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**AN OPTIMAL ENERGY AND WATER MODEL FOR  
DESIGN AND ANALYSIS OF WATER RESOURCES  
OF A RIVER WITH CONSTRAINTS ON  
ENERGY AND ECOLOGY**

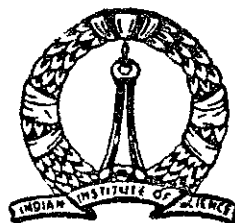
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**TECHNICAL REPORT 8**

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Present day water resources systems have many uses like (i) water for irrigation, (ii) energy (hydro-electric) (iii) water for industries and (iv) direct energy (transportation, water wheels etc). Similarly, designs of systems of storage and canals are constrained by energy, ecology, terrains, crops criteria.

This paper introduces a model for optimal utilization of water and energy in the water. The constraints introduced are (i) constraint on hill ecology - storage at hilly areas and forest areas, (ii) constraints on crop types and area covered, (iii) water economy on crops, trees - shares of each to be cultivated, (iv) power generations - peak powers, with minimum storage to balanced power throughout the year, (v) energy balance - water and firewood.

The model is a parametric one and it can be solved for various scenarios. This is because of the fact that some of the constraints can not be directly modelled by means of mathematical equations for want of data. Also constraints vary. For example, hydroelectric power has the following options:

- (i) carry over large reservoirs on the mountain range holding the year's water available (using the head and energy evenly throughout the year).

- (ii) Peak power plants at the higher plateaus with minimum reservoirs and annual power plants at mid-ranges
- (iii) locations of power plants at many points
- (iv) run of the river plants

Similarly crops have their options: (i) cereal crops - heavy water consuming, least water consuming etc. (ii) pulses (iii) trees. Again storage is a common point between these two. Yields of crops based on water is used in the optimizing objective function.

The fall out aspects are separately discussed. The optimization has the following stages (i) parameter selection (ii) sub optimization at different ranges (iii) over all optimization. The model is being tested and some of the aspects are illustrated through actual case studies.

This paper discusses a model for tapping maximum energy and irrigation from a river. Many rivers in India and in other countries start from hilly ranges, flow through undulating areas and plains before reaching the sea. Many tributaries join them at different places. The present pattern of utilization of such rivers lead to predominantly the following set of solutions.

- (a) Impounding of a large quantity of water in the higher hilly ranges mainly with a view to generate power. Such hydroelectric plants have been designed primarily with a view to maximize power production. Since power demand throughout a year is very nearly even and since in the early days, hydroelectric generation was a major source of power (even today the States of Karnataka and Kerala in South India get their electric power only from hydroelectric plant, Karnataka is constructing a thermal plant based on coal and is expected to be commissioned in a few years), the designers approached the problem of power generation from the point of view of storing water and getting power throughout the year. This philosophy replaced run of the river plants and other plants by a hydro station backed by a large

reservoir. The reservoir impounds such quantity of water as can meet the power demands for a year. The design of Linganamakki reservoir of the Sharavathi Valley project in Karnataka is designed on such principles - as a carryover reservoir so that energy can be carried over from a surplus year to a lean year.

Further since construction costs were low and costs of generators were high in the earlier era, economics of scale played an important role. This resulted in the construction of a large reservoir impounding as much rain water as possible and a large power plant with unit sizes in the range of 100-200 MWs. Some rain water can be harvested only for a short duration - of three months say - the reservoir is built with a capacity to store required water for nine months. To sum up, objective was to mop up every cc of water and use every centimetre of head and as far as possible to go in for larger sized power plants.

b) The requirements of water for irrigation are met by two different approaches:

- (i) To impound water on a dam or a set of 2 or 3 dams and take it to the various command areas through canals. This allows use of water for a longer duration, permits double cropping etc.

(ii) to draw water directly from rivers by canals, small lift irrigation systems and tanks at various villages. This system, which is an older system in India, is still working in many parts of our country. Again in this scenario also, the shift of technology is to move towards larger dams and canals running from them towards the far end of the command area. Sometimes canal water needs to be taken via aqueducts and also we need large bridges to cross highways. This development is due to convenience, easier management general applicability and ease of control of water flow in canals. In many rivers both systems are prevalent - major dams in hilly terrains and minor dams and tanks in plains and places with small undulations. In some instances water is used both for irrigation purposes and to produce electrical energy.

Let us now look at some of the problems and motivations in the model being developed.

(i) As already explained, hydroelectric projects are designed on a large scale and to store maximum quantity of water. This does not take into account the problems of forest denudation.

Early days, the number of power projects coming up was few and hence the effect of them on ecology was not felt. But with large areas of forests being denuded for various activities such as power projects, agriculture, population settlements, industries and many natural causes, the availability of prime forest areas for water submersion in a power project is becoming difficult and costlier.

Also earlier designs did not take into account the effect of water submersion on catchment areas also, the revenue from forests, the cost of rehabilitation and resettlements of persons displaced, and the effect of soil erosion were ignored totally. Since we can look at forests also as a source of energy - they provide firewood, a fuel essential to the living of majority of rural people in India, Firewood constitutes more than 80 percent of rural energy source and it meets a sizeable component of urban domestic energy needs - any design should optimize the area of submersion. This opens up the following possibility at the extreme,

We design a power plant with two sections (a) peaking power and (b) steady power,

Peaking power is available only during monsoon. All excess rain water beyond storage in a reservoir can be converted into peaking energy.

Steady power - the capacity will be quite less than peaking power - is available throughout a year. This power and consequent energy are maintained by the water stored in the reservoir.

Since peaking power is available for a short duration only, its load factor is low (about .2 or so). This results in two problems (i) cost of energy is higher (ii) we need a matching thermal plant to generate equivalent amount of power and energy during the lean period - when peaking power is not available.

In a well mixed system, the second aspect mentioned above can be taken care of. Only the cost factor remains. Since the proportion of cost for construction is increasing and the percent component of cost of generating station is decreasing (due to technological improvements) the cost/unit of peaking energy is becoming economical. An example will show this clearly.

If  $x$  is the total annual cost for a project and let us assume that 66.7 percent of this cost goes towards construction of reservoir etc and 33.3 percent

of this cost for generating station. If such a plant of capacity  $Y$  is replaced by a plant with a steady capacity of  $Y/2$  for one year and a peaking capacity of  $2Y$  for 3 months (sa) then total energy produced is the same in both cases assuming no large variations in daily load factors. Then the cost of such a plant will be (without economics of scale)

(a) annual cost of construction =  $x/3$

(b) annual cost of steady plant =  $x/6$

(c) annual cost of peaking plant =  $2x/3$

Total cost =  $1.167x$ .

Thus cost of this alternate design is only 17 percent more than the cost of the earlier design. If costs of revenue loss from forests and other factors are considered, the proposal becomes economical.

The model proposed has a decision variable pertaining to the area of submersion and this value is an outcome of this optimization model. The model as will be shown later, considers revenue from forests and other costs also.

(ii) The second problem looks at irrigation usage. Again, in order to maximize revenue, the existing systems consider changeover to high profit varieties like sugarcane, paddy etc. Paddy cultivation in some irrigation commands have led to water logging and

salinity problems resulting in a loss of cultivable area. Further as sugarcane consumes more water and inputs, it may not be economically the best option. Hence the model introduces different crop production. This becomes important in a country with an objective to provide basic food for a maximum number of people.

Presently, projects are chosen (in India) based on a benefit to cost ratio. Such a ratio results in going in for high profit crops rather than water conserving low profit crops. This is due to

- i) A high profit crop gets a higher profit due to market situations examples being tobacco, sugar cane etc.
- ii) if a lower cost water conserving crop is chosen (like jowar, ragi, onion etc) the command area increases, this means more management problems.
- iii) Multiple cropping pattern implies more extension programs, intensive education of farmers.

As a first approximation, the proposed model incorporates a few crops and is only approximate as far as global crop selection is concerned. A global algorithm should include crop requirements, failure rates, cost of inputs availability of inputs, soil fertility etc. Whereas this model has two decision variables one to select a set

of crops and the second to find the area under each crop.

The next section describes the optimization model.

## 2. Statement of the problem:

We would like to maximize annual returns from a river - indirectly optimizing utilization - both from energy and irrigation point of view subject to constraints on ecology and availability. The basic approach is to divide the entire length into a number of sections and optimize each section individually. Normally, water distribution amongst these sections can be initially chosen and can be refined further. The other approach is to optimize for the entire river - since the number of variables is not large and an algorithm can be easily fitted in, it is possible to generate an integrated model.

2.1 The objective function: It is intended to maximize annual returns. The objective function consists of the following components:

revenue from net energy production, annual costs for capital costs of construction and generating stations (negative), net annual operation and maintenance costs (negative),

revenue from peak energy, net loss due to denudation of forests due to submergence (other than that for energy from biomass), net loss due to displacement of population,

#### 2.1.1 Revenue from net energy production:

From the rainfall-runoff-statistics, it is possible to estimate the maximum annual quantity of water available. By storing this water we get hydroenergy. But the submerged area can grow biomass which gives us energy that can be used in domestic, industrial and other end uses. This energy is not insignificant. Only when the head of water is very high and the reservoir profile is a deep valley with steep walls at its sides, can the hydroenergy be very competitive compared to firewood. But, when the head is not much and when the terrain of the reservoir has a slow slope, then a smaller depths of the reservoir, the firewood is attractive and below certain values of depths, it is more efficient storage device than water. Table - 1 illustrates this.

Let us assume that the surface of the reservoir is a circle. This can be changed to other

geometrical shapes. But it is easier to illustrate this. Then there is an optimum surface area. Let  $x$  be the radius of the circle, then if we assume that the depth radius relationship to be

$$Y = Y_{\max}(1 - e^{-ax}) \quad (1)$$

Then we can write total hydroenergy as

$$e_h = V.W.H.\eta.C_e \quad (2)$$

where  $W$  = weight of water/unit volume

$H$  = net head of water

$\eta$  = Efficiency of conversion

$C_e$  = evaporation factor

$V$  = total volume of water

$V$  is given by

$$V = 2\pi Y_{\max} \left( \frac{x^2}{2} + \frac{1}{a} x e^{-ax} + \frac{1}{a^2} e^{-ax} - \frac{1}{a^2} \right) \quad (3)$$

From the area to be submerged ( $= \pi x^2$ ), the energy lost (due to biomass) is

$$\begin{aligned} e_f &= k(\pi.x^2).r.c.v.\eta_c \quad (3) \\ &= f_2(X) \end{aligned}$$

where  $r$  = annual rate of growth

$cv$  = energy equivalence factor

$\eta_c$  = energy conversion efficiency, if any,

$k$  = ratio of apparent area to actual area

$$\text{Net energy} = e_h - e_f = f_1(X) - f_2(X) \quad (4)$$

where  $f_1(x)$  is a function for  $e_h$ ,

$$R_1 = \text{Revenue from energy} = C_u(e_h - e_f) \quad (5)$$

where  $C_u$  is cost/unit of energy

Equation (5) gives us net revenue from energy.

### 2.1.2 Annual charges on capital costs:

The capital cost depends on construction cost that depends on energy and cost of generating unit that depends on the capacity. The capacity (MW) is calculated assuming a normal load factor,

$$R_2 = \text{annual costs} = \alpha (f_3(x)cc + ck.eh/(\text{Pf.lf } 8760)) \quad (6)$$

where  $\alpha$  is the fraction of capital cost assumed as annual cost, based on interest, depreciation, rate of return etc.,

cc - cost of construction/unit of water stored

ck - Cost/KVA of generating station

lf - load factor

pf - power factor

### 2.1.3 Peak energy revenue:

If  $Q$  is the total quantity of water available due to rainfall in the catchment area and inflows minus outflows, then quantity of water available for peak power is

$$Q_p = Q - V \quad (7)$$

energy is given by

$$e_p = W \cdot Q_p \cdot H \cdot \eta \cdot c_e \quad (8)$$

$$R_3 = \text{Nett revenue} = \text{earnings from energy} - \text{annual charrges} \quad (9)$$

(In the case of annual charges, only the part pertaining to additional generation is to be considered, the secondpart of equation (6)).

#### 2.1.4 Net loss due to forest reduction:

Since the forest area is submerged, the benefits we get from that area are lost. One aspect i.e. firewood energy - is already considered. The other aspects are (i) by products (ii) grass and other biomass as food for cattle (iii) improvement of environment - water and soil conservation properties and reduction of floods, (iv) raw material etc. Since these are proportional to area of submersion, we can unite it as  $R_4 = f_4(x')$  where  $x' = kx$  is the apparent area (the area of submergence effects the neighbourhood areas also, hence sometimes the area affected is more than this submerged area. This is taken into account by the factor k).

#### 2.1.5 Annual cost due to displacement and resettlement:

This depends on area of submergence and population and can be written as

$$R_5 = f_5(x, p) \quad (10)$$

where  $p$  is the population density

### 2.1.6 Yield from agriculture:

If we assume that a set of crops are possible to be cultivated in that area, then let  $x_{ji}$  -

area to be cultivated for  $j$ th crop in  $i$ th section

$y_j$  = is the net yield in rupees/unit area for crop  $j$ ,

$q_{ji}$  = is the water required by crop  $j$  in section  $i$  for a unit area.

then yield is given by

$$R_6 = y = \sum_{j=1}^n y_j x_{ji} \quad (11)$$

while calculating net yield  $y_j$ , we should deduct the yield obtainable due to rainfed cultivation and other input costs, similarly the area  $x$  includes double cropping as additional area.

The total annual return is given by

$$\phi = R_1 - R_2 + R_3 - R_4 - R_5 + R_6 \quad (12)$$

This is the function to be maximized.

$$\text{For } I \text{ sections we get } \bar{\phi} = \sum_{i=1}^I \phi_i \quad (13)$$

The next section deals with constraints.

### 3. Constraints

(i) Water available in each section ( $Q_1$ )

$$Q_1 \leq \begin{aligned} & \text{total water inflow from previous section} \\ & - \text{total water outflow to the next section} \\ & + \text{local water harvesting} \end{aligned}$$

$$i = 1, 2 \dots I \quad (14)$$

Some of the inflows/outflows are scheduled, others are to be treated as variables. In the separation algorithm for each section, these are assumed initially and refined by repeating the algorithm until convergence.

(ii) Irrigable area in each section

In each section the maximum area under cultivation is known and also the maximum area reachable by irrigation.

Hence we get the constraint the sum of total area under each crop should be less than this.

$$\sum_{j=1}^n x_{ji} \leq a_{\max}^i \quad (15)$$

$$i = 1, 2 \dots I$$

where  $a_{\max}^i$  is the maximum area (given) in section  $i$ .

(iii) Water requirement of crops in each section.

Since we know the water requirement/unit area for each type of crop ( $q_{ij}$ ) we should see that total water available should be greater than total water requirement by various crops. That is

$$\sum_{j=1}^n q_{ij} x_{ij} \leq Q_i \quad (16)$$

$$i = 1, 2 \dots I$$

$x_{ij}$  is the area of crop  $j$  in sect  $i$ , to be determined by solving the problem.

- (iv) Maximum and minimum quantities for water storage and crop areas

$$V_{imin} \leq V_{imax} \quad (17)$$

$$i = 1, 2, \dots, I$$

$$X_{ijmin} \leq x_{ij} \leq X_{ijmax} \quad (18)$$

$$i = 1, 2, \dots, I$$

$$j = 1, 2, \dots, n$$

$V_{imin}$ ,  $V_{imax}$ ,  $X_{ijmin}$ ,  $X_{ijmax}$  are known/assumed quantities.

- (v) In some subsections (say a hilly terrain), the same quantity of water cannot be used both for power generation and irrigation. Then  $Q_i$  is split as  $Q_{ip}$  and  $Q_{iw}$  and  $Q_{ip}$  is used in all constraints pertaining to power and  $Q_{iw}$  for water.

$$Q_i = Q_{ip} + Q_{iw} \quad (19)$$

is included in the model.

- (vi) For power production, we should state that total volume of water should be less than the quantity available.

$$V_i \geq Q_{ip} \quad (20)$$

$$i = 1, 2, \dots, I$$

- (vii) In order to compare with other power plants under consideration, the cost/unit of energy should be less than the prevailing rate. This constraint can be included as a check on the solution. If the cost works out as higher, the project can be rejected.
- (viii) Positivity constraints.

Our decision variables are positive

$$\begin{aligned}
 X &\leq 0 \\
 x_{ij} &\leq 0 \quad (i = 1, 2, \dots, I) \\
 &\quad (j = 1, 2, \dots, n) \quad (21)
 \end{aligned}$$

$$Q_{ip} \leq 0$$

$$Q_{iw} \leq 0$$

Now the problem is to maximize  $\phi$  subject to these constraints. The problem is a nonlinear one, but solution is very straightforward one.

We solve a Lagrangian multiplier given by

$$L = \phi + \varepsilon_i (Q_i - Q_{ip} - Q_{iw}) \quad (22)$$

Then we check for inequality violations. Wherever inequalities are not obeyed, the boundary values are chosen and the problem is resolved. This procedure is repeated until all constraints are obeyed. The resulting solution gives the first order solution which can be fine tuned by detailed subsequent analysis.

#### 4. CASE STUDY: A HYDROELECTRIC PROJECT

In recent years, the Silent Valley project of the Kerala State in India has evoked considerable attention from various sources. The project expected to generate power will submerge a large part of virgin rain forest, thereby destroying one of the oldest unique ecosystems. The argument in this case was to weigh the advantages of power generation vs the maintenance of a unique ecosystem which is not fully understood and which may have a reservoir of 'gene pools' of many unidentified and very old plants. Whereas it is possible to obtain alternate ways of getting the power, there is no alternative to get a similar ecosystem. This introduced lively discussions amongst various sections of scientists.

Similarly another hydroproject in Karnataka also got a good attention. This project is on Bedthi river in Uttara Kannada dist. This river is a short one and flows through some of the dense and good forests of Karnataka. The project is expected to generate about 200 MWs of power submerging about 10,000 hectares of prime forest area and displacing about 6000 people. The capital cost has a major component going to the construction

of dams and tunnels. Table 2 shows the cost/unit and benefit/cost ratio for this plant. Here it is shown that benefit/cost ratio is less than one and hence the plant is not a variable one as designed now.

Instead, it if is modified so as to produce 400-500 MWs in monsoon season - for three months and to produce 80-100 MW in the remaining period with the help of a smaller storage unit, cost/unit of energy remains the same and benefit to cost ratio also improves. In addition, this saves forest area from submersion and lesser number of families will be displaced.

The model is being further refined to include a number of mini and microhydel plants and direct water conversion systems so that an overall optimum can be obtained.