Optimal design of hydroelectric projects in Uttara Kannada, India

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Abstract The planning of water resources depends on the type and size of projects, the ecological factors involved, etc. Emphasis is placed on presenting an overview of water resources through meteorological, hydrological, ecological and economic data. Economic data include all costs and benefits, specifically those hitherto under estimated, environmental social costs and benefits. This study was carried out on the Bedthi and Aghnashini rivers in the Uttara Kannada district of the Western Ghats region, Karnataka State, India. It is estimated that 720 and 510 million kWh of electricity can be generated in Bedthi and Aghnashini River basins, respectively, if all the streams are harnessed. Focusing on land submergence impact, a model is proposed to minimize submergence and maximize net energy in a region with seasonal power generation, reservoir storage capacity (to meet the region's demand during all seasons) and installed generation capacity as the decision variables. Net energy analyses incorporating biomass energy lost in submergence show that maximization in net energy at a site is possible if the hydroelectric generation capacity is adjusted according to the seasonal variations in the river's water discharge. A Decision Support System (DSS) used for optimal design of hydroelectric projects in Uttara Kannada district is discussed.

Un système d'aide à la décision pour la conception optimale de projets hydroélectriques en Uttara Kannada
Résumé La planification des ressources en eau dépend de la nature et de la taille des projets, du cadre écologique, etc. Nous avons surtout voulu présenter ici un panorama concernant les ressources en eau à travers des données météorologiques, hydro-logiques, écologiques et économiques. Les données économiques incluent tous les coûts et bénéfices, en particulier ceux qui ont jusqu'ici été négligés, de même que les coûts et bénéfices environnementaux et sociaux. Cette étude a été entreprise sur les rivières Bedthi et Aghnashini du district Uttara Kannada de la région Ghats occidentaux (Etat de Karnataka, Inde). On estime à respectivement 720 et 510 millions de kWh les quantités d'électricité pouvant être produites par les rivières Bedthi et Aghnashini si elles étaient totalement aménagées. En nous intéressant particulièrement à la submersion des terres, nous proposons un modèle minimisant les submersions et maximisant la production énergétique, les variables de décision étant la production saisonnière d'énergie, la capacité de stockage des réservoirs (devant satisfaire la demande en eau quelle que soit la saison) et la puissance installée. Un bilan énergétique incluant les pertes de production de biomasse résultant des submersions montre que la maximisation de l'énergie nette produite est possible si la puissance installée est adaptée au régime des débits. On examinera enfin un système d'aide à la décision utilisé pour la conception optimale des projets hydroélectriques de l'Uttara Kannada.

INTRODUCTION

Karnataka state has the unique distinction of having set up the first hydropower plant in India at Shivanasamudram in 1942. Since then, hydroelectric plants have contributed significantly to both the State's and national demand for electricity. Most of Karnataka's hydroelectric plants are located in Uttara Kannada district. Construction of

large reservoirs is restricted due to environmental constraints, necessitating the development of ecologically sound alternatives.

Hydroelectric power development—present status and approaches in design

At present hydroelectric power development is undertaken on an *ad hoc*, project-by-project basis with capacity based on 90% availability of water annually, estimated on the basis of a 10-day period. Since seasonal and yearly fluctuations of rainfall/ streamflow are high, planners tend to opt for large reservoirs to achieve their goal. There is a need to consider integrated systems planning of supply and demand for optimal development of the potential considering 90% reliability of the system in the region. Demands of appropriate benefit–cost ratio (e.g. greater than 1.5), or least cost of generation for clearance, ignore the energy/economic costs of submergence and alternative designs involving seasonal variation in generation. Optimization (programming) and descriptive (predictive) model approaches are usually adopted to accomplish this complicated task (Falkenmark, 1989). Decision Support Systems (DSS) focus more on providing flexible tools for policy analysis than on providing models to answer structured problems (Parker & Ul-Ataibi, 1986). This paper focuses on the design of a hydroelectric project using DSS, emphasizing economic efficiency and engineering soundness, subject to social, environmental, ecological, cultural, institutional and legal constraints.

OBJECTIVE

The objective is to design a hydroelectric plant utilizing optimal energy in the water, with minimum submergence and economic costs, considering seasonal variation in power generation to meet the region's demand during all seasons

STUDY AREA

Uttara Kannada district lies between 74°9′–75°10′E longitude and 13°55′–15°31′N latitude with 67% of its area under forest, 27% under habitation and reservoirs, and the rest under various cultivation covering 10 291 km^2 (Fig. 1). The large reservoirs for hydroelectricity generation of Kali and Sharavathi have submerged vast tracts of natural forest and dislocated a large number of people. Therefore, an attempt is made to explore ecologically sound means of harnessing the hydroenergy of the Bedthi and Aghnashini rivers.

STREAMFLOW MEASUREMENT AND COMPUTATION OF POWER

Streamflow depends on drainage efficiency of hill slopes, moisture content of the soil, subsurface geology and vegetation cover (Gordon *et al*, 1992). Streamgauging using a current meter indicates that streams in these catchments are seasonal. The relationship between runoff at gauged sites and rainfall was determined by regression analysis. This relationship was used to assess the potential of ungauged streams. It was estimated that
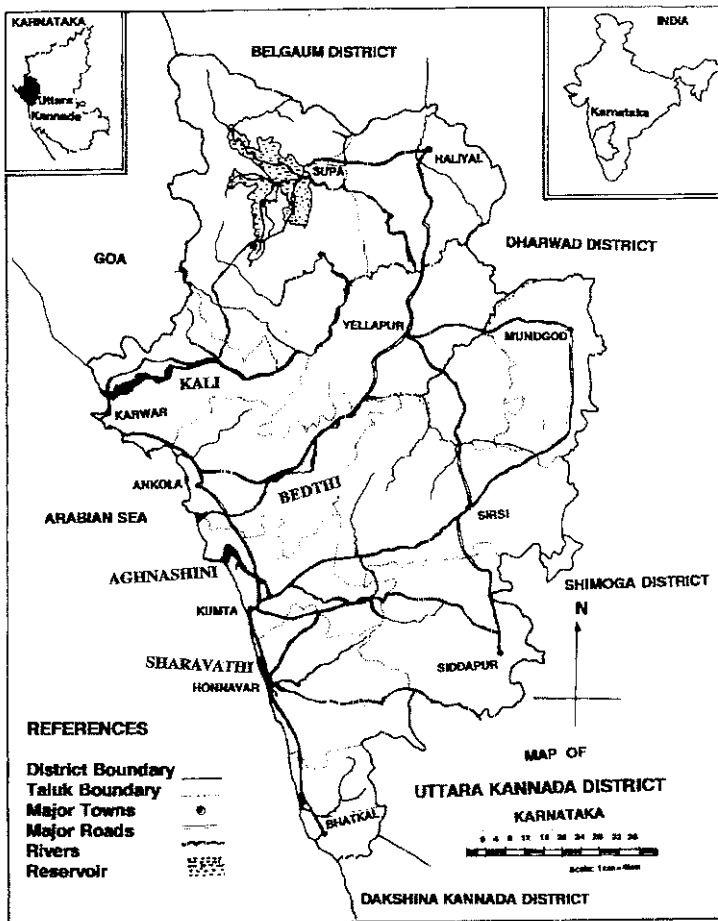
Fig 1 Geographical location of Uttara Kannada district.

about 720 and 510 million kWh of electricity could be generated in Bedthi and Aghnashini River basins, respectively.

The potential assessment shows that most of the streams would cater to the needs of local people in a decentralized way during the monsoon, ensuring continuous power supply, which would otherwise be disrupted by dislocation of electric poles/pylons or falling of trees/branches on transmission lines due to heavy winds. A detailed household survey of villages in hilly areas shows that people have to spend at least 60–65% of the season without electricity when depending on a centralized supply. In view of this, an ecologically sound alternative is proposed, which would generate maximum electricity during the monsoon season and sufficient electricity during the "lean" season.

DESIGN OF A RESERVOIR WITH ENERGY AND ECOLOGICAL CONSTRAINTS

The environmental impacts associated with large reservoirs necessitate the design of reservoirs of appropriate sizes to meet the target demand of a region (Mutreja, 1976)

Because of the negative aspects of hydroelectric projects in ecologically fragile hilly terrain; the submergence area should be minimized; the project should be subject to reasonable cost, minimum or no wastage of water and seasonal constraints (the region receives maximum rainfall during southwest monsoon). Based on 90 years' precipitation data and 18 months of river runoff data, a methodology is proposed to design a storage reservoir at Magod to meet the region's demand during all seasons.

Hydroelectric energy operation module

A decision support system for optimal design and operation of a large network of small reservoirs for agriculture is described elsewhere (Labadie, *et al.*, 1988; Albuquerque, 1993). The operation module is designed based on predetermined hydrological flow (database, environmental and socio-economic modules), a GIS module, technical data, economic data and a certain user selected reliability level. It also generates adaptive operation policies based on this reliability level. An adaptive optimum control module decides the quantity of water to be drawn from the reservoir considering seasonal constraints, volume of water stored for particular height of dam, seepage loss, evaporation loss, dead storage capacity of dam and rate of sedimentation, to ensure there is no wastage of water. It also decides the storage capacity during the non-monsoon season. The net energy available in the region is also presented in this module. Figure 2 shows the components of the planning operation module.

Design assumptions and parameters

Assumptions Detailed geological and topographical investigations carried out by the Department of Mines and Geology (KPCL, 1993) to determine the best site for the dam, pressure shaft alignment, power house location, etc., can be used for implementing this design.

Parameters Input data consist of site specific data (discharge, water yield, generation head, evaporation rate, seepage rate etc.), technical data (efficiency of turbine and generator, and dependability norm for storage capacity, load factor, etc.) and economic
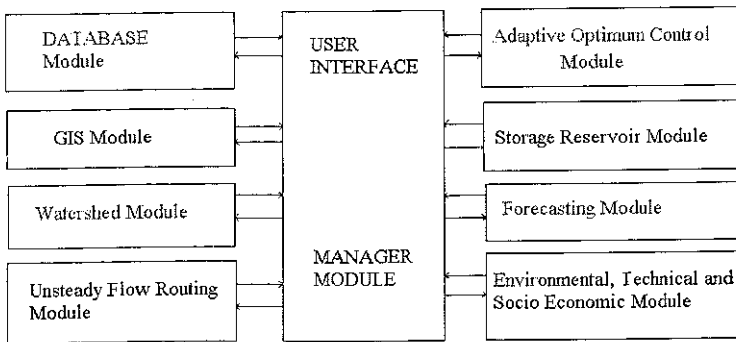

Fig. 2 Design of hydroelectric power station with optimal storage option: detailed operation module

data (civil construction costs for various types and heights of dam, cost of electrical machinery of various capacities, environmental costs, rehabilitation costs, etc).

Decision variables The decision variables determine the optimum storage capacity, installed generation capacity and seasonal power drafts; net energy availability in the region (objective function) needs to be maximized subject to seasonal hydrological constraints, and costs and submergence area are to be minimized

NET ENERGY MODEL—PARAMETRIC OPTIMIZATION

The broad outline of an optimization model for exploiting a river for hydropower and irrigation, incorporating energy cost and net increase in yield due to irrigation, with constraints on arable area and crop water requirement and seasonal variation in precipitation, has been formulated by Subramanian (1985). On the same lines, with detailed engineering design and quantification of data, the parametric optimization approach is used with an objective to maximize the net energy subject to ecological constraints, given by:

$$E_{net} = Eh - E_{bio} \tag{1}$$

where E_{net} is net energy, Eh is hydroenergy and E_{bio} is bioenergy This model is solved for various scenarios for optimal utilization of hydropower and thermal energy in the region This includes an equation which computes monthly hydropower production as a function of volume of water discharged (Q), gross head of this water (H) and efficiency of the couple turbine generator (η, between 0 7 and 0 85)

Hydropower (kW) is given by:

$$P = 9.81\,Q\,H \tag{2}$$

The corresponding approximate electricity produced $Eh = P\,t\,\eta$, where Eh is electricity (kWh) and t is operating time The monthly hydroelectricity generated in million kWh is given by:

$$Eh_t = \Sigma 9.81 D_t\, H\,\eta \tag{3}$$

where $t = 1, \ldots, 12$ and D_t is the power draft from the reservoir during a month (million cubic meters, Mm^3) Replacing 9 81 $H\,\eta$ as constant k_1:

$$Eh_t = \Sigma k_1\, D_t$$

This is decomposed for seasonal drafts:

$$Eh_t = \Sigma k_1\, D_{tm} + \Sigma k_1\, D_{td} \tag{4}$$

where D_{tm} and D_{td} are water drawn during monsoon ($tm = 1, \ldots, 4$) and dry period ($td = 5, \ldots, 12$), respectively

Energy loss due to submergence is given by:

$$E_{bio} = A_{sub}\, Gr\,(CV)\,\eta_c \tag{5}$$

where A_{sub} is the submerged area classified on the basis of land use, Gr is the annual

rate of growth or productivity, η_c is energy conversion efficiency and CV is the energy equivalence factor in terms of primary energy content (e g a ton of dry fuelwood with a calorific value of 4400 kcal kg^{-1} has a thermal content of 5112.8 kWh).

This model is subject to the following constraints:

Hydrological constraints These operate on a monthly basis and consist mainly of the following continuity equation (Maass *et al.*, 1962):

$$V_{t+1} = V_t + I_t - S_t - E_t - D_t \tag{6}$$

where V_t is the volume of the reservoir at the beginning of month t, I_t is inflow to the reservoir, S_t is seepage loss, E_t is evaporation loss, and D_t is discharge from the reservoir during the month t Equation (6) is solved using inputs such as the functional relationship between surface area, seepage, evaporation *vs* volume, sequence of monthly inflows into the reservoir and policy for determining the discharges from the reservoir A certain amount of "dead" storage capacity was added to account for sedimentation.

Dependability The storage capacity (V) of any reservoir is the function of both targeted draft (D) and reliability (R), given by:

$$V = f(D,R) \tag{7}$$

It is seen that the required reliability of targeted draft has a direct relation to effective storage capacity, which has to be provided For a given draft, particularly the one approaching a mean flow, the required storage is extremely sensitive to reliability. Similarly for a given level of reliability, increase in targeted draft would result in large storage. Thus, for a given draft, storage would increase substantially with increased reliability levels. For hydropower planning, in the case of power generation schemes, a dependability criterion of 90% on a yearly basis is normally adopted

Constraint on seasonal variation in generation capacity If no variation is allowed:

$$P_{tm} = P_{td} \tag{8}$$

Allowing seasonal variation:

$$P_{tm} \geq P_{td} \tag{9}$$

If variation of "r" is allowed:

$$P_{tm} \geq r P_{td} \tag{10}$$

The variables P_{tm} and P_{td}, are hydroelectric generation capacity during monsoon and dry months, respectively, written in terms of power draft as:

$$P_{tm} = k_1 D_{tm}/LF_{tm} \tag{11}$$

and

$$P_{td} = k_1 D_{td}/LF_{td} \tag{12}$$

where LF_{tm} and LF_{td} are average load factors during monsoon and dry months, respectively Therefore:

$$D_{tm}/LF_{tm} = D_{td}/LF_{td} \tag{13}$$

$$D_{tm}/LF_{tm} \geq r\ D_{td}/LF_{td} \tag{14}$$

Assuming

$$LF_{tm} = LF_{td} \quad (\text{as } 0\ 5) \tag{15}$$

Equations (13) and (14) would become

$$D_{tm} = D_{td} \tag{16}$$

and

$$D_{tm} \geq r\cdot D_{td} \quad r = 1, 2,\ ..,\infty \tag{17}$$

Constraint on minimum storage

$$Ka \geq V_t \text{ for } t = 1, 2, ..,12 \tag{18}$$

where Ka is the active storage capacity

Operating policy of the reservoir The feasible operating policy, considering seasonal variation in water inflow, would be: {$(S1\ P_{tm} + S2\ P_{td})\ 30\ 24\ LF$ (amount of water/million kWh) = total quantity of water (in Mm^3) available at site} The load factor, LF is the ratio of average load to peak load

From equations (12) and (15), with $S1 = 4$ (monsoon) and $S2 = 8$ (lean season) this constraint reduces to:

$$4D_{tm} + 8D_{td} = V_{t+1} \tag{19}$$

The regulation through storage could be shown as follows:

If $V_t + I_t - S_t - E_t - D_t \leq V_s$

then $D_t = V_t + I_t - S_t - E_t$ (20)

and

If $V_t + I_t - S_t - E_t - D_t \geq V_s$

then $D_t + d = V_t + I_t - S_t - E_t$ (21)

where V_s is the storage volume of the reservoir and d the excess quantity available for generation.

Positivity constraints Decision variables are positive

$$D_t \geq 0 \text{ for all } t = 1, 2, ..,12 \tag{22}$$

and

$$V_t \geq 0 \text{ for all } t = 1, 2,.. ,12 \tag{23}$$

Therefore

$$Ka \geq 0 \tag{24}$$

CASE STUDY

This design is implemented for the hydroelectric scheme at Magod

River discharge

The average annual yield at Magod is 1105 Mm^3 measured by empirical method. The 90% dependable water yield is estimated as 995 Mm^3 Water yield computed with 90 years precipitation data, shows that water quantity varies from 0.25 ± 1.25 during January to 364 ± 136 during July

Evaporation, seepage loss and silting capacity

Evaporation and seepage losses for the region are estimated as 99 Mm^3 $year^{-1}$ for 100 km^2 The silt rate per annum is given by $S = C(A)^{3/4} = 4.25$ (where C is the catchment coefficient and A is the catchment area (in m^2)) assumed for a basin with plain and forested tracts. With the silt rate of 0.83 Mm^3 $year^{-1}$, the life of the reservoir at *FRL* 450–455 m is about 50 years.

Dam site

The site proposed 0.91 km upstream of Magod Falls, at longitude 74°45′28″E and latitude 14°51′41″N commands a basin area of 2084 km^2 and has exposed rocky bed at either side The river bed level here is 373 m and it is 36 m wide

Dam height and submergence area

When the water head is very high and given the reservoir profile—a deep valley with steep walls, hydroelectric energy becomes very competitive compared to bio-energy When the water head is lower and the terrain has a slope less than 25°, the smaller reservoir depths and smaller submergence area make firewood an attractive option A dam at this site would submerge areas having bioresources such as firewood, that are used for domestic, commercial and other purposes.

The volume of water stored for a particular dam height, computed by assuming the volume between two consecutive contours to be trapezoidal, is:

$$V_{12} = (a_1 + a_2) \cdot 0.5 \, h_{12} \tag{25}$$

where V_{12} is the volume between contours 1 and 2, a_1 and a_2 are the area of contours 1 and 2 respectively, and h_{12} is the height difference between contours 1 and 2. The generalized form could be written as:

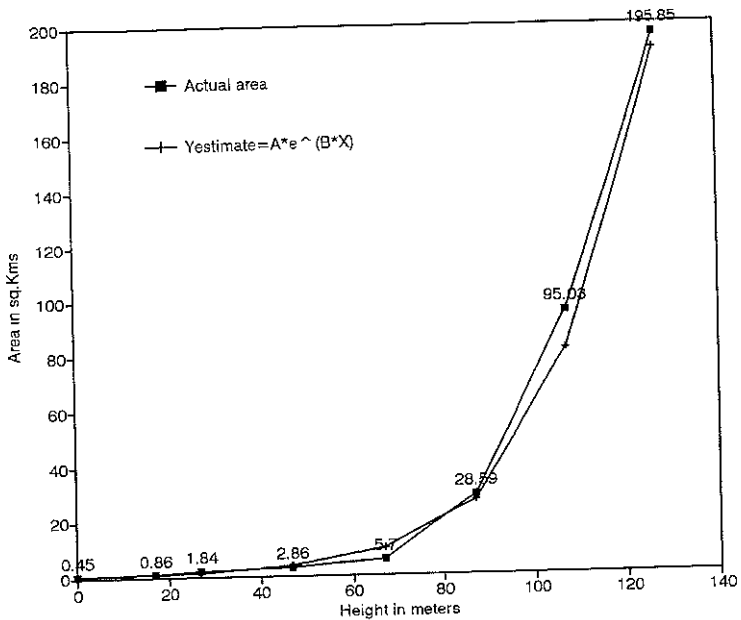$$V_{ij} = \sum_{k=1}^{j-1} V_{k \, k+1} \quad i = 1, \, j = i+1, i+2, \tag{26}$$

Fig 3 Submergence area for various heights of dam at Magod

The submergence area, A_{sub}, and corresponding volume computed for different dam heights at Magod are depicted in Fig 3 This shows that when the dam height, H_{dam} is 67 m, the submergence area is 5 7 km^2 and the volume is 106.35 Mm^3. Beyond 87 m, there is a steep increase in submergence area, as is evident from submergence area of 95.03 km^2 for dam height of 107 m. The relationship between submergence area and height of the dam is exponential ($A_{sub} = 0.38 \ e^{0.048 \cdot Hdam}$) with $r = 0.99$ and percentage error = 0.45. Similarly, the probable relationship between volume of water, V_{dam}, and height of the dam is exponential ($V_{dam} = 5.03 \ e^{0.054 \ Hdam}$) with $r = 0.99$ and percentage error = 0.22 This relationship between volume and height (actual and predicted), for Magod, is shown in Fig 4

NET ENERGY ANALYSIS

Hydropower at each site has been computed before maximizing the net energy function Energy from water is computed based on parametric optimization techniques, listed in Table 1. If variation is allowed between P_{tm} and P_{td} (equations (8)–(12)), it reduces the storage capacity requirements Figure 5 shows a graph of submerged area (in km^2) vs hydroelectricity generated, Eh. Regression analysis of these variables gives a hyperbolic relationship More hydroelectric energy is harnessed by drawing the water during monsoon on a run-of-river basis and sufficient quantity is stored to meet the non monsoon requirement By allowing a P_{tm} to P_{td} ratio of 3, the submergence area saved is about 69 97% with an increase in electrical energy. This is because, for smaller heights of the dam, the submergence area is smaller and therefore evaporation and seepage losses are also lower. This saved area would also meet the bio-resource requirement of the region.
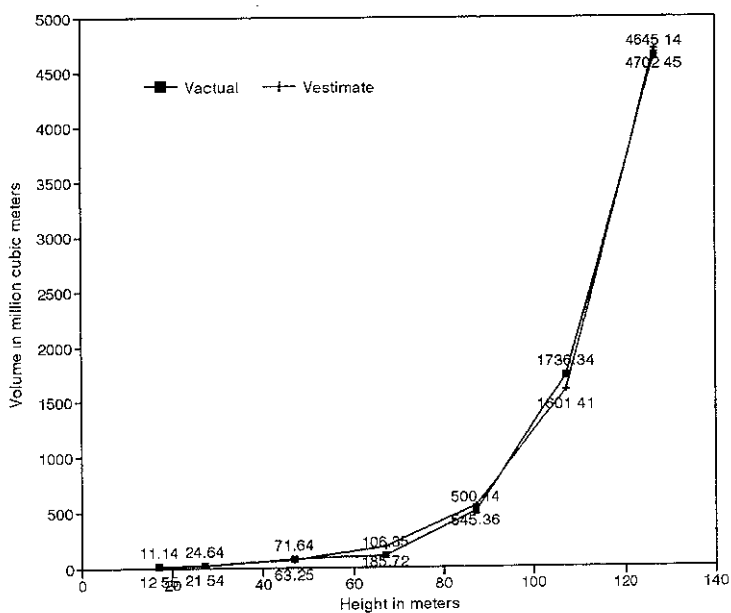
Fig. 4 Storage volume for various heights of dam at Magod

Table 1 Power (MW) and energy (in million kWh) at Magod

Height (m)	Contour (m)	Sub-area (km^2)	Volume (million Mm^3)	Hydropower: P1/P2	P1 (MW)	P2 (MW)	Energy (million kWh)
107	480	95 03	1736 35	1 00	85 00	85 00	746 66
97	470	63 23	1134.53	1 00	90 00	90 00	790 55
87	460	28 59	545 36	3 00	157 51	52 50	768 62
87	460	28 59	545.36	4 00	138 04	34 51	768 65
87	460	28.59	545 36	6 00	199 82	33.30	780 08
82	455	20.77	416 61	6 00	203.98	34.00	796.36
82	455	20 77	416 61	4 00	180.00	45 00	790.55
82	455	20 77	416 61	3 00	163 37	54 46	796 27
77	450	16 27	416 61	6 00	210 00	35 00	819 87
77	450	16 27	416 61	4 00	184 63	46 16	810 90
77	450	16 27	416 61	3 00	166 15	55 38	810 82
72	445	12 74	243 12	10 00	250 03	25 00	806 48
				8	200 02		
70	443	9 98	185 72	16 00	319 95	20 00	823 55
				8	159 98		
67	440	5.70	106 35	32 00	320 00	10.00	823 55
				16	160.00		

Note: for dam heights of 72, 70 and 67 m, multiple P1/P2 ratios are possible

Biomass energy from lands to be submerged

The land-use pattern for various heights of dam shows area under natural forest as the major constituent, consisting of evergreen, semi-evergreen and deciduous forests The primary production of biomass is estimated to range between 6.5–27 5 t ha^{-1} year^{-1}
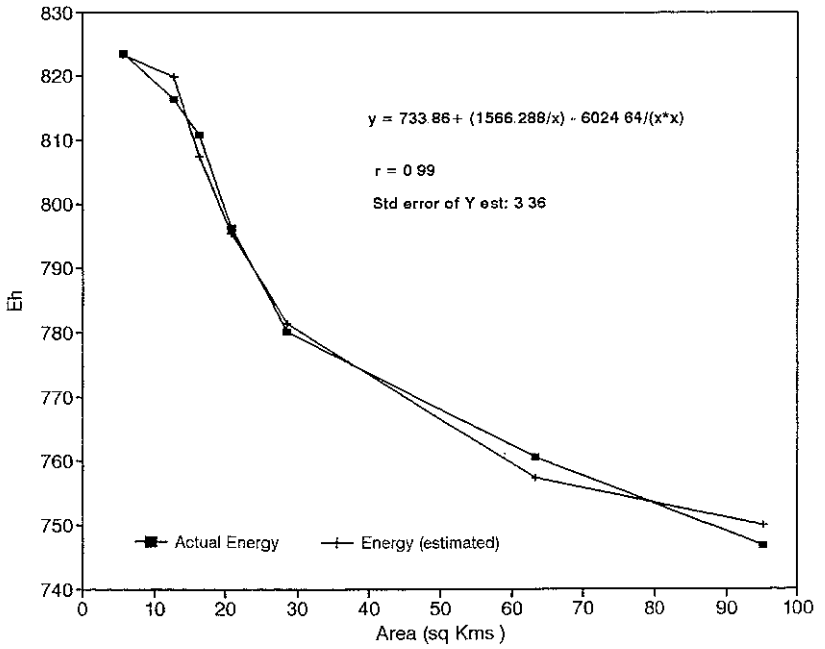
$$y = 733.86 + (1566.288/x) - 6024.64/(x*x)$$

$$r = 0.99$$

Std error of Y est: 3.36

Fig. 5 Energy generated *vs* submergence area

(Ramachandra, in press). Areca and coconut residues from gardens are in the range of 3–4.5 t ha^{-1} year^{-1}. Considering the lower productivity of 6.5 t ha^{-1} year^{-1}, the dam at Magod with a height of 107 m submerges about 95.03 km^2, of which 88.53 km^2 is under evergreen and semi-evergreen forests, rich in biodiversity and worth 34.21 MW in biomass (thermal) energy. A reduction in dam height to 67 m brings this value down to 1.93 MW, due to the decrease in the submergence area.

The net energy computed (Table 2), considering thermal value of bioresidues, indicates that, with decrease in dam height, the net available energy increases. At Magod, the net energy increases from 416.89 (dam height of 107 m) to 803.14 million kWh (dam height of 67 m). Considering the efficiency of the couple turbine generator as 70%, the net energy function becomes:

$$E_{net} = Eh' - E_{bio} \tag{27}$$

Table 2 Hydroenergy, thermal and net energy (million kWh) available from submerged area at Magod

Damheight	Hydroenergy, Eh	Bioenergy, E_{bio} (@6.5 t ha^{-1} year^{-1})	Net energy (million kWh): $Eh - E_{bio}$	$Eh' - E_{bio}$
107	746.66	329.77	416.89	407.24
97	760.55	219.42	541.13	455.59
87	780.08	100.36	679.72	510.93
82	796.27	72.91	723.36	531.87
77	810.82	58.25	752.57	547.19
72	816.48	45.62	770.86	555.57
70	823.55	35.74	787.81	563.97
67	823.55	20.41	803.14	569.34

Note: $Eh' = 0.7\ Eh$

where Eh' is $0.7 Eh$. To account for only the final amount of electricity, the thermal energy content of source is discounted by the conversion efficiency of 35%. Thus:

$$E_{net} = Eh' - 0.35 E_{bio} \tag{28}$$

The result of this computation is given in the last column of Table 2. It shows that variation in net available energy at Magod ranges from 407.24 to 569.34 million kWh.

The domestic fuelwood consumption survey revealed that 82–90% of households still depend on fuelwood and agricultural residues, estimated to be 312 million kWh, to meet their domestic requirements annually. Considerations of system efficiency, peak power and socio-economic factors, all rule out the possibility of electricity entirely substituting fuelwood as a source of domestic energy. This necessitates ecologically friendly options to reduce the submergence of valuable forests.

The model and subsequent quantitative analyses demonstrate that much of the land could be saved from submergence if the hydroelectric power generation capacity is adjusted according to seasonal variations in the river's runoff. The viability of a mixed hydroelectric power and biomass generation system is shown in energy terms, which leads to a significant reduction in the total area used for power generation. Apart from this, there is scope to generate hydroelectric energy from streams in a decentralized way.

ECONOMIC ANALYSIS

Computation of costs: net loss due to forest submersion

Forests play a role, not only in the social and economic well being of the society, but also in maintaining the ecological balance. The direct costs of the submerged area are assessed by considering standing biomass in the area, which is based on species diversity studies carried out in sample plots at Sonda, Kallabe, etc. The cost of timber, fuelwood and minor forest produce works out to be in the range of 2.25–4.55 million Rs (Indian Rupees: Rs 42 = US\$1) per hectare depending on vegetation cover. In this computation, the price of forest land is taken as Rs 111 200 ha^{-1}. Some attempts have been made to quantify the environmental cost of the loss of a forest arriving at 14.13 million Rs ha^{-1} for tropical forest and 12.87 million Rs ha^{-1} sub-tropical forest (Maudgal & Kakkar, 1992).

Loss due to submersion of agricultural and horticultural land

The details of villages submerged and number of households affected are obtained from government agencies such as the Village Accountant's office. Displacement and rehabilitation costs were based on data from earlier hydroelectric projects. Economic valuation of submerged lands is done using the market value per hectare of arecanut garden: Rs 890 000, of paddy: Rs 99 000 and of coconut plantation: Rs 218 000.

Annual charges on capital costs

The capital cost depends on: (a) civil construction costs (size and type of dam) and (b) cost of the generating unit, which depends on the capacity (calculated using normal

load factor of 0 5) The schedule of rates approved recently by the government has been used in computing civil and electrical costs This calculation, carried out for different heights, is listed in Table 3. The annual capital recovery factor (annuity factor) is calculated for the total cost (civil + electrical + environmental + rehabilitation) at 12% interest for 50 years of satisfactory functioning of the power station.

Table 3 Civil, electrical, environmental, rehabilitation costs (million Rupees) at Magod, for various heights of dam

Dam height (m)	Civil + El	Env (land)	Rehabilitation	Env cost	Total cost	Annual expenditure
107	3902 75	1282 99	173 25	20 00	5378.99	798 67
97	3318 21	583 64	138.60	9 10	4040.45	599.93
87	3497.07	427 76	23 85	3 03	3948 68	586 30
82	3592 17	339.01	1 12	0.80	3931 19	583 70
77	3718 18	287 29	0 09	0 18	4005 74	594.73
72	3872 65	225 15	0 02	0 03	4097.85	608.44
67	4029.24	218.60	0 02	0.02	4247.88	630.72

Civil + El: civil and electrical construction costs;
Env (land): land cost due to submersion;
Env cost: cost due to loss of environmental benefits

Operation and maintenance (O & M) charges

Annual O & M charges are taken as 1% of the total cost of the project The depreciation works out to be 1 80%, taking into account the life of the dam as 70 years; that of surge shafts, penstock, power house equipment, power house building and substation equipment as 50 years, and of roads, etc as 35 years. Hence, the annual cost, C, is computed as:

$$C = (\text{Annuity factor} \times \text{Total cost}) + \text{O \& M charges} + \text{Depreciation cost} \qquad (29)$$

With this annual cost and energy information, the cost per kWh of energy, has been computed in Fig 6. It shows 40 5% reduction in cost (Rs 1 53 kWh^{-1} to Rs 0.92 kWh^{-1}) for a dam height reduction of 32.75% If one considers electricity from water resources only, then the cost reduction is from Rs 1 53 kWh^{-1} to Rs 1.09 kWh^{-1}

Benefits

Benefit would be the revenue accrued as a result of electricity consumption in various sectors The percentage share of each sector, calculated considering the annual consumption pattern in Uttara Kannada district, shows that the industrial sector, with a share of 86.38%, is a major consumer, followed by the domestic sector, with a share of 10 20% Based on tariff information provided by Karnataka Electricity Board, sector-wise revenue has been computed. The benefit, B, from the power project is given as:

$$B = \sum_{j=1}^{6} e_j \cdot t_j \qquad (30)$$

where $j = 1, \ldots, 6$ (representing various sectors) and e_j and t_j are electricity consumption and tariff, respectively, in Rs kWh^{-1} for sector "j".
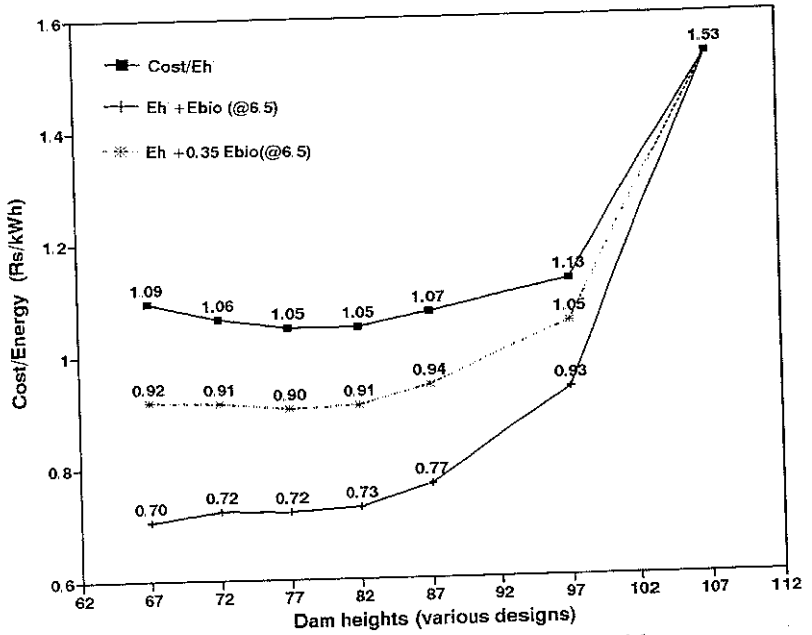
Fig. 6 Cost per kWh of electricity generated for various heights of dam
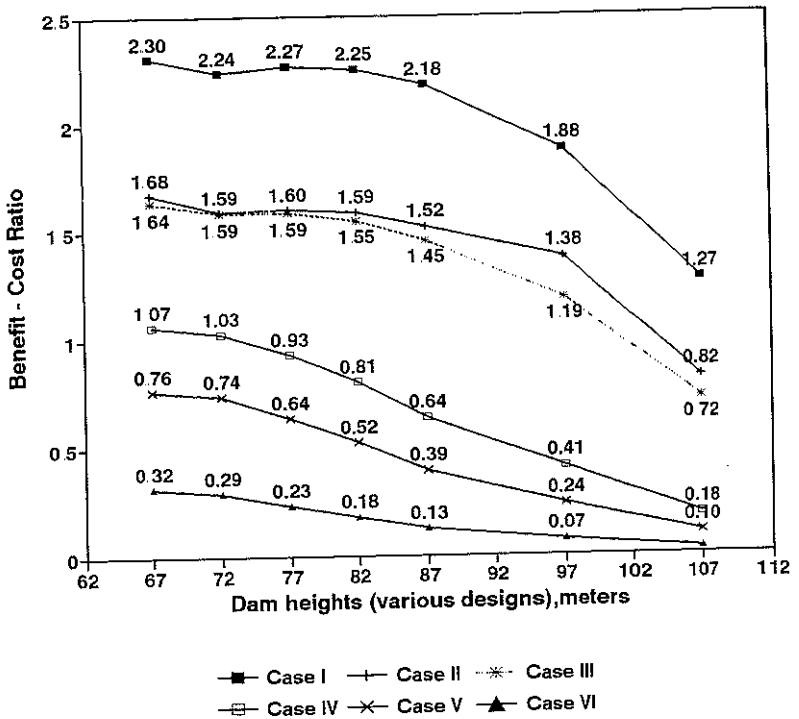

Fig. 7 Benefit–cost ratio for various environmental costs.

The benefit-cost ratio, *B/C*, for various dam heights, considering the following cases, is depicted in Fig 7

The value of forest land for Cases I, II and III is Rs 37 065, Rs 111 200 and Rs 111 200 (+ Rs 12 000, minor forest produce + fuelwood) per hectare, respectively. However, for cases IV, V and VI, the value of a hectare of forest land with standing biomass is Rs 2.25 million, 4.55 million and 2.25 million (+ environmental value as Rs 14.13 million), respectively

The value *B/C* is greater than 1.5 for dam heights less than 97 m in Case I, 87 m in Case II and 82 m in Case III, while for Cases IV, V and VI, *B/C* is less than 1.5 for all heights of dam. This means that, by assigning environmental values, taking all components into consideration, the hydroelectric generation through storage (for minimum submergence also) becomes a less attractive option.

SUMMARY

The hydroelectricity potential of streams in the Bedthi and Aghnashini river basins is estimated to be about 720 and 510 million kWh respectively. In order to reduce the submergence of prime forests, it is necessary to look for an optimal range of reservoir size and installed generation capacity, based on certain site specific factors. Quantification of the energy cost of land submergence reveals that net energy in the region (hydropower and thermal energy in the potential biomass increment), could be maximized by optimal project dimensions

This analysis explains the upper limit on the height of the dam and therefore the area of the reservoir for the project to yield a positive net energy. Also, it is noticed that savings in land submergence could be achieved by adjusting hydroelectric generation capacity according to seasonal variation in the river runoff. By parametric optimization technique, allowing a seasonal generation ratio of 3, the submergence area saved is about 69.97% with subsequent increase in electricity generated. This is mainly due to less evaporation and seepage loss due to reduced submergence area for smaller dam heights

Net energy analyses carried out by incorporating bioenergy lost in submergence at Magod show a gain of 63.9% for a reduction of 37.3% in dam height. Apart from the distinct reduction in submergence area, the overall reliability of a combined hydropower and thermal energy system is much higher than that of pure hydropower systems (which are very sensitive to fluctuations in rainfall).

Net energy computed for various dam heights shows that a reservoir with dam of height 67 m stores enough water to meet the region's lean season electricity requirement and the area saved has a bio-resource potential of 319 million kWh that can cater to the domestic thermal energy demand of 312 million kWh

The calculation of cost per kWh for various designs of the dam shows a 40.5% reduction in cost for a dam height reduction of 32.75%. The benefit to cost ratio, computed considering forest land value as Rs 111 200 ha^{-1} is greater than 1.5 for dam height less than 87 m.

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