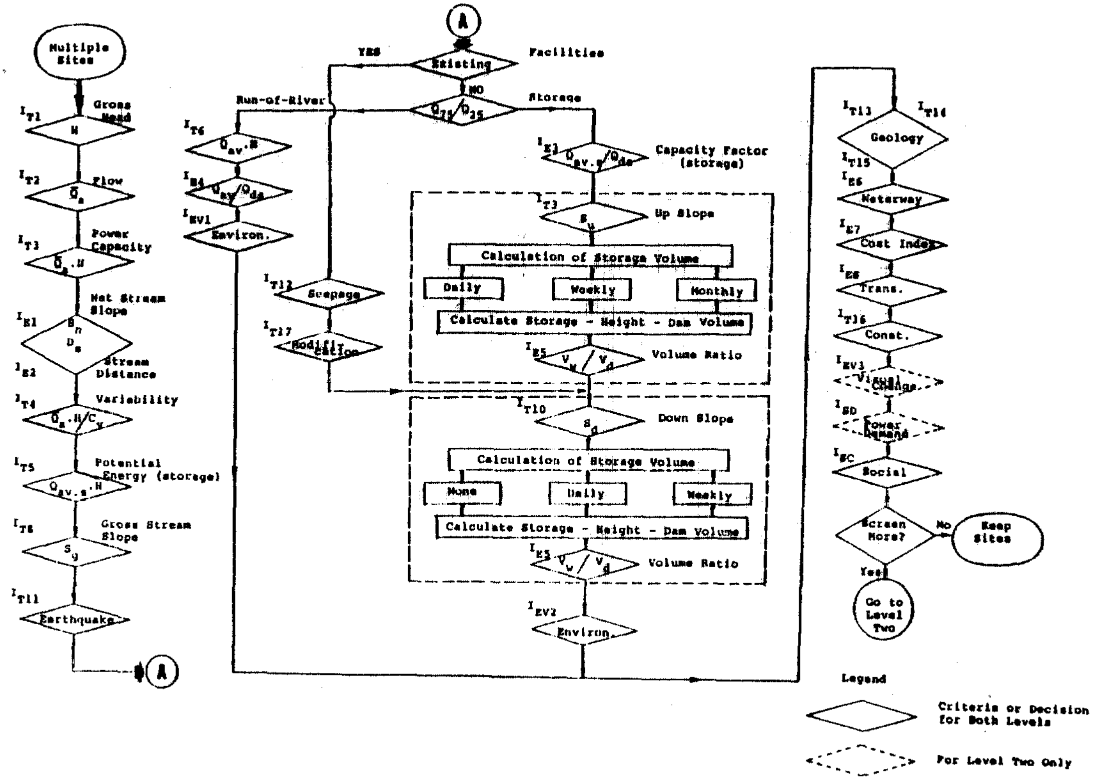


Fig. 7. Procedure for Rapid Screening of Small Hydropower Sites

can be easily obtained from the topographic map and some kinds of reports for flow discharge. From these basic data, power capacity, its reliability and stream slope can be compared with criteria without complicated calculations.

The next step is the preparation of flow duration curves from the average monthly flows for a certain period of records. Given the flow duration curves, potential installed capacity and total amount of energy output can be calculated for either storage or no-storage types.

The third step is to decide the option of storage capacity from the developed flow duration curve. When it needs storage capacity, it should be checked for each type of storage capacity at upstream and downstream reservoir sites. For example, the site which passed in the criteria for any one of storage capacity means that it has the potential for development with the option of that storage capacity. However, this criterion does not provide any information about which type of storage capacity, i.e., daily, weekly or monthly storage capacity at the upstream reservoir site, is most desirable for the site. This kind of study may be performed in the feasibility study after completing all screening processes, not in this study. The squares drawn with dotted lines in Fig. 7 show the steps for these storage options. If the site fails in all of these indices, it should be discarded. Once the site passes at the step of storage capacity for both up- and downstream reservoir, the environmental impacts by inundatiou of the reservoir and geologic conditions at the site will determine the potential of the site.

The fourth step will be tested for the possible routes of waterways and transmissions lines to load center which are important factors for construction costs. Finally, the criteria for the overall social benefits will decide if the site has any potential for development.

From the decision of storage option, the site without storage capacity, i.e., run-of-river type, does not require a check of the process concerning storage potential. In cases of sites which have already existing impoundment facilities, storage potential should be checked at the downstream reservoir sites only.

The priority in the order of the index as shown in Fig. 7 might not be so important because the purpose of these screening criteria is not to find the best site, but to screen out unfeasible sites. Therefore, the criteria should screen out the bad projects which are likely unfeasible. However, the order of procedure in Fig. 7 is aimed at saving time and cost because it is better to drop off the bad projects as early as possible.

When the site has no available data for any particular stage, the planner can proceed to the next stage without any screening at that stage. If the criteria are set too high and eventually eliminate too many projects after the whole process of screening at level one, the planner may go back to the first steep of level one with lower criteria.

After completing the whole process of level one, the planner can go on to level two with more detailed information through field investigation when it needs more screening.

4. Conclusions

(1) The criteria developed in this study contribute to screening techniques for analysis of potential hydrosites.

(2) There may be some difference in the criteria, i.e., potential energy (I_{T5}) and capacity factor (I_{E3}) from the real values because the effect of flow regulation was

not considered in the flow duration curve.

(3) The criteria show the desirability of the project on the basis of ordinal measurement. The errors of data in a screening study are less important than those in the reconnaissance or feasibility study.

(4) The order of procedure may be more important than the errors of data. The priority of this order may be changed according to the circumstances. For example, social criteria may be more important than the environmental criteria in most developing countries. However, in developed countries, the situation may be reversed.

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