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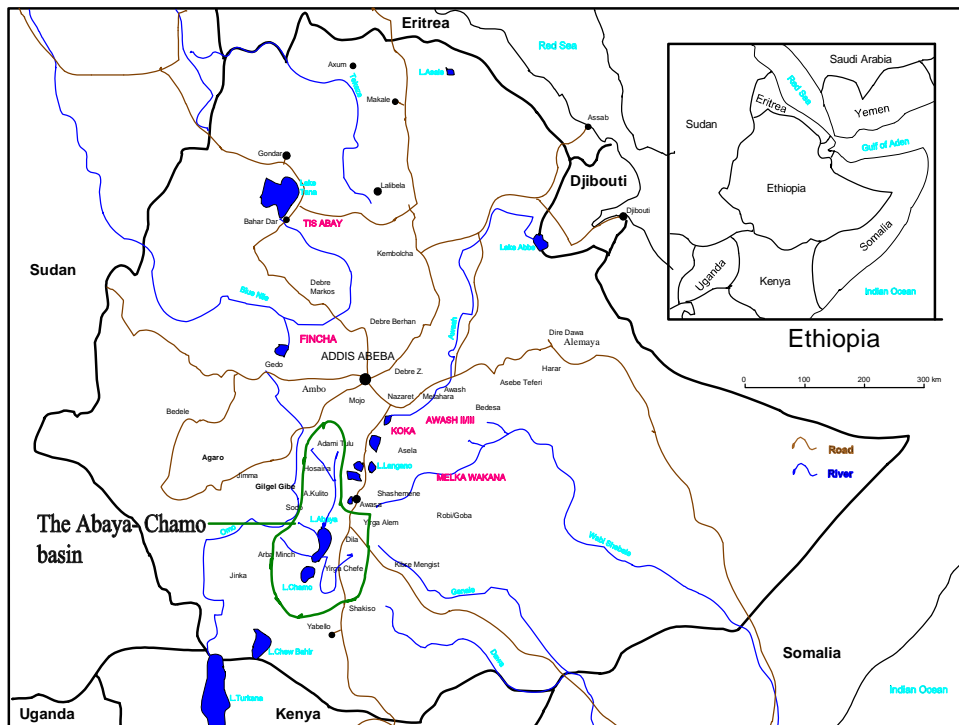
# Sustainable small hydropower development in Ethiopia Case study Ropi hydropower plant (Bilate basin, Ethiopia)

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## 1 Introduction

The paper considers a case study of the Ropi hydropower site in the Bilate basin in Ethiopia to show the effect of seasonal variability of river flow on the magnitude and reliability of power supply. The Bilate basin is found in the rift valley lakes region and its geographic location is south west of Addis Ababa as shown in Figure 1. The Ropi hydropower site is situated at  $7^{\circ}08'N, 38^{\circ}07'E$  on the upper part of the Bilate river.

Storage as well as diversion types of developments are considered in this paper



to show that the operation at firm yield (say at 90% reliability) results in the under utilisation of the energy potential of the river flow. Suggestions are made for the increased utilisation of the energy potential of the river by increasing the installation capacity.

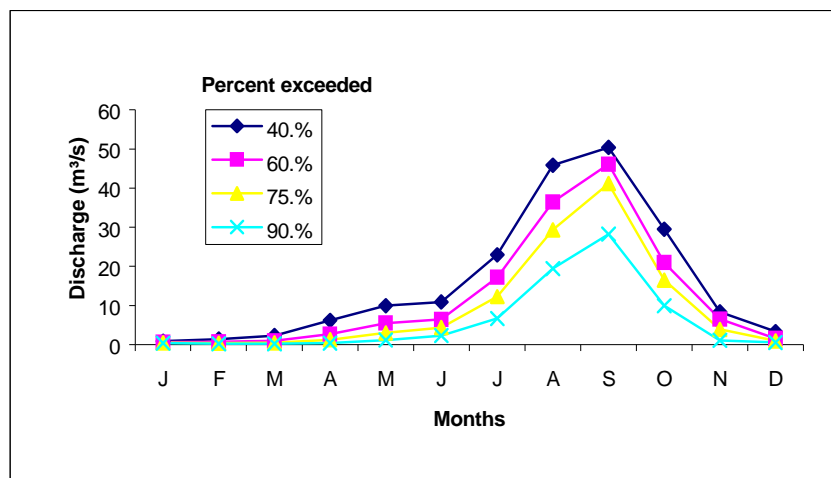
## 2 Nature and Effect of Stream flow Variability

Two gauging stations with more than twenty years of service are found upstream and downstream of the Hydropower site. The data of the two gauges showed a very strong correlation and provided the database for estimating the flow-duration at the hydropower site. Figure 2 is a month-by-month flow-duration curve for the Ropi site based on daily flow data. It shows how excess flow is concentrated during few months of the year while there is very limited flow during the remaining period. This

is typical characteristic of mountain rivers in tropical regions with high runoff factors. Most of the runoff occurs during the wet season leaving an insignificant amount of base flow during the dry season.

Even without deducting the minimum downstream requirements, the dependable flow (90% exceedance) seems to be very low except for the few wet months of the year. This fact baffles designers of small hydropower plants in the choice of optimum design flow. If a reliable supply is to be assured throughout the year, the design discharge must be set so low that it would lead to under-utilisation of the power potential of the river. On the other hand, stand alone hydro plants sized to operate on wet season flows have trouble delivering power during the dry season because of lack of water, *Leaf 2000*.

**Figure 2 Flow-duration curve at the site**



Often, the provision of storage is proposed as a solution to the above dilemma. But, such a solution can be approved only when the associated impacts are tolerably low. Issues revolving around impacts caused by reservoirs vary from context to context, *Egre et al 1999*. For this reason, particular facts of the Bilate basin are discussed in a little more detail before proposing a general solution to the dilemma.

## 2.1 Small-scale Storage Development in the Bilate River

Storage reservoirs represent the most effective means of time-redistribution of water according to socio-economic requirements. In serving such purposes, reservoirs must be in compliance with environmental, and social criteria of development. Otherwise, the human and environmental impact of water control and storage may outweigh any benefits to be gained from it.

Reservoirs often inundate arable and pasture lands as well as places of historical or cultural value to communities. Water impoundment has often deprived people from having access to traditional common property resources. Flora and fauna also become submerged leading to the loss of bio-diversity.

A sad experience of negligence to observe questions revolving around environmental issues has already occurred in the upper part of the Bilate basin. Despite the

completion of the construction of a dam in 1990, it could not go into operation because of the unwillingness of upstream dwellers to move to downstream settling zones. The people rejected offers of compensation because they were unwilling to see their indigenous village submerged by the filling of the reservoir. They won the legal controversy and managed to protect their village. The experience is an outstanding lesson for the need to take the interests of the population very seriously before undertaking the construction of dams.

### **2.1.1 Environmental Compatibility Vs Reliability**

An ideal dam site may be defined as a site which has little negative environmental impacts and which provides high reliability of supply of the design flow with minimum requirement of foundation treatment and minimum volume of dam body. However, such sites hardly exist, since the satisfaction of one criterion usually causes the violation of another criterion. In particular, the criterion for environmental compatibility stands in conflict with the criterion for reliable supply.

To be environmentally compatible, a reservoir has to be as small as possible to minimise the negative impacts. Small scale projects have in general modest and localised impacts, OECD 1998. In contrast to this, a reservoir has to be big enough to guarantee reliability of supply of the forecasted load. Compromising these two criteria is a challenge facing water resources engineers in general. The challenge assumes greater proportions in semiarid regions which are characterised by very high seasonal variability of river flow. Reservoir reliability analysis for dams in such areas shows the need for substantial storage volume to regulate the seasonal variation. Moreover, the requirement to allow sufficient dead storage for sediment deposition minimises the usable live storage. Thus, the need for a still greater storage volume has to be accommodated.

In a large scale storage, the episodes for shortages occur at the end of relatively long wet and dry periods, and the fluctuations of flow during most individual years are largely inconsequential since they cannot induce either spills or shortages. On the other hand, for small scale storage, the uncertainty in long-term fluctuations is irrelevant since the reservoir fills up every year and a water shortage also can occur every year. The probability of occurrence of either of the two episodes depends exclusively on the conditions in that one year only, *Klemes 1983*. Therefore, the preparation and use of a reliability curve for the selection of the capacity of small scale dams is highly recommended.

### **2.1.2 Steps in Establishing the Reliability Curve**

The reliability of a reservoir is defined as the probability that it will deliver the expected demand throughout its lifetime without incurring deficiency. In this sense lifetime is taken as the economic life, which is usually between 50 to 100 years. For the period of the economic life an operation study is made on assumed future inflow to determine the reservoir reliability. The study may analyse only a selected critical period of very low flow, but modern practice favours the use of a long synthetic record. In the first case the study can only define the capacity required during the selected drought. With the synthetic data it is possible to estimate the reliability of reservoirs of various capacities, *Linsley 1979*.

The sequent-peak algorithm suits itself to operation study based on long synthetic data. As a first step, values of the cumulative sum of net inflow i.e. inflow minus withdrawals are calculated. The first peak and the sequent peak are then identified. The required storage for the interval is taken as the difference between the initial peak and the lowest trough in the interval. The process is repeated for all cases in the period under study and the largest value of required storage is determined. This is done for many scenarios of inflow and the different storage values are analysed by probabilistic methods to establish the reliability curve. Gumble's distribution to estimate the reliability  $R$  corresponding to a random storage variable  $S$  is given by Equation ( 1), Linsley 1979.

$$R = e^{(-e^y)} \quad (1)$$

where

$$y = - \left[ \frac{S - \bar{S} + 0.45\sigma}{0.7797\sigma} \right]$$

$\sigma$  - *Standard deviation of storage values*

$\bar{S}$  - *Average value of the storage volume*

Once the reliability curve is fixed, it can be used to estimate the reliable release corresponding to an acceptable storage volume and to a predetermined value of reliability. In so doing, the topographical and environmental limits at the dam site are considered to determine the acceptable storage volume. Topographical features of the Ropi reservoir site are obtained from an elevation-volume curve established by the Water Resources Commission, *WRC 1974*.

### 2.1.3 Reliability for Ropi Reservoir

The reliability at Ropi reservoir is estimated by stochastically generating 100 traces of equal length to the adopted project life (50 years.). Each trace may then be said to represent one possible example of what might occur during the project lifetime, and all traces are equally likely representatives of this future periods. The Thomas-Fiering model which considers the month to month correlational structure of mean monthly flows is used for the generation of stochastic data, Equation 2, *Mutreja 1982*. The month to month correlational structure is represented by the correlation coefficient of the flows of consecutive months  $r_j$  and the slope of the correlation equation  $B_j$ . Independent random numbers of a uniform density function ( $t_p$ ) are generated in the interval (0,1) which are then transformed into random normal variate using the *Box and Mullers* method, Press et al 1992.

$$Q_{p,j+1} = \bar{Q}_{j+1} + B_j(Q_{p,j} - \bar{Q}_j) + t_p s_{j+1} (1 - r_j^2)^{1/2} \quad (2)$$

where:

$$\bar{Q}_j = \frac{1}{N} \left[ \sum_{p=1}^N Q_{j,p} \right] \quad (2-1)$$

$$s_j = \left[ \sum_{p=1}^N \frac{(Q_{j,p} - \bar{Q}_j)^2}{N-1} \right]^{1/2} \quad (2-2)$$

$$r_j = \frac{\sum_{p=1}^N (Q_{p,j} - \bar{Q}_j)(Q_{p,j+1} - \bar{Q}_{j+1})}{\left[ \sum_{p=1}^N (Q_{p,j} - \bar{Q}_j)^2 \right]^{1/2} \left[ \sum_{p=1}^N (Q_{p,j+1} - \bar{Q}_{j+1})^2 \right]^{1/2}} \quad (2-3)$$

$$B_j = r_j (s_{j+1} / s_j) \quad (2-4)$$

$Q_{pj}$  = Flow at the  $p^{\text{th}}$  year and the  $j^{\text{th}}$  month

$N$  = number of years for which record is available

$t_j$  = random normal deviate with zero mean and unit variate

$p$  = index for year

$j$  = index for months;  $j=1$  corresponds to the month of January, and so on

$\bar{Q}_j$  = mean of  $j^{\text{th}}$  month flows

The storage required to deliver a specified demand is calculated for each trace by the sequent peak algorithm, and the resulting values of storage are fitted to the Gumble frequency distribution. The result is a family of reliability curves which indicate the probability of satisfying demand throughout the project life for a selected reservoir capacity, Figure 3. In constructing the curves, a portion of the reservoir volume is left for the dead storage which is necessary to prevent the dam from filling up with sediment. In the absence of adequate data to estimate sediment yield, a 30% allowance is made based on recommendation from local experience, *Mohammed 1984*.

The family of curves provide a useful basis for determining a compatible reservoir level. A hydropower engineer and an environmentalist can examine the curves to ascertain an acceptable storage level from their own perspective. Of course, the hydropower engineer would prefer to choose storage values from the upper right part of the curves as far as the topography permits. On the other hand, the environmentalist would prefer to look at the lower left part of the curves in order to minimise environmental impacts. The curves provide them with a summarised information which can help these experts in their search for a compromising solution.

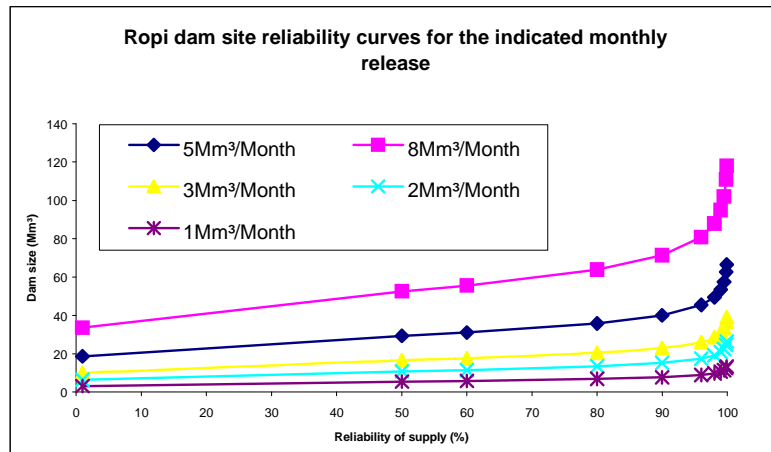


Figure 3 Ropi dam – reliability curve

### 2.1.4 Under utilisation of potential in storage type hydropower plants

Storage type SHP plants in stand alone operation must be designed with sufficient reliability for continuous supply. A design discharge corresponding to high reliability is very low and thus the installation capacity is low too. But the natural inflow is not always found at the extreme low level and it is at times possible to release higher flow than the design discharge for more power production. By designing the power conduit and the turbines to entertain more flow than the design discharge, it is possible to produce several times more energy in the operation period of the plant. To give an image of the situation, the optimal release policy of the Ropi dam is carried out with a discrete dynamic programming technique for one random trace of the generated data series.

## 3 Optimum reservoir operation

Dynamic Programming (DP) is a mathematical optimisation technique used for making a series of interrelated decisions. Usually, a multi-stage decision Process is transformed into a series of single-stage decision processes as shown in Figure 4 for a reservoir system with an operation rule based on monthly release. As a result, certain large operational problems can be decomposed into a series of smaller decision problems which are readily solvable, *Kuester 1973*.

### 3.1 Inputs and Constraints of the DP Formulation

Use of DP recursive relationship requires that the inflows  $R$  be known for each time period. The synthetically generated stream flow provide the stochastic inflows  $R$  in the recursive relationship. The adopted objective function is the maximisation of energy production and the decision variable is the release at any particular month. The amount of release lies within the upper limit of conduit capacity and the lower limit of reliable reservoir yield which determine the maximum and minimum power production potential ( $P_{\min}$ ,  $P_{\max}$ ) respectively. These limits are used to establish the constraints in the dynamic programming algorithm. Equation 3 presents the constraints for both cases where  $P_t$  is the power produced at a particular month. The

lower and upper bound of power production limits correspond to a reliable release of 3 hm<sup>3</sup>/month and a maximum pipe capacity of 9 hm<sup>3</sup>/month respectively. The firm release level was selected such that it corresponds to a reasonable impoundment size for the site topography. In terms of discharge, the lower and upper bound correspond to 1m<sup>3</sup>/s and 3m<sup>3</sup>/s respectively. The range between these boundary values will be discretised into a reasonable number of points according to the accuracy desired. The discrete points will serve to represent the state of the system.

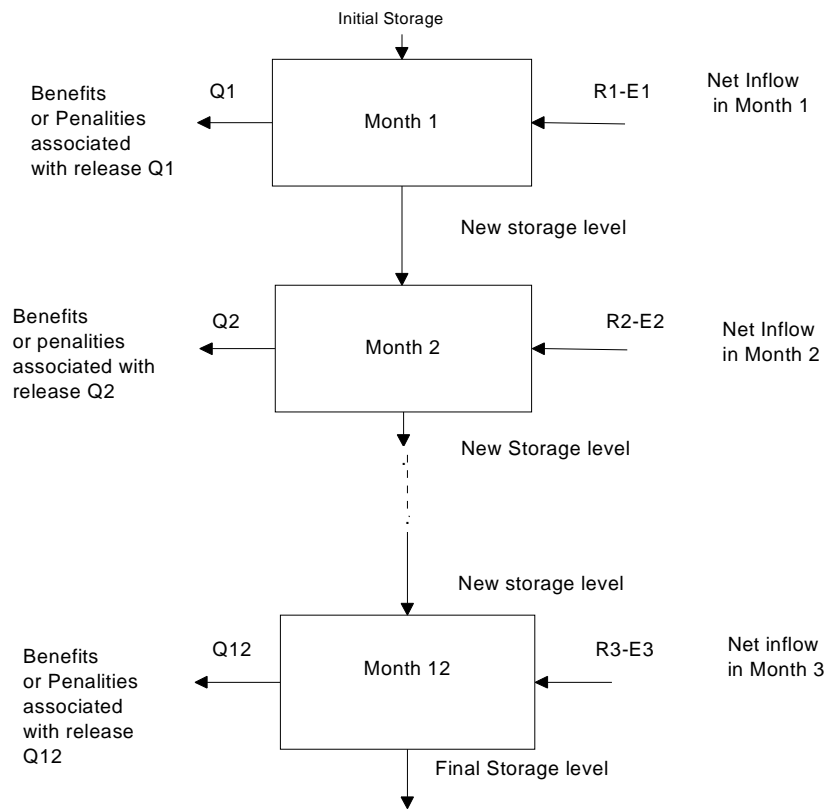


Figure 4 Stages in dynamic programming algorithm

$$\begin{aligned}
 P_{min} - P_i(S_t, S_{t+1}, Q_t) &\leq 0 \\
 P_t(S_t, S_{t+1}, Q_t) - P_{max} &\leq 0
 \end{aligned}
 \tag{3}$$

where

- $R_i$  ----Monthly mean inflow
- $E_i$  ----Monthly mean evaporation
- $P_i$  - actual power production for the given state
- $P_{min}$  - lower bound on power production
- $P_{max}$  - upper bound of power production



### 3.2 Objective Function

Equation 4 is a formulation by *Mimikiou 1987* that expresses the objective function in its non-linear form. The monthly energy production  $B_t$  is estimated as a function of the average release rate through the turbines  $Q_t$  and the average head  $H$  over a month's period. It is seen from equation 4 that the average head is expressed as a function of the storage  $S_t$  at the beginning and  $S_{t+1}$  at the end of a particular month. The factor  $k$  depends on the units in use.

$$B_t = kQ_t H \left( \frac{S_t + S_{t+1}}{2} \right) \Delta t \quad (4)$$

### 3.4 Computational Procedure of DP

The computational procedure of dynamic programming is based on the original work of Bellman 1957. The sequential decision technique is designed such that it steps from stage to stage and determines the optimal volume of water that should be released based on the natural inflow and water balance conditions of the reservoir, equation 5.

$$S_{t+1} = S_t - Q_t - E_t(S_t, S_{t+1}) + R_t \quad (5)$$

where

$R_n$  – Natural inflow to the reservoir

$E_t$  – Average Evapo-transpiration

A typical recursive formulation of dynamic programming is given by equation 6:

$$f_n(n, S, Q) = g[B(n, S, Q), f_{n-1}^\#(S^\#)] \quad (6)$$

where  $n$  = the stage of the problem

$S$  = the state of the system at stage  $n$

$Q$  = the decision (policy) being evaluated at stage  $n$

$B(n, S, Q)$  = the immediate return associated with decision  $Q$  at stage  $n$   
when the state of the system is  $S$

$S^\#$  = the state of the system at stage  $n-1$  resulting from decision  $Q$

$f^\#(S^\#)$  = the return associated with the optimal sequence of decisions at stage  $n-1$  when the state is  $S^\#$

Typically, the first stage in a dynamic programming formulation refers to the last decision which must be made in a series of sequential decisions. The results of this stage are then included in the next to last stage. This recursive procedure is applied backwards at each stage until the first stage is encountered, at which point it is possible to determine the optimal policy and value for the initial decision of the problem. The optimal policy can then be determined for each sequential decision by retracing the steps through the set of optimal policies that were found for each state of the system at previous stages. The flow-chart of the procedure is shown in Figure 5.

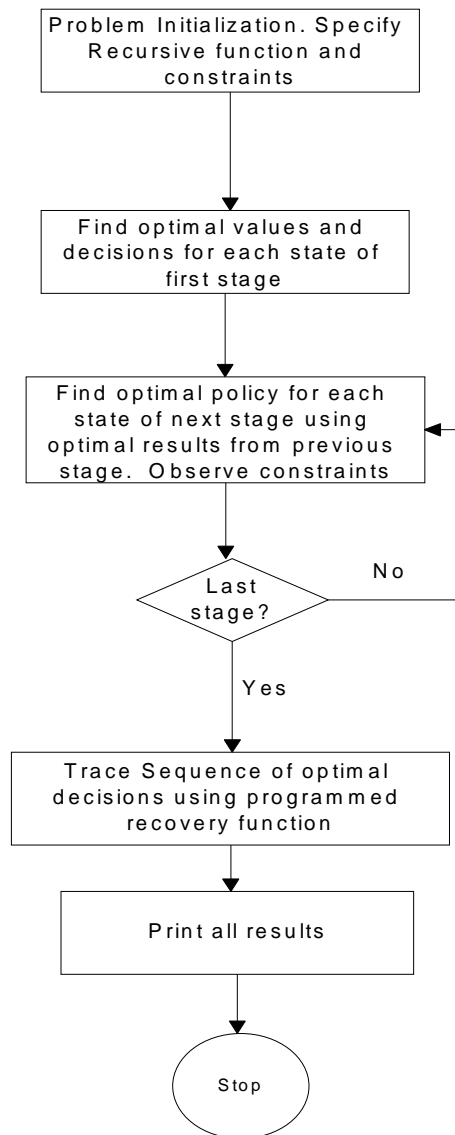
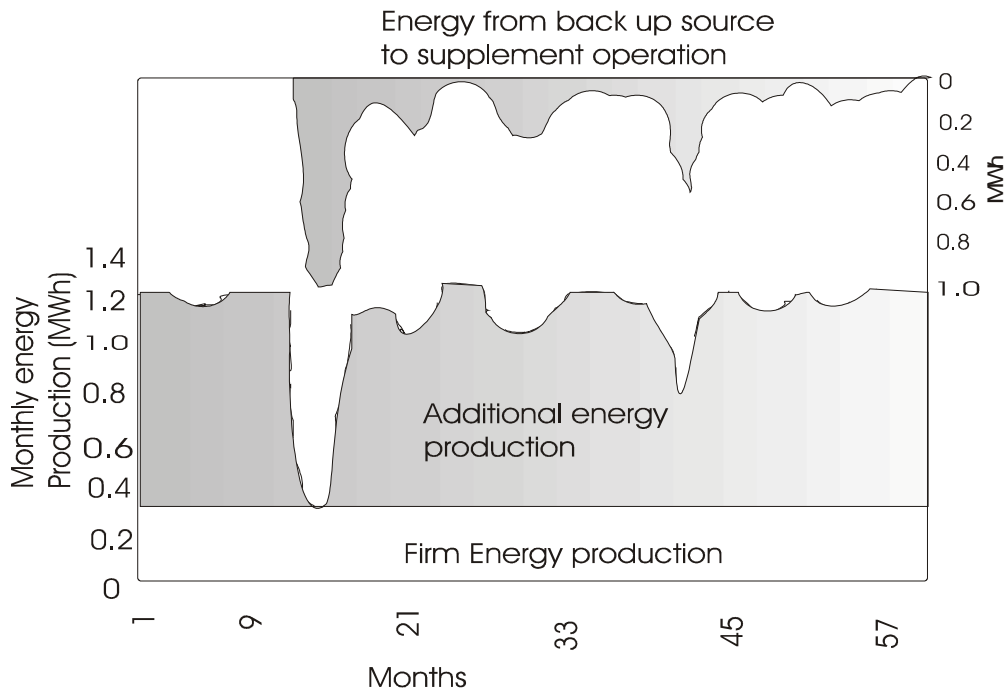


Figure 5 Flow chart of dynamic programming algorithm

### 3.5 Output of the Applied DP Procedure

The DP procedure produces the optimal energy production curve on a monthly basis. The advantage lies in the flexibility of operation of the power plant which enables the maximum utilisation of the storage for energy generation. Such a curve for the Ropi dam is shown in Figure 6. The optimal monthly energy production for arbitrary five

Figure 6 Monthly optimal energy production



years period shows that there is a considerable increase in the total energy production as a result of setting the installation capacity of the power plant higher than the firm capacity.

However, shortage occurs at times of extreme low flow during which the power plant's operation would be restricted to the reliable reservoir yield. In order to maintain a constant supply at a higher production level, the provision of a standby supply source seems mandatory. A diesel generator or any other appropriate source can be used as a supplement to the storage dam during such extreme conditions.

#### 4 Run-off-River Plant

To avoid the difficulties of storing water, small hydro projects are designed as run-off-river schemes. Since such schemes rely on the natural inflow, they cannot provide the same level of services as a hydroelectric plant with a reservoir. Therefore, run-off-river plants must be coupled with other generating plants so that they can meet seasonal and daily demand fluctuations, *Egre 1999*.

For run-off-river plants, the extent of availability of natural flow is determined from the flow-duration curve as discussed in a previous section. A more elaborate information of the power potential can be given in a power-duration curve. A power-duration curve is similar in feature to a flow-duration curve except that it contains additional information on the available head at the site. Figure 7 shows a power-duration curve for the Ropi site. The curve provides a useful basis for determining the relationship between installation capacity and its degree of dependability. A design limited to 90% exceedance, for instance, leaves a greater portion of the energy generation potential unutilized. In contrast, design for higher flows, say 75%

exceedance, would result in higher energy utilization as shown in the power-duration curve. However, the later requires substantial back up energy than the former.

The above discussion points to the need for an optimum choice of installation capacity. In general, a way has to be found to increase the energy production while at the same time maintaining the reliability of supply. As mentioned before, one solution

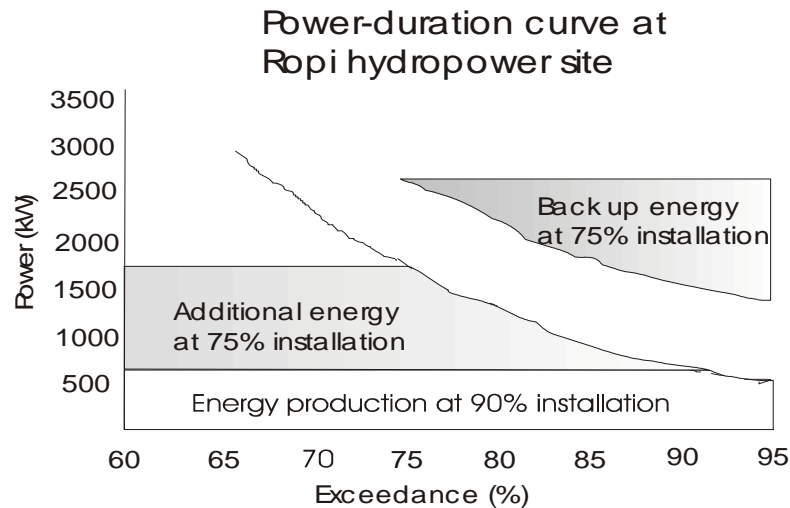


Figure 7 Power-duration curve -Ropi hydropower plant

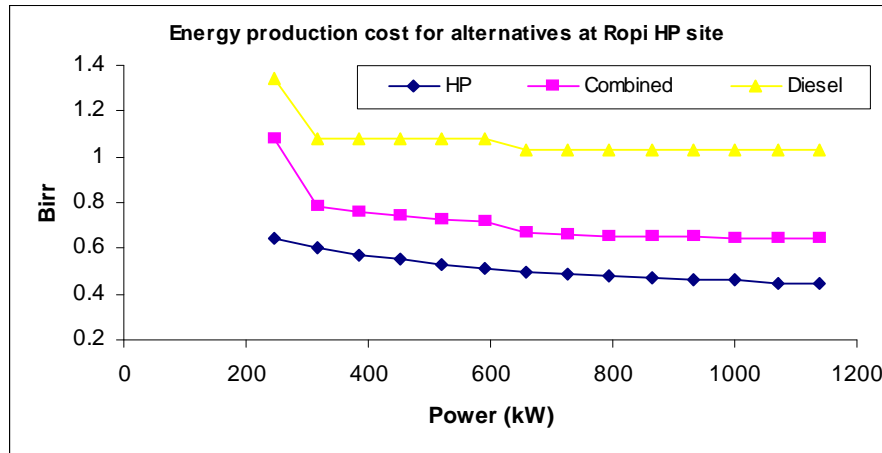
could be to supplement the hydropower production with another source of energy such as diesel generation. The role of the diesel generator being the contribution to the attractiveness of small scale hydropower utilisation.

#### 4.1 Diesel backed hydropower generation

Figure 8 shows the energy production costs for diversion type hydropower, for diesel generation and for a combination of the two at the Ropi site. The production costs of the hydropower plant are smaller than the diesel generator. But, the diesel generator can supply at its guaranteed installation capacity as long as there is no shortage in diesel supply. The hydropower plant on the other hand can be operated at installation capacity level only during sufficient flow periods. Thus the energy production falls down to lower levels during drier seasons.

It is apparent from Figure 8 that the combined operation of a diesel and a run-off-river plant gives a slightly higher production cost than a purely hydropower supply. But, the combined system provides more guarantee for covering the peak demand. Consequently, investment in backup generators can be considered to be an insurance against adverse effects of power outages, *Hakkarainen et al 1993, Mathur 1999*. In fact, the difference in production cost between the pure hydropower option and the combined system is the price that must be paid to ensure reliability of supply.

Figure 8 Energy production costs of alternatives



It is necessary to limit the use of the diesel generation both from economical and environmental aspects. In the considered case, the total energy production by the diesel unit is less than 20% of the overall production. However, the diesel generator plays the role of improving the reliability and the maximised utilisation of the hydropower supply.

Gradually, the use of diesel backup will have to be abandoned in favour of other environmental friendly sources. In this regard, operating small hydropower plants in combination with other renewable energy sources could be the best solution. It is a pity that in most of the recent renewable energy studies, hydropower is not given a primary role. In fact, there seems to grow a wrong notion that other renewable energy sources such as wind power could replace hydropower. However, since most of the other renewable energy systems are dependent on a supplementary power source, they can not be considered more renewable than hydropower, *Gagnon 1997*. In reality, hydropower poses a lower financial risk as compared to other renewable energy sources because of its longer operating life, *Eichenberg 1999*.

Hybrid systems are a potentially significant solution to rural electricity needs, but further technology development and industry expansion will be required, *Taylor 1998*. In this regard, thorough research is necessary to achieve the smooth operation of combined renewable energy systems. Research must also be geared towards reducing the relatively high unit cost of production from solar energy, *Horlacher 1994*. This is so because solar energy is the most important candidate among the renewable energy sources in tropical regions. Renewable energy hybrid systems should be favoured by Global Environmental Facility (GEF) since one of the focal points of the facility is lowering barriers to the success of renewable energy and energy efficiency technologies, *Barnes et. al 1998*. The Clean Development Mechanism (CDM) can also contribute substantially to the success of renewable energy promotion in developing countries, *Parkinson et. al. 1999*.

## **4.2 Supply to Grid....a possible compromise**

A possible way of increasing the load factor of a stand alone power plant is through supply to the national grid. Such a strategy has a mutual benefit to all concerned bodies. First and foremost, the public will benefit from assured energy supply. Secondly, the burden on national electric utility will partly be shared by the private power developer. Thirdly, the developer will have the incentive of operating the power plant at full production level to maximise the energy production and thereby his profit. Last but not least, the variable energy production from a diversion type or from a storage type small hydropower plant can be admissible since the grid can compensate for periodic lower level of production from excess production at other supply points. As a whole, the power supply can be composed of purely renewable sources satisfying both economic and environmental criteria of power development.

## **1.4 Key institutional and legal aspects of small hydropower development**

Reliable, well-designed, and integrated technology is important, but it is the institutional aspects of a project that make or break long term sustainability, *Taylor 1998*. Legislation in most countries has been or is in the process of being amended, to permit small producers connection to the public grid, at the same time obliging the large utilities to buy power from small producers, *Biermann 1995*. However, the record of disseminating energy technologies into rural areas of east Africa has not been particularly good and previous approaches have been criticised for failing to involve relevant stakeholders in the process, *Salter 1997*. Due to this, a number of sub-Saharan African countries have considered legal instruments that would facilitate independent and decentralised electricity generation, as well as sale to the grid, *Karekezi 1995*. In line with this, Ethiopia announced that its power market is open for foreign investment as of 1999, *EIA*. It remains, however, a lot to be done with respect to the development of institutional and technical capacity for small hydropower development. In this regard, lessons have to be gathered from the experience of Asian countries.

In many Asian countries, the policies of the early 1990s, to encourage private sector participation, have progressively been translated into new legislation and implementation rules with the intention of attracting private small-scale mini hydro developers. However, with the exception of China, the number of private mini hydro plants brought on-line in Asian countries were not significant, *Eichenberg 1997*. The success of mini hydropower in China lies in the fact that government support was combined with the initiative of enthusiastic rural farmers, *Luan 1999*. In this regard, the "Three-self-reliance policy" promoted by the government of China was instrumental for the success of private involvement in the energy market. This policy gives the people who invest and construct mini hydropower plants the right to manage, consume the generated electricity and to collect revenues from the plants. In effect, power plants operated this way do not suffer from the problem of low load factor which is a common problem of stand alone mini hydropower plants for rural electricity supply. This is so because local participation helps by-pass two of the major constraints to rural electrification: high costs connected with distribution services, such as meter reading and billing; and lack of income generating uses of electricity, *Gerger et al 1995*.

## **Conclusion and recommendation:**

The paper showed that the variability of stream flow is one of the major constraints of small hydropower development in semi-arid regions. Even though the study is not considered to be sufficient to make a generalisation, an adequate insight has been provided as to how the operation of small hydropower plants could be highly restricted unless necessary measures are taken either to regulate the river flow or to supplement the power supply of the hydropower plants. Flow regulation by means of small reservoirs can prove to be a solution only so long as care is taken to keep the reservoir size within environmentally tolerable limits. The paper recommends the use of reservoir reliability curves for the choice of optimum and environmentally compatible reservoir size.

Storage type hydropower plants with environmentally acceptable storage level can be made to deliver economically attractive amount of energy if their operation is backed up by other energy sources. The same applies for unregulated run-off-river type of developments. At present, the most suitable form of back up source is diesel generation. However, the paper recommends the provision of back up from viable renewable energy sources as the best strategy for future. This, of course, requires focusing due attention on making energy accessible to the rural poor. Provision of adequate energy in general and renewable energy in particular is the only solution that could prevent the threat of environmental degradation that is hovering over most developing countries.

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