A decision support system for optimal design of hydroelectric projects in Uttara Kannada

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The first hydropower plant in Karnataka state, India, was set up at Shivanasamudram in 1902. Gradually, the capacities of hydropower plants became very large due to increased electricity demand. Large-scale hydroelectric plants now contribute significantly to meeting the state's and the nation's 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 and necessitates the development of ecologically sound alternatives to cater for the needs of the region. The planning of water resources depends on 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 includes all costs and benefits, specifically hitherto underestimated, environmental social costs and benefits. This study was carried out in Bedthi and Aghnashini rivers in Uttara Kannada district of the Western Ghats region, Karnataka state, India. An estimated 720 and 510 million kWh of electricity can be generated in Bedthi and Aghnashini river basins 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 (so as 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 in water resource planning for electricity generation is discussed in this paper.

1. Introduction

Hydraulic potential is the combination of the possible flow and distribution of gradients, and hydraulic resource is that fraction of hydraulic potential which is still accessible after economic considerations. Hydropower owes its position as a renewable resource to the varying but more or less continuous flow of a certain amount of water in the stream. This water, supplied by rain, is always moving from the mainland to the sea, where it evaporates into the atmosphere in an unending cycle controlled by two opposing forces, the heat of the sun and the earth's gravity. The river is thus very dynamic, with fluctuation due to gains from precipitation, losses through evaporation and consumption, and reduced flow caused by obstacles, which include turbulence in a torrent or soil permeability leading to entrapment of water that continually tries to reach its lowest gravity potential, the sea. The various time-lags introduced while traversing this geological maze modulate the initial variability of the rains and determine the different patterns of the streams, which form an image of rain fallen on the catchment area after filtering through complex geological and topographical environments.

Installed electrical energy capacity in Karnataka state is 3005 MW, out of which 79 % is through hydropower sources (2375 MW) and the balance 21 % in coal-based thermal power stations. At present, hydroelectric development work is undertaken on an ad hoc project-by-project basis with capacity fixed on the basis of 90 % availability of water annually, estimated over a 10-day period. The current planning approach is characterised by an attempt to provide constant power throughout the year, maximising the electrical energy output through supply expansion options without considering environmental impacts. The seasonal and yearly fluctuations of rainfall/stream flow being high, planners try to achieve their goals by opting for large storage reservoirs having greater submergence area, ignoring energy (in terms of bioresources) and economic costs of the submerged area. Also, this approach ignores the complementarity of the different options, such as (1) run-of-river hydro plants, (2) seasonal peak power generation and (3) other options, especially the thermal option from available biomass in the region on renewable basis. There is a need to consider 90 % reliability of the system in the region, and not of the individual projects, to prevent gross underutilisation of the natural resources. Besides, the integrated systems planning of supply and demand, which would help in optimal development of the potential, should be considered.

This paper focusses on the design of a hydroelectric project with emphasis on economic efficiency and engineering soundness subject to social, political, environmental, ecological, cultural, institutional and legal constraints. The complexity is compounded by lack of methodologies that can quantify these constraints or express them in tangible terms. Some of these constraints are not mutually exclusive and are even conflicting. Clearly, these involve trade-offs between different constraints that may be qualitative. Thus, satisfying these constraints plays a dominant role in achieving the objectives in water management. Optimisation (programming) and descriptive (predictive) model approaches are usually adopted to accomplish this complicated task [Falkenmark, 1989]. The optimisation models aid in decision-making attempts to derive the optimal water management scheme for a set of objectives. The descriptive models attempt to predict the consequences of a management scheme for a known quantity of water. The steps involved in developing a water management scheme are: evaluation of water availability, specification of constraints, specification of objectives and their expression in terms of quantitative criteria, selection of appropriate model scenarios, derivation of alternative schemes, evaluation of each scheme and comparative evaluation of schemes in measurable terms.

Hydroelectric projects are decided on the basis of two criteria in India. The Planning Commission specifies that the benefit-cost (B-C) ratio should be greater than 1.5 for clearing any hydroelectric project, while the state agencies, such as the Karnataka Power Corporation Ltd. (KPCL), choose least cost of generation between the alternatives. These approaches do not take into account energy/economic costs of submergence and alternative designs involving seasonal variation in generation. The land area submerged can be viewed either specifically as a source of bioenergy in the form of fuel wood, etc., or as a source of economic benefits in general. In view of these, the following alternatives are suggested for calculating the benefits:

1. computation of benefit-cost ratio strictly on energy terms: this involves calculation of net energy from the project, defined as the annual electrical energy generated minus the energy lost from the potential annual increment of wood biomass in the submerged land.
2. assigning monetary value to the submerged land and including it in the construction cost of the project itself.

The main objective of economic analysis in developmental projects is to see whether the resources are put to effective use. This analysis has to be carried out by incorporating a number of socio-economic and environmental variables. This incorporation is different from the conventional economic analysis in which cost minimisation and profit maximisation are the primary objectives.

Economic feasibility consists of examining the total benefits that result from a project and finding out whether they would exceed those that would accrue in the absence of the project by an amount in excess of the project cost. It depends on engineering feasibility that assures benefits and environmental feasibility, minimum submergence. In 1958, the Planning Commission while reviewing five major projects showed that large benefits accrued from irrigation in terms of double-cropping, diversification and better quality crops, higher yields, larger income and greater employment opportunities. The indirect benefits were the establishment of processing industries, expansion of consumer industries, retail trade, transport and communications. The committee recommended that economic benefit criteria be adopted instead of financial criteria for sanctioning hydropower projects for irrigation or power. In 1966, the Ministry of Irrigation and Power, Government of India, laid down that a project has to be considered worthwhile only if the B-C ratio is not less than 1.5. However, there is special consideration for scarcity and backward areas.

The main objective of cost-benefit analysis (CBA) discussed in this paper is to look for economic viability of a project. It tries to include all technical, physical, socio-cultural and environmental variables affected by the project in terms of economic value fixed for the pre-determined year. Cost includes any expenditure incurred by the project authorities or society directly or indirectly over the economic life of the project. This includes construction cost, and operation and maintenance cost till the end of the life of the project.

2. The decision support system approach

Decision support systems (DSS) focus on providing flexible tools for policy analysis rather than providing models to answer structured problems [Parker and Ul-Ataibi, 1986]. Indeed, modelling tools are only a part of DSS, which comprises three component subsystems, namely:

1. the database management: manages an integrated database to drive all models;
2. the model management: this helps in creating new models, cataloguing and editing existing models, inter-relating models by links through the database and integrating small models (building blocks) into larger model systems.
3. the dialogue management: using consistent and familiar interface (like spreadsheet or word processing programs), this design is guided by various methodological considerations, such as
   a. scenario approach: simulates alternative energy and economic futures under different assumptions;
   b. integrated energy environment planning: stresses the importance of integrating the analyses within comprehensive planning while emphasizing a disaggregated approach; and
   c. flexibility and user friendliness: designed as a set of flexible, expandable and comprehensive modules.

2.1. *Objective*

The objective is to design a hydroelectric plant utilizing optimal energy in the water, with minimum submergence and economic costs, taking into account inter-seasonal variation in generation to meet the region's demand during all seasons and develop DSS in water resource planning for electricity generation.

2.2. Methodology

Feasibility investigations in the catchment area and potential assessment at selected sites were carried out.

2.2.1. Feasibility study

The hydrology of the river and streams under consideration was studied by:

1. measurement of basin area;
2. pre-feasibility study of all streams with water head greater than 3 m;
3. analysis of 90 years' precipitation data collected from India Meteorological Department;
4. computation of discharge by empirical method based on precipitation history of last 90 years and comparison of this with the values obtained by actual stream gauging;
5. computation of discharge and power in ungauged streams by empirical/ rational method; and
6. computation of power and total energy in all streams.

2.2.2. Computation of stream discharge

Both direct and indirect methods were used. Indirect method was tried in order to assess the potential of ungauged streams.

1. Direct estimation of flows at site. Stream discharge is the rate at which a volume of water passes through a cross-section per unit of time, usually expressed in units of cubic metres per second (m^3/s). The velocity-area method using a current meter is used for estimating discharge. The cup-type current meter is used in a section of a stream, where water flows smoothly and the velocity is reasonably uniform in the cross-section. As far as possible a cross-section is chosen where the current is reasonably regular over the whole width. This measurement of five readings for three consecutive days every month is carried out for 18 months to account for day-to-day fluctuations and seasonal variations.
2. Indirect estimation of flows at site. The runoff from rainfall was estimated by: (1) empirical relationship between runoff and precipitation (by regression analysis of field data) and (2) rational approach by assuming a suitable runoff coefficient (C) based upon soil types, vegetation, geology etc. (for example rocky and permeable C=0.8-1.0, slightly permeable C=0.6-0.8, heavy forest C=0.1-0.2, sandy soil C=0.2-0.3)
   The runoff yield = C×A×P (where A = basin area and P = precipitation)

2.2.3. Potential assessment at selected sites

1. Hydrology. The hydrology of the Bedthi and Aghnashini rivers at Magod and Unchalli sites was analysed daily and weekly using five years' daily precipitation data.
2. Engineering design aspects. Information on topographic mapping (contour map), geological feasibility, best dam site, tunnel alignment and power house location was obtained from the Department of Geology at Karwar and Karnataka Power Corporation Limited [MPCL, 1977; KPCL, 1973, 1993].
3. Stream discharge data analyses. Average, standard deviation, maximum and minimum of inflow data were computed for 90 years on monthly basis.
4. Mapping of contours. Various contours at dam site for different heights were traced and area determined using planimeter.
5. Calculation of submergence area. Submergence area was determined for various heights of the dam and the corresponding full reservoir level (FRL)
6. Computation of reservoir volume for various heights of the dam. A certain amount of "dead" storage capacity was added to account for sedimentation.
7. Parametric analysis. Computation of seasonal power drafts and annual electricity generation for various heights of the dam
8. Net energy analysis. Net energy was computed by determining the total electrical energy generated minus the energy lost from the potential annual increment of wood biomass.
9. Design and cost estimates. The preliminary designs and cost estimates for all the components of the project – dam, pressure shaft, power house, intake and outlet structures (civil, electrical etc.) were determined.
10. Economic analysis. Benefit-cost analyses incorporating environmental costs, such as submergence area, rehabilitation costs, etc., for various heights of the dam at each site.

3. Study area

Uttara Kannada district lies between 74°9′ and 75°10′ E longitude and between 13°55′ and 15°31′ N latitude and covers 10,291 km^2 (Figure 1). The recent Landsat imageries show 67.04 % area under forest, 1.94 % under paddy and millet cultivation, 1.26 % under coconut and areca orchards, 1.94 % under rocky outcrops and the balance 27.82 % under habitation and reservoirs. Among the four rivers, the hydro-potential of the Kali and the Sharavati has been tapped for power generation through large reservoirs, submerging vast tracts of natural forests and dislocating a large number of families. In view of these facts, we have tried to assess the potential of Bedthi and Aghnashini rivers, exploring ecologically sound means of harnessing the hydro-energy.

3.1. The Bedthi or Gangavali river

The Bedthi or Gangavali is formed by the confluence of two streams near Kalghatgi (Dharwad district), namely, Shalmala from Dharwad south and Bedthi originating from Hubli taluk. After flowing westward for about 25 km, it enters Uttara Kannada district and flows on a fairly south-westerly course for about 30 km before falling into the sea, about 30 km south of Kalinadi. The united stream flows about 8 km south-east to the border of Uttara Kannada, and during the course of 95 km (out of the total length of 160 km) across the district, it receives no feeder of any size. At Magod village, about 40 km from where it enters the district, the Bedthi tumbles over the western face of the Sahyadris in a cataract known as the Magod falls. The river network in the district is shown in Figure 2.

The Bedthi river, flowing mostly in hilly tracts and deep gorges, cannot be used for irrigation development. On account of the available water potential and the many waterfalls, the topography of the course offers ideal sources for hydropower development. Suitable dam sites have been identified near Magod falls in the upstream for hydropower development. On the basis of the model explained earlier, water would be drawn on a run-of-river basis (during the monsoon period) and a small storage facility would meet the non-monsoon requirement of the region.

The Bedthi catchment is bounded by the watersheds of Kalinadi in the north, Aghnashini in the south and Tungabhadra and Malaprabha in the east. The river drains a total area of 4060 km^2 of which about 2080 km^2 comes under the command of the proposed dam site above Magod falls. The river Sonda (Shivganga falls) drains an area of 1077 km^2, while the Bedthi drains a total of 1980 km^2 below Magod falls, flowing mostly in the hilly tracts and coastal plains receiving rainfall mainly from the south-west monsoon. The shape of the Bedthi basin is elongated from its origin up to the Arabian sea. The maximum length of the basin is 160 km and the maximum width 40 km. At the proposed dam site, the shape of the catchment is elongated, the maximum length and width being 80 and 25 km respectively. The perimeter of the catchment is 240 km. The river-bed at the proposed dam site is at an elevation of 373 m. The maximum altitude of the catchment is about 780 m above mean sea level.

3.2. The Aghnashini or Tadri

The Aghnashini or Tadri or Donihalla river (total length 120 km) originates at Manjguni near Sirsi and after a winding westerly course of about 70 km falls into the sea about 10 km south of the Gangavali river. It receives no feeder of any size throughout its course. It has two sources, the Bakurhole rising in a pond at Manjguni about 25 km west of Sirsi and the Donihalla whose source is close to Sirsi. The streams meet near Mutthalli, about 15 km south of Sirsi, under the name of Donihalla and the river flows about 25 km south of Sirsi in a winding westerly course to the western face of the Sahyadris down which, about 13 km north of Bilgi at Unchalli, it drops as the Lushington or Unchalli Falls. The shape of the Aghnashini catchment is also elongated from its origin to the Arabian Sea. At the proposed dam site, above Unchalli Falls, it commands an area of about 606 km^2

3.3. Stream flow measurement (direct method) and computation of power (kW)

Stream flow and ecology are affected by basin conditions. The rate of runoff depends on drainage efficiency of hill slopes, moisture content of the soil, subsurface geology and vegetation cover [Gordon et al., 1992; Holland, 1967]. Stream gauging shows discharge ranging from 1.12 (in August) to 0.015 m^3/s (in February) for the Boosangeri stream. In the case of Muregar, it ranges from 1.395 to 0.026 m^3/s. This indicates that streams of this kind are seasonal. Power generated during June-September is sufficient to meet the energy needs of nearby villages (consisting of 28 households).

An earlier study explored the possibility of harnessing hydro potential in an ecologically sound way (by having run-of-river plants with no storage options) to suit the requirements of the region [Ramachandra et al., 1995]. Sirsi, Siddapur and Yellapur taluks of Uttara Kannada district, being located in a hilly terrain amidst evergreen forests with a large number of streams, are ideally suited for micro-, mini- or small hydropower plants. Monthly stream gauging at Muregar and Boosangeri has revealed that mini-hydropower plants could be set up at these sites. The stream at Muregar is perennial and with a flow of about 0.26 m^3/s during summer, 10-20 kW of power could be generated, while during the monsoon season, 300-400 kW could be harnessed.

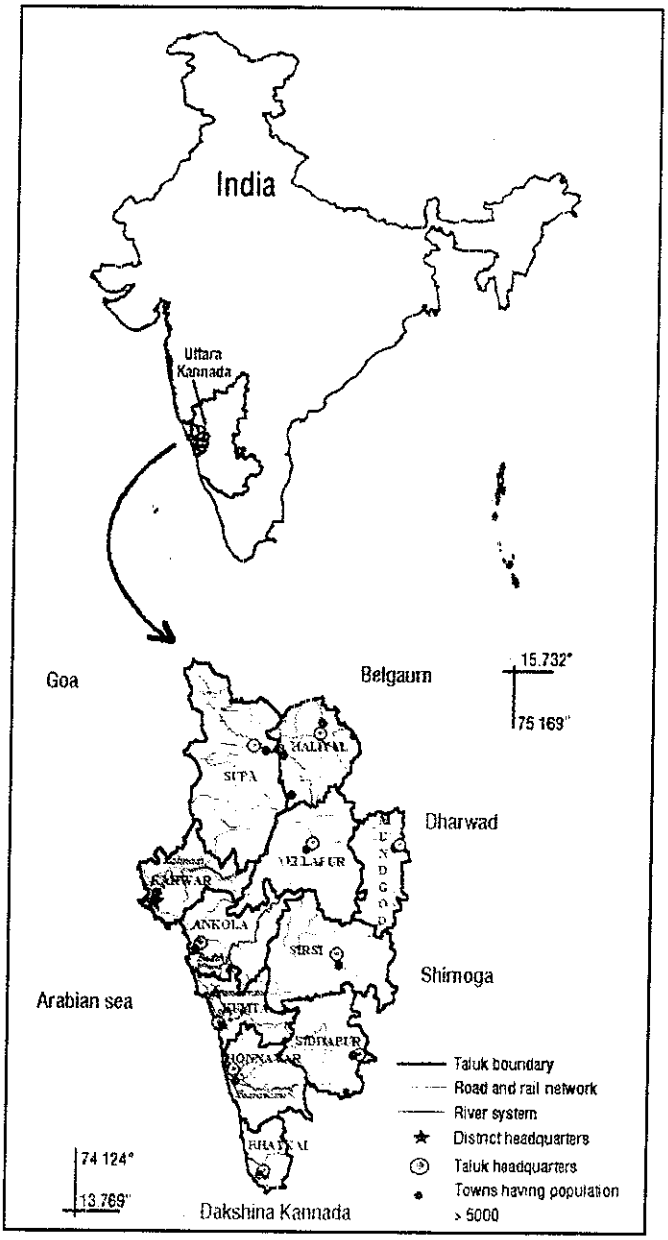

Figure 1 Uttara Kannada district

3.4. Stream flow measurement (indirect method) – empirical/rational method

The relationship between runoff (R) and rainfall (P in cm) is determined by regression analysis of field data where $R = 0.85 \times P + 30.5$. Discharge computed by empirical/rational method and the subsequent power calculated is in

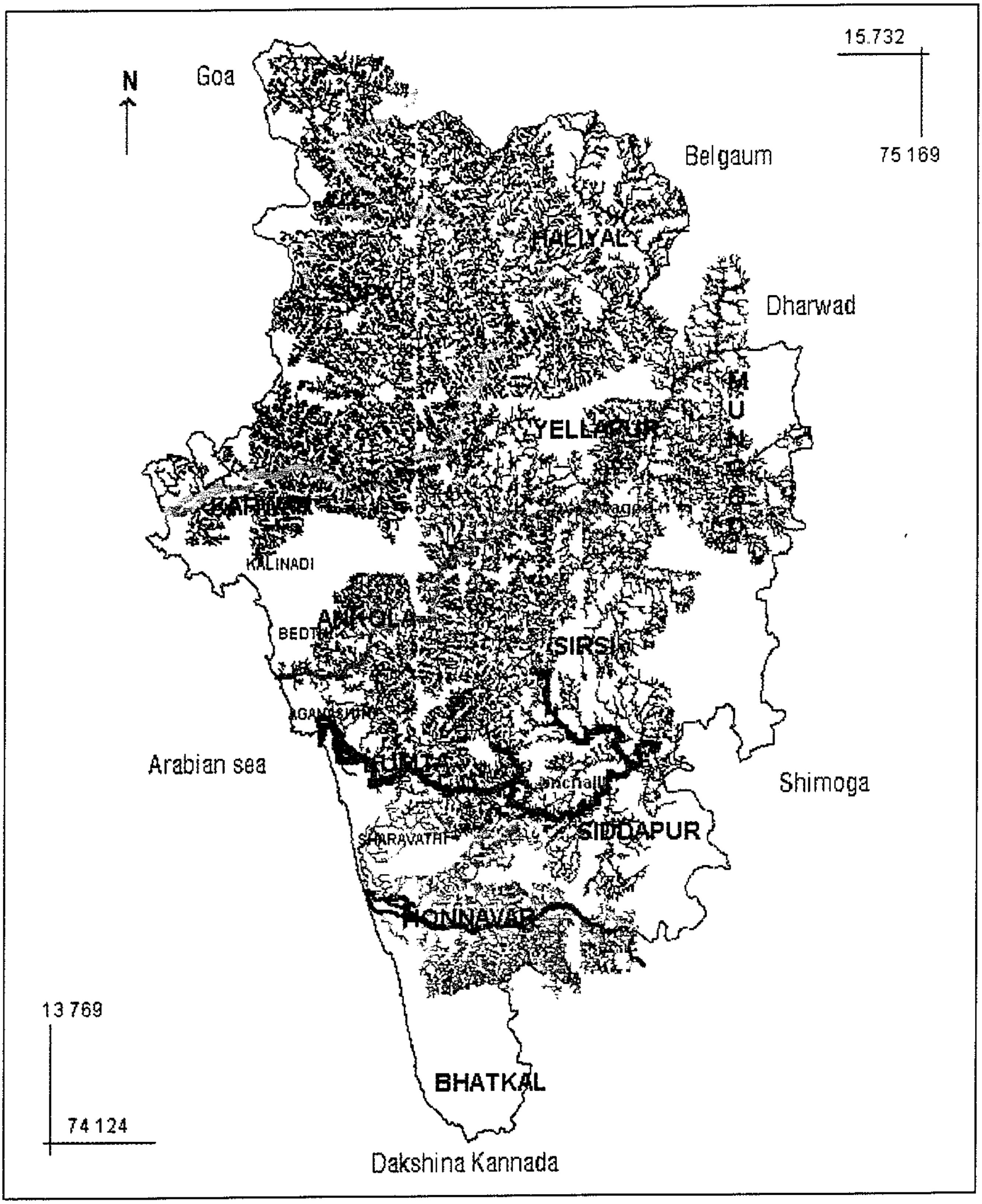

Figure 2. River network in Uttara Kannada district

conformity with power calculated by stream gauging.

Computations of discharge on empirical basis/rational method, based on precipitation history of last 90 years, and subsequent power calculated are in conformity with the power calculations based on stream gauging. On the basis of this field experience of gauged sites, an attempt has been made to compute water inflow (using indirect methods), hydraulic power available and energy that could be harnessed monthwise for all ungauged streams in Bedthi and Aghnashini catchments. By this method, it is estimated, about 720 and 510 GWh of electricity can be generated in Bedthi and Aghnashini river basins respectively [Ramachandra et al., 1999].

The potential assessment shows that most of the streams are seasonal and cater for the needs of local people in a decentralised way (during the monsoon season). This assures continuous power supply during heavy rain, which otherwise gets disrupted due to dislocation of electric poles or falling of trees/branches on transmission lines due to heavy wind. Detailed household survey of villages of hilly areas shows that [Ramachandra, et al., 2000b], during the monsoon people have to spend at least 60 to 65 % of the season without electricity depending on centralised supply (grid supply from Karnataka Power Transmission Corporation Limited, KPTCL). In view of this, an ecologically sound alternative is proposed, which would generate maximum electricity during the monsoon and sufficient electricity during the lean season by storing enough water to meet the region's requirement.

4. Design of a reservoir with energy and ecology constraints

Reservoirs have become the most important technique for regulating surface runoff to match supply and demand. Nature does not meet the demand for water at all times and in all places. Owing to environmental impacts associated with large reservoirs, it has become necessary to estimate their proper sizes to meet the target demand of a region. Thus, planning and decision on size of reservoirs and management of water resources represent a very important research topic both in practical and theoretical terms. In the practical/engineering approach, basically, the water input data for the previous year is used to determine the storage capacity assuming the operation of the reservoir started at the beginning of data collection and lasted until the end of the available data series [Mutreja, 1976].

Design of storage systems for power generation in a hilly terrain is constrained mainly by ecological factors nowadays. The negative aspects of hydroelectric projects necessitate the minimising of submergence area and are subject to reasonable cost, minimum or no wastage of water and seasonal constraints (the region receives maximum rainfall during the south-west monsoon). On the basis of 90 years' precipitation data and 18 months of river runoff data, a methodology is proposed to design storage reservoirs at Magod and Unchalli to meet the region's demand during all seasons.

4.1 Hydroelectric energy operation module

DSS is used elsewhere for optimal design and operation of a large network of small reservoirs for agriculture [Labadie, et al., 1988; Albuquerque, 1993]. This module answers the following questions

1. How much energy can be generated using flowing water of a river/stream and what is the reliability of such decisions?
2. How to operate a reservoir on a daily basis, taking into account seasonal constraints, in order to achieve this goal?
3. How to maximise the net energy available in the region, while reducing submergence and construction costs?

The operation module is designed based on predetermined hydrological flow (database, environmental and socio-economic modules) GIS module, technical data, economic data and a certain user-selected reliability level. It also generates adaptive operation policies based on this reliability level. Figure 3 shows the components of the planning operation module. The sequential operation of this module is as follows

1. Start at beginning of monsoon season
2. User determines reliability level
3. Manager module queries database record of the previous years' flow of the system and watershed module to predict inflows in the system
4. Manager module starts the statistical module to generate mass curves and statistical parameters.
5. Manager module starts the environmental and socio-economic module for determining demands and constraints on the system (minimum reservoir level, water demands, downstream flows, etc.), and forecasting module to forecast rainfall and demands at a defined lead time.
6. Manager module starts unsteady flow routing module to give initial guesses on routings and flow constraints
7. GIS module, with contour mapping details, provides the submergence area for various heights of the dam, land-use particulars with bioresource availability.
8. Technical data module provides technical details of electrical machinery, efficiency of turbine and generator, and dependability norm for storage capacity
9. Energy demand data module provides electricity and fuelwood demand in the region which helps in determining operation policies during lean season.
10. Economic data module provides civil construction costs for various types and heights of dam, cost of electrical machinery of various capacities, environmental costs, rehabilitation costs, land-use details, land submergence costs, construction time of each design, inflation rate, operation and maintenance costs, and depreciation costs.
11. Adaptive optimum control module decides on the quantity of water drawn from the reservoir taking into account 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 on the storage capacity during non-monsoon season.

    Net energy available in the region is also presented in this module. Step 6 is again called by manager module to update routing and flow constraints. This is repeated till convergence is obtained. Manager module starts GIS module to present changed submergence area for changed height of dam and reservoir levels (due to changed water-drawn policies). Thus, for various reliability levels and heights of the dam, the process is repeated at Step 6
12. Results are tabulated using spreadsheet software.
13. Operating rules are presented and return to main module.

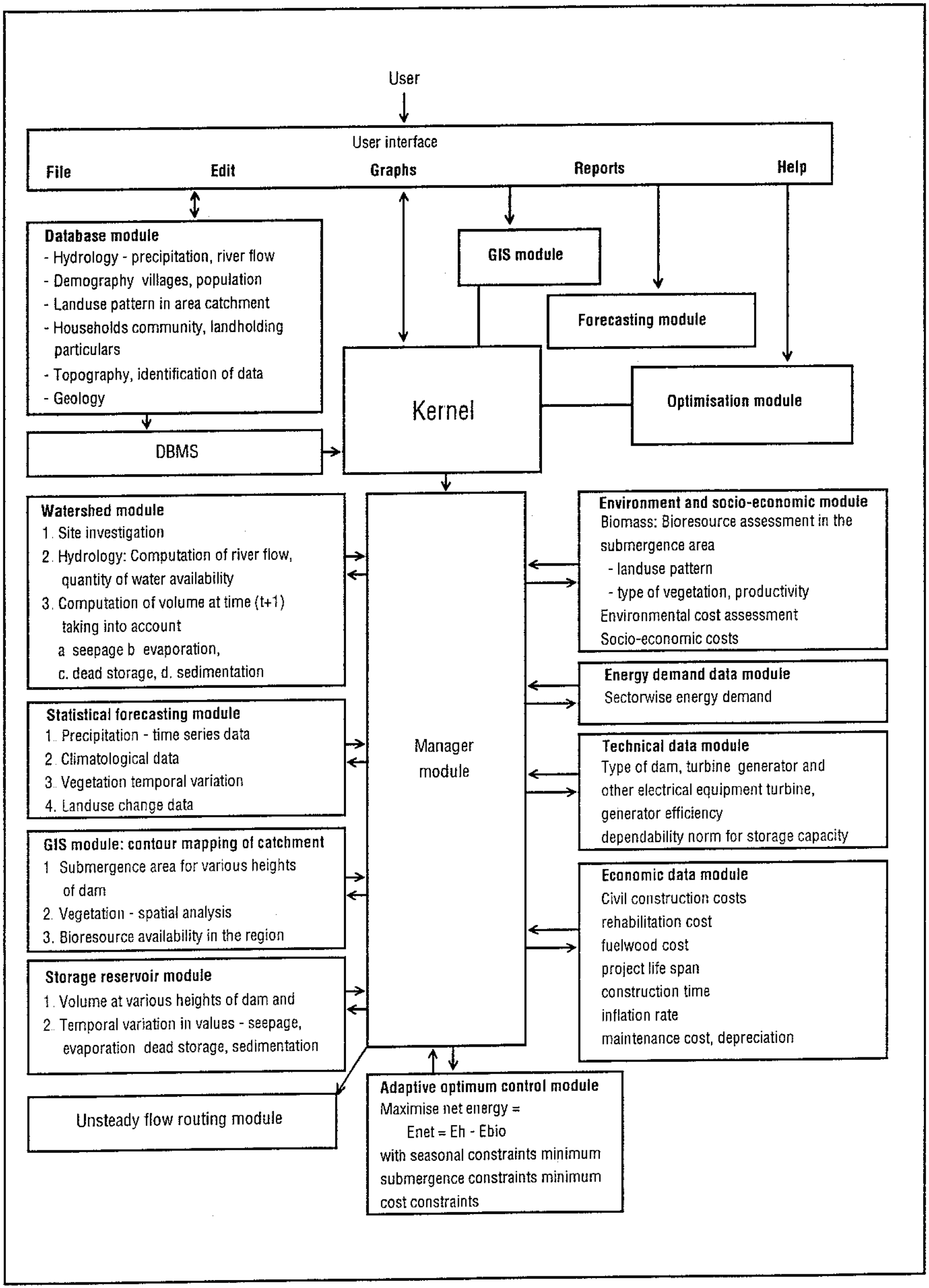

Figure 3. Design of hydroelectric station with optimal storage option: detailed operation module

4.2. Design assumptions and parameters-scenario creation

1. Assumptions. Detailed geological and topographical investigations carried out to determine the best site for the dam, pressure shaft alignment, power house location, etc., can be used for implementing this design.
2. Parameters: Input data consists of site-specific, technical and economic data.
   a. Site-specific data: Water discharge, water yield in the basin, generation head, evaporation rate, seepage rate, type of basin, area spread for each contour, volume of water stored, submersion area for various heights of the dam and dead storage capacity of the dam.
   b. Technical data: allowable inter-seasonal variation in power generation, load factor, generator and turbine efficiency, project life span (dam, electrical machinery), dependability norm for storage capacity, potential biomass productivity of submerged land, sectorwise regional electricity and fuelwood demand.
   c. Economic data: Costs of civil, electrical and other accessories, environmental cost, electricity tariff, fuelwood cost, interest rate, project life-span, construction time, inflation rate, and operation and maintenance costs.
3. Decision variables: These are to determine the optimum storage capacity, installed generation capacity and seasonal power drafts, to maximise net energy availability in the region (objective function) subject to seasonal hydrological constraints, and minimise costs and submergence area.

5. 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, was formulated earlier by Subramanian [1985]. On the same lines, with detailed engineering design and quantification of data, the parametric optimization approach is used, to find out the alternatives for Magod and Unchalli sites, to get maximum energy subject to ecological constraints.

The parametric model is solved for various scenarios for optimal utilization of energy in the water and thermal energy in the region. The objective is to maximise the net energy available in the region, which is given by

$$E_{net} = E_h - E_{bio} \qquad (1)$$

where E_{net} : net energy available in the region,
E_h : the annual electrical energy generated from hydel source and
E_{bio} : energy lost from the potential annual increment of wood biomass in the submerged land

This model includes an equation which computes monthly hydropower production as a function of (1) volume of water discharged, (2) gross head of this water and (3) efficiency of the couple turbine generator.

Hydropower is given by

$$P = 9.81 \times Q \times H \qquad (2)$$

The corresponding electricity produced taking into account the efficiency of turbine-generator assembly is $E_h = P \times t \times \eta$, where E is the electricity produced (in kilowatt-hours), P is hydraulic power (in kilowatts), t is operating time (in hours) and η, the turbine-generator assembly efficiency (between 0.7 and 0.85). Because of the estimates of the couple turbine-generator and gross height, this is only an approximate characterization of the energy harnessed for the purpose of illustration.

The monthly hydroelectricity generated in GWh is given by

$$E_h' = \Sigma 9.81 \times D_t \times H \times \eta \qquad (3)$$

where t = 1 ...... 12, H = average net generation head, η = efficiency of turbine-generator combination and D_t = power draft from reservoir during a month (million cubic metres, Mm^3). This can be written as

$E_h' = \Sigma k_1 \times D_t$ where $k_1 = 9.81 \times H \times \eta$

This equation may further be decomposed to indicate seasonal draft

$$E_{h'} = \Sigma k_1 \times D_{tm} + \Sigma k_1 \times D_{td} \qquad (4)$$

where, D_{tm} (tm = 1 ... 4), water drawn during monsoon months (June-September), and D_{td} (td = 5 ... 12), water drawn during non-monsoon months (dry period).

Energy loss due to submergence is given by

$$E_{bio} = A_{sub} \times Gr \times (CV) \times \eta_c \qquad (5)$$

where A_{sub} = area submerged, Gr = annual biomass yield or productivity, CV =energy equivalence factor and η_c = energy conversion efficiency.

Area submerged is further classified as forest, agricultural lands, gardens, etc. Primary productivity of biomass in forests is in the range of 6.5 to 27.5 t/ha/yr. Paddy yield from agricultural land is 1.8 to 2.4 t/ha/yr. Areca and coconut residues from orchards are in the range of 3.0-4.5 t/ha/yr. The thermal content of biomass is computed in terms of its primary energy content [Ramachandra, et al., 2000a]. For example, a tonne of dry fuelwood with a calorific value of 18.41 MJ/kg has a thermal content of 5112.8 kWh, which is considered equivalent to the same amount of electrical energy.

This model is subject to the following constraints.

1. The hydrological constraints: These operate on a monthly basis and consist mainly of the following continuity equation [Maass et al., 1962].

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

where V_t = volume of the reservoir at the beginning of month t, and
I_t = inflows to the reservoir,
S_t = seepage loss,
E_t = evaporation loss and
D_t = discharge from the reservoir during the month t.

For solving this, several inputs are required:

a. functional relationship between volume, surface area and water level in the reservoir,
b. relationship between seepage and volume,
c. relationship between evaporation and volume,

   - d. sequence of monthly inflows into the reservoir,
   - e. policy for determining the discharges from the reservoir and
   - f. volume of the reservoir when the simulation begins.

2. Dependability: The storage capacity (V) of any reservoir is a function of both targeted draft (D) and reliability (R), given by
   $V = f(D,R)$ (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 one approaching a mean flow, required storage is extremely sensitive to reliability. Likewise 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 hydro planning, in the case of generation schemes, a dependability criterion of 90 % is normally adopted. Failure for a month in a decade would mean a reliability of 99.2 % on monthly, but 90 % dependability on yearly, basis. This is because, failure in any one month is considered to be failure for the whole year.
3. Constraint on seasonal variation in generation capacity: If no variation is allowed, $P_{tm} = P_{td}$,
   that is, $P_1=P_2$ (8)
   That is, hydroelectric generation capacity during monsoon months (P_{tm} or P_1) is the same as that during non-monsoon period (P_{td} or P_2).
   If seasonal variation is allowed, $P_{tm} \geq P_{td}$
   If variation of "r" is allowed, $P_{tm} \geq r \times P_{td}$ (9)
   P_{tm} and P_{td} are written in terms of power draft as
   $P_{tm} = k1 \times D_{tm}/LF_{tm}$ and $P_{td} = k_1 \times D_{td}/LF_{td}$ (10)
   where, D_{tm} = power draft from reservoir during monsoon (in Mm^3),
   LF_{tm} = average load factor for the monsoon months, assumed as 0.5,
   D_{td} = power draft during dry months and
   LF_{td} = average load factor during dry months.
   Therefore,
   $D_{tm}/LF_{tm} = D_{td}/LF_{td}$ (11)
   (with no seasonal variation)
   $D_{tm}/LF_{tm} \geq r \times D_{td}/LF_{td}$ (12)
   (if seasonal variation is allowed)
   We have the same load factor for monsoon and dry months, $LF_{tm}=LF_{td}=LF$ (13)
   Seasonal variation in generation capacity could be written as
   $D_{tm} = D_{td}$ (with no seasonal variation) (14)
   $D_{tm} \geq r \times D_{td}$ (if seasonal variation is allowed) (15)
4. Constraint on minimum storage: Active storage capacity $K_a \geq V_t$ for $t = 1, 2, \ldots 12$ (16)
5. Operating policy of the reservoir: The feasible operating policy, considering seasonal variation in water inflow, would be:
   $\{S_1 \times P_{tm} + S_2 \times P_{td}\} \times 30 \times 24 \times LF \times$(amount of water/million kWh) = total quantity of water available at site
   where $S_1 = 4$ (monsoon season) and $S_2 = 8$ (lean season) and substituting for P_{tm}, P_{td} (from equation 10) and LF (from equation 13),
   this constraint reduces to $4 \times D_{tm} + 8 \times D_{td} = V_{t+1}$
   where $D_{tm} = D_{td}$, if no variation is allowed
   $D_{tm} \geq r \times D_{td}$ where value of r ranges from $1, 2 \ldots, \infty$
   and $V_{t+1} = V_t+I_t-S_t-E_t-D_t$
   With change in dam height, submergence area and storage volume changes. Submergence area and volume computation is discussed later in case studies. The regulation through storage could be shown as follows:
   If $V_t+I_t-S_t-E_t-D_t \leq$ storage volume of reservoir (V_s)
   then $D_t = V_t+I_t-S_t-E_t$ (17)
   If $V_t+I_t-S_t-E_t-D_t \geq$ storage volume of reservoir (V_s)
   then $D_t + d = V_t+I_t-S_t-E_t$ (18)
   where d = excess quantity available for generation
6. Positivity constraints: Decision variables are positive.
   $D_t \geq 0$, for all $t = 1, 2 \ldots 12$
   and $V_t \geq 0$, for all $t = 1, 2 \ldots 12$
   Therefore, $K_a \geq 0$ (19)

6. Case-studies

This design is implemented for hydroelectric schemes at Magod (Bedthi river) and Unchalli (Aghnashini river).

6.1. River discharge

River discharge is the rate at which a volume of water passes through a cross-section per unit of time. It is seen that the average annual yield at Magod is 1125 Mm^3 by rational method, compared with 1105 Mm^3 by empirical method. 90 % dependable water yield is estimated as 995 Mm^3. Water yield computed at Magod by empirical method with 90 years' precipitation data shows that water quantity varies from 0.25 (avg.) ± 1.25 (Sd.) during January to 364 (avg.) ± 136 (Sd.) during July. At Unchalli the yield ranges from 0.19 (avg) ± 0.74 (Sd) for February to 442 (avg) ± 91 (Sd) for July. This indicates good flow only during four months in a year.

6.2. Evaporation, seepage loss and silting capacity

These losses are estimated as 99.14 Mm^3 per annum for 100 km^2 of the region. About 48 % of the basin area is plain with partial vegetation cover receiving moderate rainfall. The remaining area is hilly with evergreen vegetation. The silt rate per annum (S) is given by $S = C(A)^{3/4}$ where C = 4.25 assumed for basin with plain and forested tracts. For Magod, silt rate is found to be 0.83 Mm^3 per year. At this rate of siltation, the life of the reservoir at full reservoir level (FRL) 450-455 m is approximately 50 years.

6.3. Dam site

The river Bedthi, flowing in a deep and well-defined gorge, drains a total area of 4060 km^2. The site proposed is about 0.9 km upstream of Magod falls, at longitude 74°45′28″E and latitude 14°51′41″N. This site commands a basin of 2080 km^2 and has exposed rocky bed at the flanks on either side. The river bed level here is 373 m and the river bed is 36 m wide. At 450, 460 and 480 m contour elevations, the length of the dam would be 392, 436 and 579 m respectively. At the proposed dam site, above Unchalli falls of Aghnashini, the basin commands an area of about 606 km^2.

6.4. Dam height and submergence area

A dam at this site would submerge areas having biomass

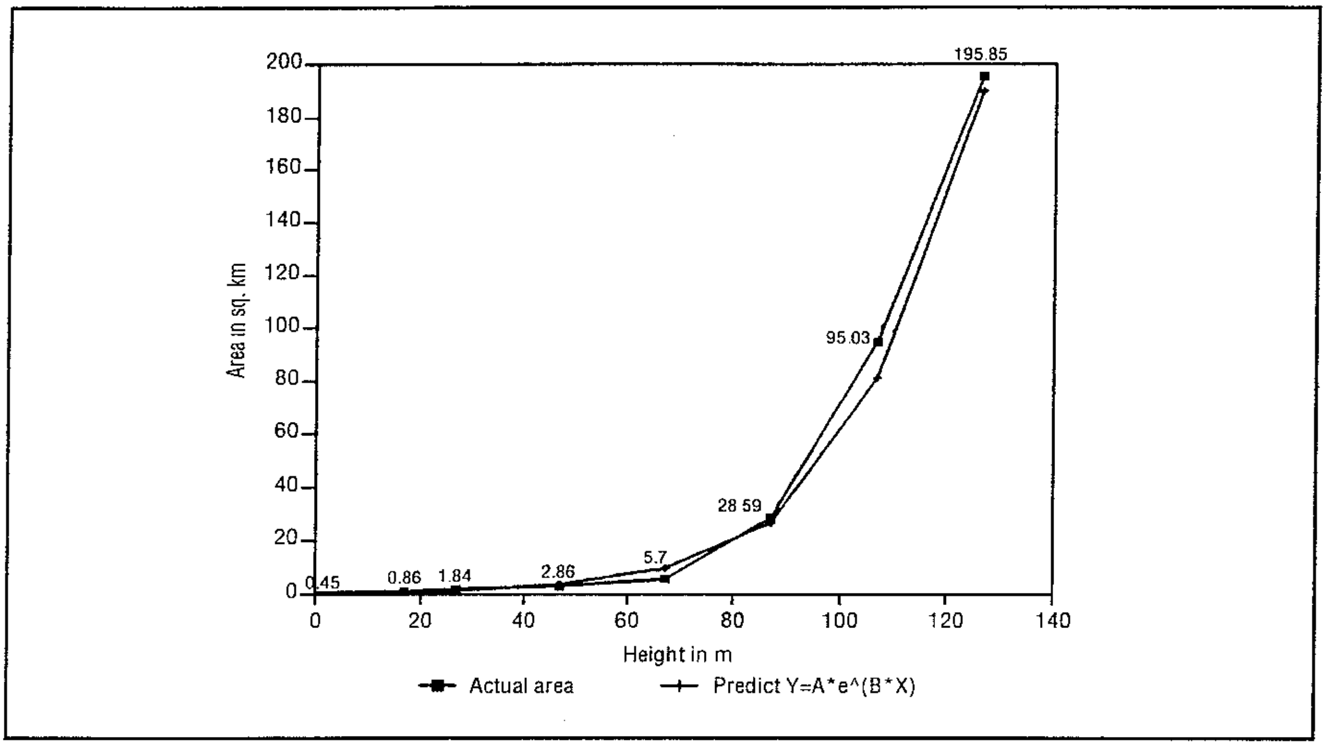

Figure 4 Submergence area for various heights of dam at Magod (Bedthi river)

such as firewood and twigs, and bio-residues of agricultural and horticultural lands, which are used for domestic, commercial and other purposes. This energy is significant. Only when the water head is very high and the reservoir profile is a deep valley with steep walls at its sides can hydroelectric energy be very competitive compared with bio-energy. When the water head is not much and the terrain has a slope less than 25°, then the smaller depth of the reservoir and less submergence area make firewood an attractive option

In order to find the contours of submergence areas corresponding to certain dam heights, the Survey of India's 1:50,000 scale toposheets are used Area is computed using a planimeter. Volume of water stored for a particular dam height, computed by assuming the volume between two consecutive contours to be trapezoidal, is given by

$$V_{12} = (a_1+a_2)\times 0.5\times h_{12} \qquad (20)$$

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

$$V_{ij} = \sum_{k=i}^{k=j-1} V_{k,k+1} \text{ and } i=1,\ j=i+1,i+2,\ldots, \qquad (21)$$

Submergence area and corresponding volume computed for different dam heights at Magod are depicted in Figure 4 This shows that, when the dam height is 67 m, submergence area is 5 7 m^2 and volume is 106 35 Mm^3 With increase of this height to 70 m, submergence area increases to 9 96 km^2 Beyond 87 m, there is steep increase in submergence area, as is evident from submergence area of 95 km^2 for dam height of 107 m. Both linear and nonlinear regression analyses were carried out of the variables – dam height, submergence area and volume. The relationship between submergence area and height of the dam is found to be either power law or exponential ($A_{sub} = 0.38\times\exp(0.048\times H_{dam})$). The correlation coefficient (r) for this relationship is 0 99, and percentage error is 0.45. Similarly, the probable relationship between volume of water and height of the dam is exponential ($V_{dam} = 5.03\times\exp(0.054\times H_{dam})$) where r = 0 99 and percentage error is 0 22. This volume-height relationship, for Magod, is shown in Figure 5 Actual and predicted area and volume for different dam heights are also shown in the figure. This best fit relationship helps in predicting submergence area and storage volume for any other height of the dam at Magod site We have used this to predict submergence area and volume at dam heights 77 m and 82 m, that is at FRL 450 m and 455 m respectively A similar exercise was carried out for Unchalli The relationship between submergence area and height of the dam is found to be either power law or exponential ($A_{sub} = 0.091\times\exp(0.082\times H_{dam})$). The correlation coefficient (r) for this relationship is 0.989, and percentage error is 0.445. Similarly, the probable relationship between volume of water and height of the dam is exponential ($V_{dam} = 0.0036\times\exp(0.18\times H_{dam})$), where r = 0 8754 and percentage error is 1 44

7. Net energy analysis

We have computed hydropower equivalent at each site 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} (or P_1) and P_{td} (or P_2), it reduces the storage capacity requirements. By allowing the P_1 to P_2 ratio to be 3, we notice that the submergence area saved is about 69 97 %. That is with $P_1 = P_2$, area required is about 95 km^2

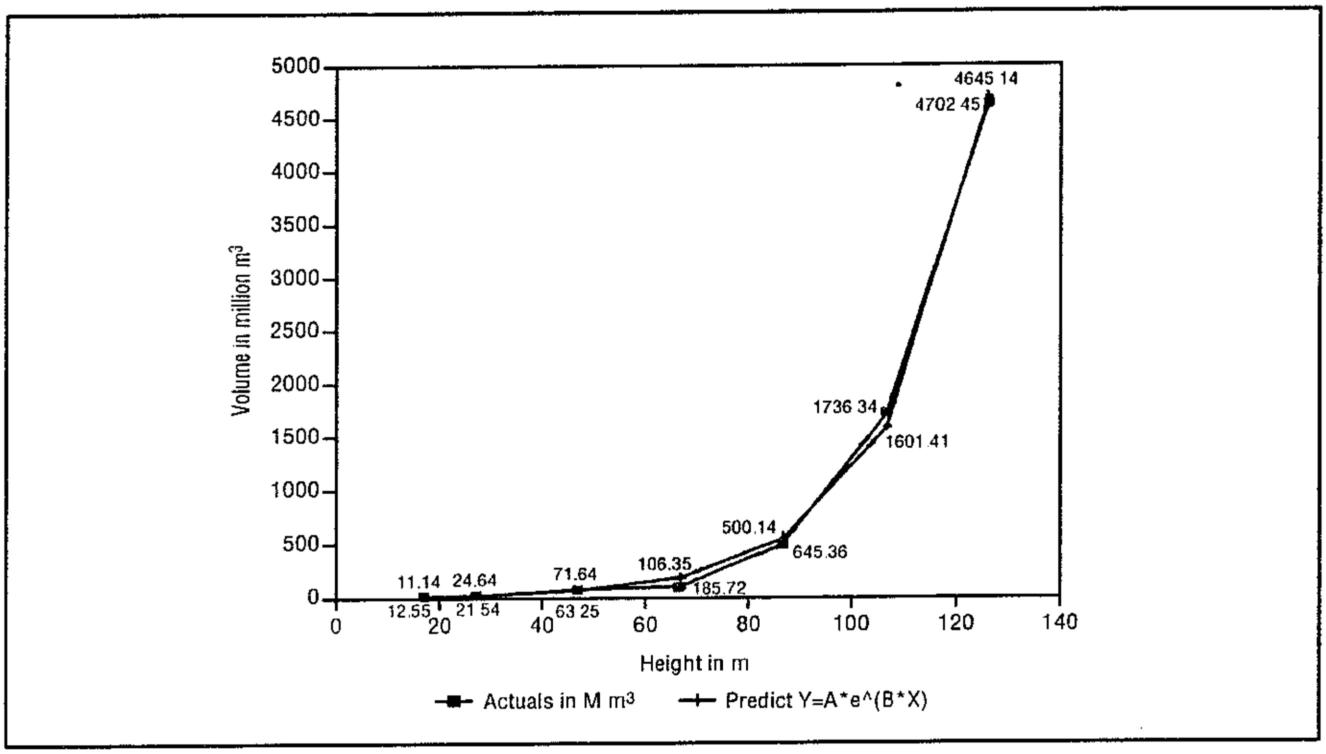

Figure 5 Storage volume for various heights of dam at Magod (Bedthi river)

Table 1. Power (MW) and energy (GWh)

						Effective power		
Site	Height (m)	Contour (m)	Sub area (km²)	Volume (million m³)	P₁/P₂	P₁ (MW)	P₂ (MW)	Hydel energy (GWh)
Magod	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	7 (for 2 months)	245.01	35.00	771.14
					4 for 2 months	140.00		
	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		
Unchalli	60	500	65.92	1059	1	210.00	210.00	1814.40
	45	485	28.71	451.14	4	420.00	105.00	1814.40
	40	480	18	220	12	700.00	58.33	1840.80
					24	345.00		
	35	475	8.38	86.9	40	600.00	15.00	1864.40
	30	470	5.55	52.27	70	600.00	7.17	1829.30

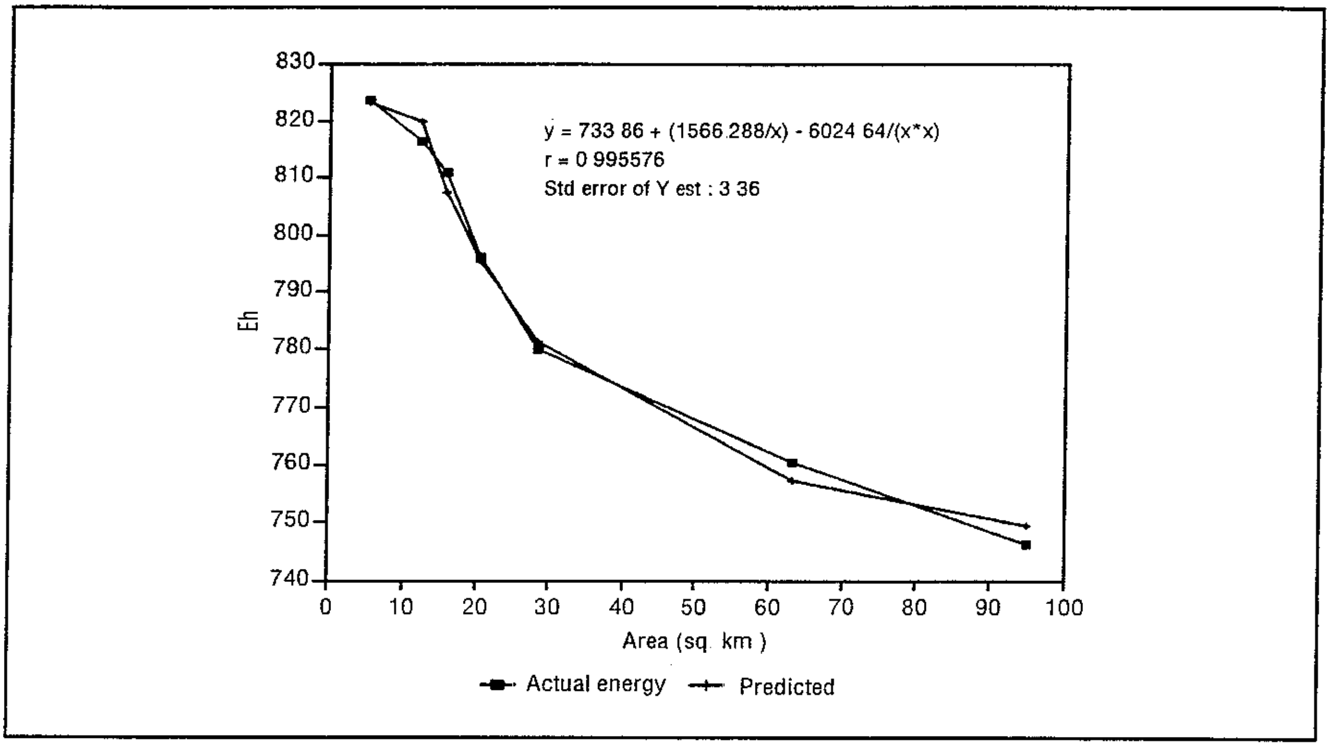

Figure 6 Energy generated versus submergence area

which comes down to 28.6 km^2 by allowing $P_l = 3\times P_2$. With this, the height of the dam comes down to 87 m from 107 m. This results in reduction of civil costs of the project.

With reduction in the height of the dam from 107 m to 67 m, the submergence area changes from 95.05 km^2 to 5.70 km^2. We can harness more hydroelectric energy by drawing the water during monsoon on run-of-river basis and storing a small quantity to meet the non-monsoon requirement. This saved area would also help in meeting the bio-resource requirement of the region, such as firewood and leaf manure for agriculture and horticulture lands. We notice that by allowing variation in the P_{tm} to P_{td} ratio, there is an increase in electric energy generated. For example, at Magod, for a dam height of 107 m (when $P_l = P_2$) energy generated in a year is 746.66 GWh, while for a dam height of 77 m (when $P_l = 3\times P_2$) it is 810.92 GWh, and for a dam height of 67 m the electrical energy generated is 823.55 GWh. This is because, for smaller heights of the dam, submergence area is less and therefore evaporation and seepage losses are also less. Similarly, at Unchalli, for a dam height of 60 m, the energy generated is 1814.40 GWh and for a dam height of 35 m, the energy generated is 1864.40 GWh. Figure 6 is a graph of submerged area versus energy generated. Regression analysis of these variables gives a hyperbolic relationship, given by $E_n = 733.86+[(1566.28)/\text{area}]-[(6024.64)/(\text{area})(\text{area})]$, with r = 0.9966 and percentage error = 1.04.

7.1. Biomass energy from lands to be submerged

The land-use pattern in the area to be submerged for various heights of dam is listed in Table 2. It shows that the area under natural forest is the major constituent of the submerged land, consisting of evergreen, semi-evergreen and deciduous forests where primary production of biomass is estimated to range between 6.5 and 27.5 t/ha/yr [Ramachandra, 1996]. Table 3 lists the thermal equivalent of bio-energy (in MW) in this area. It shows that, at a productivity of 6.5 t/ha/yr, a dam height of 107 m at Magod submerges land worth 34.21 MW in biomass energy. With reduction in dam height this value comes down to 3.38 MW due to the corresponding decrease in the submergence area (for a height of 67 m). The corresponding energy for 107 m and 67 m dam heights is 329.77 and 20.41 GWh respectively.

The reduction in submergence area implies reduction in loss of thermal energy. The net energy computed (Table 4) taking thermal value of bioresidues available in the region indicates that with decrease in dam height, the net energy available increases. At Magod, the net energy increases from 416.89 (for a dam height of 107 m) to 803.14 GWh (for a dam height of 67 m). The efficiency of a hydropower station is the combined efficiency of the turbine, generators, etc. It is estimated that this efficiency is around 70 %. For this scenario, the net energy function becomes

$$E_{net} = 0.7\times E_h - E_{bio}\ (\text{lost})$$

$$E_{net} = E_h' - E_{bio} \qquad (22)$$

To account for only the final amount of electricity, the thermal energy content of the source is discounted by the conversion efficiency of a thermal power plant. The conversion efficiency of a wood-based thermal power station is taken as 35 %. With this,

$$E_{net} = E_h' - 0.35\times E_{bio}\ (\text{where } E_h' \text{ is } 0.7\times E_h) \qquad (23)$$

The result of this computation is given in Table 5. It shows that variation in net energy available ranges from 407.24 to 569.34 GWh at Magod. For productivity of 13.5 t/ha/yr this variation ranges from 282.95 to 561.64 GWh.

The domestic fuelwood consumption survey of this

Table 2. Land use pattern in submergence area for various heights of dam

				Land use classification by category				
Location	Dam height	Corr. contour	Subm. area	Forest	Garden	Paddy	Cultivable waste	NA for cultivation
Magod	107	480	95.03	88.53	2.66	1.49	0.13	2.22
	97	470	63.23	60.27	1.21	0.68	0.06	1.01
	87	460	28.59	25.93	1.32	0.69	0.00	0.65
	82	455	20.77	18.84	0.96	0.50	0.00	0.47
	77	450	16.27	14.06	1.30	0.57	0.00	0.34
	72	445	12.74	11.01	1.02	0.45	0.00	0.27
	70	443	9.98	8.62	0.81	0.35	0.00	0.21
	67	440	5.70	4.49	0.68	0.32	0.00	0.21
Unchalli	60	500	65.92	52.41	0.48	6.72	1.70	4.61
	45	485	28.71	22.83	0.21	2.93	0.74	2.01
	40	480	18.00	13.80	0.15	1.94	0.54	1.57
	35	475	8.38	6.43	0.07	0.90	0.25	0.73
	30	470	5.55	4.26	0.05	0.60	0.17	0.48

Table 3. Thermal energy computation based on biomass productivity in each category (in MW)
(Net primary production of biomass in evergreen and deciduous forests is 6.50, 13.5, 20 to 27.5 t/ha/yr)

					Total from all categories (F+G+P+waste lands)			
	Dam height	Power in MW			Thermal energy in MW			
		Forest @6.5t/ha/yr	Garden	Paddy	Forest biomass productivity (t/ha/yr)			
		F	G	P	@27.5	@20.0	@13.5	@6.5
Magod	107	33.68	0.35	0.14	141.56	105.00	71.05	34.21
	97	22.52	0.16	0.06	94.19	69.86	47.27	22.76
	87	9.81	0.18	0.07	41.56	30.85	20.91	10.07
	82	7.13	0.13	0.05	30.19	22.41	15.19	7.31
	77	5.27	0.17	0.05	22.63	16.82	11.43	5.50
	72	4.13	0.14	0.04	17.72	13.17	8.95	4.31
	70	3.23	0.11	0.03	13.88	10.32	7.01	3.38
	67	1.79	0.11	0.03	7.93	5.89	4.00	1.93
Unchalli	60	19.66	0.06	0.64	84.33	62.69	42.59	20.50
	45	8.56	0.03	0.28	36.73	27.30	18.55	8.93
	40	5.16	0.02	0.18	22.24	16.54	11.24	5.41
	35	2.40	0.01	0.09	10.35	7.70	5.23	2.52
	30	1.59	0.01	0.06	6.86	5.10	3.47	1.67

region reveals that 82 to 90 % of the households still depend on fuelwood and agro-residues to meet their domestic cooking and water-heating requirements [Ramachandra et al., 2000c]. The annual fuelwood energy requirement is estimated to be 312.05 GWh. System efficiency considerations, peak power considerations and socio-economic considerations all rule out the possibility of electricity entirely substituting fuelwood as a source of domestic energy. Therefore only a fraction of the wood energy is converted into electrical energy, that is equal to the fraction of purely non-thermal consumption of electric energy in the total wood and electric energy consumption. A dam height of 107 m at Magod submerges about 95 km^2, of which 88.53 km^2 is under evergreen and semi-evergreen forests, rich in biodiversity. This necessitates eco-friendly options to reduce submergence of prime 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 hydro and biomass generation system is shown in energy terms, which leads to

Table 4. Hydro, thermal and net energy available from submerged area (GWh)

	Dam height	Hydro energy	$E_{biomass}$				Net energy (GWh)			
		(E_h)	E_{bio}	E_{bio}	$E_{bio'}$	$E_{bio''}$	E_h-E_{bio}	E_h-$E_{bio'}$	E_h-$E_{bio''}$	E_h-$E_{bio'''}$
			@6.5t/h/yr	@13.5/t/h/yr	@20t/h/yr	@27.5t/h/y				
Magod	107	746.66	329.77	684.90	982.31	1302.60	416.89	61.76	-235.65	-555.94
	97	760.55	219.42	455.71	653.60	866.71	541.13	304.84	106.95	-106.16
	87	780.08	100.36	208.44	295.55	389.37	679.72	571.64	484.53	390.71
	82	796.27	72.91	151.44	214.72	282.88	723.36	644.83	581.55	513.39
	77	810.82	58.25	120.98	168.21	219.07	752.57	689.84	642.61	591.75
	72	816.48	45.62	94.75	131.74	171.56	770.86	721.73	684.74	644.92
	70	823.55	35.74	74.24	103.21	134.41	787.81	749.31	720.34	689.14
	67	823.55	20.41	42.40	58.95	76.77	803.14	781.15	764.60	746.78
Unchalli	60	1814.40	243.32	505.36	681.43	871.04	1571.08	1309.04	1132.97	943.36
	45	1814.40	105.98	220.11	296.79	379.37	1708.42	1594.29	1517.61	1435.03
	40	1840.80	67.28	139.74	186.11	236.05	1773.52	1701.06	1654.69	1604.75
	35	1864.40	31.31	65.02	86.61	109.86	1833.09	1799.38	1777.79	1754.54

Table 5. Net energy computation (taking conversion efficiency for biomass as 35 % and electrical machinery efficiency as 70%)

	Dam height	Hydro energy	Energy from biomass (GWh)				Net energy (GWh)			
		E_h	0.35×E_b	0.35×$E_{b'}$	0.35×$E_{b''}$	0.35×$E_{b'''}$	E_h-E_{bio}	$E_{h'}$-E_{bio}	$E_{h'}$-$E_{bio'}$	E_h-$E_{bio'''}$
		0.7E_h	E_{bio}	$E_{bio'}$	$E_{bio''}$	$E_{bio'''}$				
Magod	107	522.66	115.42	239.71	343.81	463.92	407.24	282.95	178.85	58.74
	97	532.39	76.80	159.50	228.76	303.35	455.59	372.89	303.63	229.04
	87	546.06	35.13	72.95	103.44	138.63	510.93	473.10	442.61	407.43
	82	557.39	25.52	53.00	75.15	100.71	531.87	504.39	482.24	456.68
	77	567.57	20.39	42.34	58.87	77.95	547.19	525.23	508.70	489.63
	72	571.54	15.97	33.16	46.11	61.04	555.57	538.37	525.43	510.49
	70	576.49	12.51	25.98	36.12	47.82	563.97	550.50	540.36	528.66
	67	576.49	7.14	14.84	20.63	26.87	569.34	561.64	555.85	549.62
Unchalli	60	1270.08	85.16	176.88	238.50	309.60	1184.92	1093.20	1031.58	960.48
	45	1270.08	37.09	77.04	103.88	134.84	1232.99	1193.04	1166.20	1135.24
	40	1288.56	23.55	48.91	65.14	83.87	1265.01	1239.65	1223.42	1204.69
	35	1305.08	10.96	22.76	30.31	39.03	1294.12	1282.32	1274.77	1266.05
	30	1280.51	7.26	15.09	20.09	25.87	1273.25	1265.42	1260.42	1254.64

a significant reduction in the total area used for power generation. At Magod, with a large storage reservoir, the energy generated is 522.66 GWh (taking into account efficiency of generation). Adjusting storage capacity according to the seasonal variation and with a hydro-biomass combination, the net energy increases to 823.55 GWh. Apart from this, there is scope to generate hydroelectric energy from streams in a decentralised way.

8. Economic analysis

8.1. Computation of costs: net loss due to forest submersion

With the submersion of forests, benefits such as (1) fuelwood, (2) timber, (3) grass and other biomass material, (4) forest products such as cane, bamboo, gum, resins, tendu leaves, drugs, spices, etc., (5) biodiversity, (6) recreation and (7) environmental benefits, such as oxygen production, soil conservation, control of air pollution, recycling of water and control of humidity, etc., are lost. Forests play a role not only in the social and economic well-being of society but also in maintaining the ecological balance. 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 Rs 2,250,000 to Rs 4,550,000/ha (Indian rupees: Rs 46 = US$ 1) depending on vegetation cover. In this computation,

Table 6. Environment benefits per hectare of forest during 50-year life span

Environmental benefits	Tropical Rs. 100,000	Sub tropical Rs. 100,000
1. Oxygen production	22.50	20.50
2. Conservation of animal protein	1.80	1.64
3. Control of soil erosion	22.50	20.50
4. Recycling of water and control of humidity	27.00	24.60
5. Shelter for birds, reptiles, insects fauna	22.50	20.50
6. Control of air pollution	45.00	41.00
Total	141.30	128.74

Table 7. Civil, electrical, environmental, rehabilitation costs (million rupees) for various heights of dam

Site	Height	Cost civil	Electrical	Civil+El	Env (land)	Rehabilitation	Env cost	Total cost
Magod	107	2800.77	1101.98	3902.75	1282.99	173.25	20.00	5378.99
	97	2177.87	1140.34	3318.21	583.64	138.60	9.10	4040.45
	87	1988.41	1508.66	3497.07	427.76	23.85	3.03	3948.68
	82	1761.24	1830.94	3592.17	339.01	1.12	0.80	3931.19
	77	1657.04	2061.13	3718.18	287.29	0.09	0.18	4005.74
	72	1504.59	2368.06	3872.65	225.15	0.02	0.03	4097.85
	67	1487.68	2541.56	4029.24	218.60	0.02	0.02	4247.88

the price of forest land is taken as Rs 111,200/ha. Some attempts have been made earlier to quantify the environmental cost of the loss of a forest, as Rs 14.130 million/ha for tropical forest and Rs 12.874 million/ha for sub-tropical forest [Maudgal and Kakkar, 1992]. The details of environmental benefits derived from a medium-size tree of 50 t during its 50-year life-span, excluding value of timber, fruit and flowers, are listed in Table 6.

8.2. Loss due to submersion of agriculture and horticulture land

The costs involved in the submersion of agricultural lands, arecanut orchards and coconut plantations were based on the market value of the land in this region. The value of arecanut orchard is Rs 890,000/ha, while for paddy, it is Rs 99,000/ha and coconut plantation is about Rs 218,000/ha. The details of villages submerged and number of households affected are obtained from government agencies such as Tahsildar's office at taluk level and Village Accountant's office. The displacement and rehabilitation costs were based on the data from earlier hydroelectric projects in the district.

8.3. Annual charges on capital costs

The capital cost depends on (1) civil construction costs (size and type of the dam) and (2) cost of generating unit, which depends on the capacity. The capacity is calculated using normal load factor of 0.5. The schedule of rates approved by the government recently has been used in computing civil and electrical costs. This exercise carried out for Magod is listed in Table 7. 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.

8.4. 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, surge shaft, penstock, power-house equipment, power-house building and substation equipment as 50 years, and roads, etc., as 35 years (hydel option). For the thermal option the life of the thermal plant (biomass-fuelled steam power plant) is taken as 30 years [Ramachandra, et al., 2000a].

Hence, annual cost C = annuity factor×total cost + O&M charges + depreciation cost

With this cost and energy information, we have computed cost per kWh (also referred to as unit) of energy (net energy = electric energy from hydro + electrical energy from thermal option through bio-residues). Table 8 lists cost per kWh for various designs of the dam (at biomass productivity of 6.5 t/ha/yr). It shows 40.5 % reduction in cost (Rs 1.53 per kWh to Rs 0.92 per kWh) for a dam height reduction of 32.75 %. This is shown in Figure 7. If we exclude costs of bioresources and consider electricity from water resource only, then cost reduction is from Rs. 1.53 per kWh to Rs. 1.09 per kWh. We have also computed cost per kWh without taking into account conversion efficiency. In this case (Table 8) cost varies from Rs. 1.07 to 0.56 per kWh.

Table 8. Cost per unit (kWh) of electricity (considering biomass producivity as 6.5 t/ha/yr)

	Dam height	Total cost	Int (12 %, 50 yrs)	Dep (1.806 %)	Oper. cost (1 %)	Annual expenditure	Hydro energy (E_h)	Bio energy (E_{bio})
		(million Rs)						
Magod	107	5378.99	647.74	97.14	53.79	798.67	746.66	0.00
	97	4040.45	486.55	72.97	40.40	599.93	760.55	110.35
	87	3948.68	475.50	71.31	39.49	586.30	780.06	219.14
	82	3931.19	473.39	71.00	39.31	583.70	796.36	244.94
	77	4005.74	482.34	72.34	40.05	594.73	810.82	259.78
	72	4097.85	493.46	74.01	40.98	608.44	816.48	271.42
	67	4247.87	511.52	76.72	42.48	630.72	823.55	319.86
		Net energy			Cost per unit (kWh) of electricity			
		$E_h + E_{bio}$	$E_h'+0.35\times E_{bio}$		Cost/E_h	Cost/E_h'	$E_h + E_{bio}$	$E_h'+0.35\times E_{bio}$
Magod	107	746.66	522.66		1.07	1.53	1.07	1.53
	97	870.90	571.01		0.79	1.13	0.69	1.05
	87	999.20	622.74		0.75	1.07	0.59	0.94
	82	1041.30	643.18		0.73	1.05	0.56	0.91
	77	1070.60	658.50		0.73	1.05	0.56	0.90
	72	1087.90	666.53		0.75	1.06	0.56	0.91
	67	1126.88	688.44		0.77	1.09	0.56	0.92

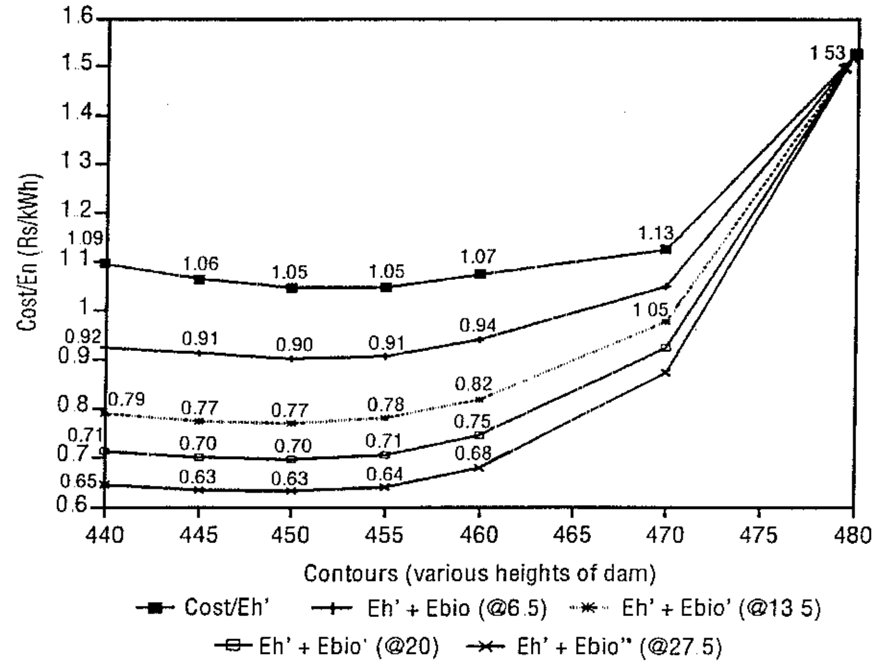

Figure 7 Cost per unit (kWh) of electricity generated for various heights of dam

8.5. Benefits

The benefit would be the revenue accruing as a result of electricity consumption in various sectors. The percentage share of each sector is calculated by looking into the annual consumption pattern in Uttara Kannada district. Table 9 shows that the industrial sector with a share of 86.38 % is the major consumer, followed by the domestic sector with a share of 10.20 %. On the basis of consumption patterns of previous years, we have estimated electricity requirements in various sectors. The percentage share of each sector is used to compute benefits for various heights of the dam. On the basis of tariff information provided by Karnataka Electricity Board (the old name of the KPTCL) at Sirsi, Uttara Kannada district, sector-wise revenue is computed. The benefit from the power project

$$B = \Sigma\, e_j \times t_j \qquad (24)$$

Table 9. Sectorwise electricity consumption (MWh) and average tariff

Sector	No of users	Consumption	% share	tariff/kWh
	(Uttara Kannada district)			
Domestic	98117	29994	10.20	0.79
Industrial	3269	254010	86.38	1.31
Agriculture	13633	689	0.23	0.07
Commercial	13089	5811	1.98	1.16
Public lighting	598	788	0.27	0.76
Others	270	2757	0.94	1.92
Total	128976	294049	100	

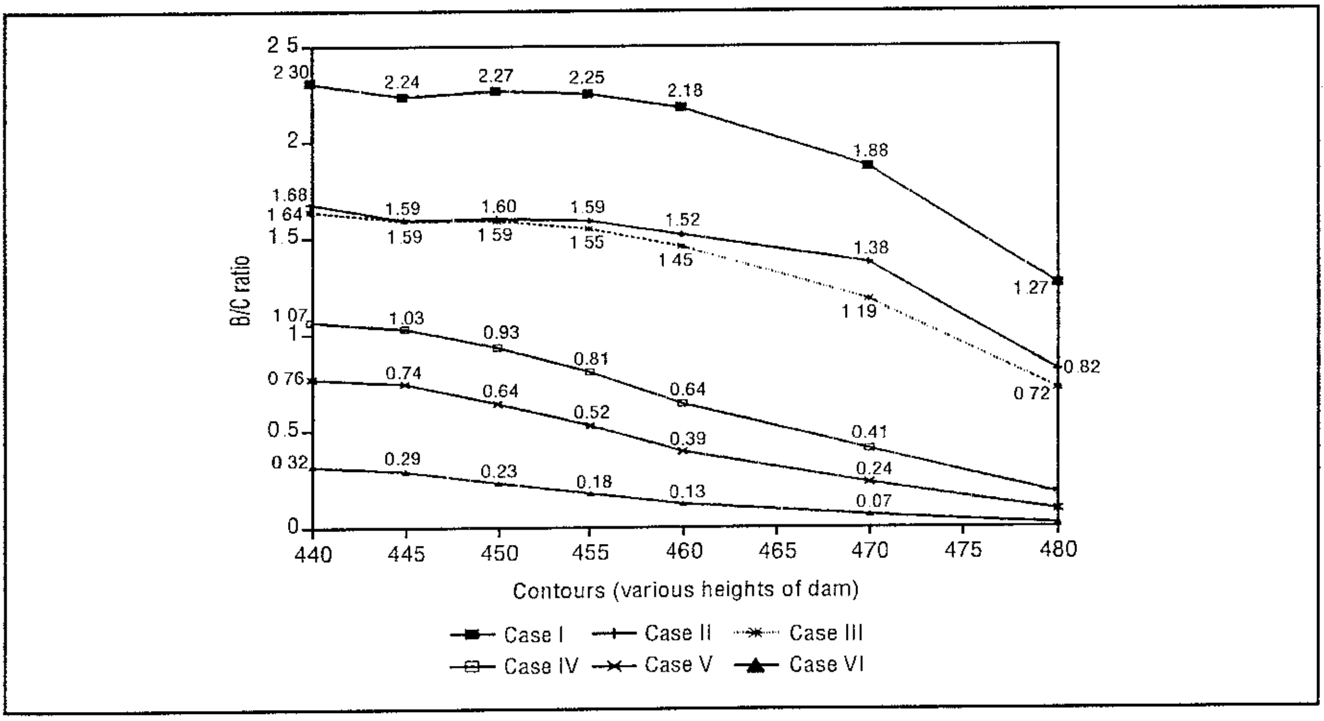

Figure 8 Benefit-cost ratio for various environmental costs

where $j = 1 \ldots 6$ (representing various sectors), and e_j and t_j are electricity consumption and tariff in Rs/kWh for sector "j"

Benefit-cost ratio = B/C (25)

B/C is computed accordingly for various dam heights, considering the following cases:

Case I: Value of forest land as Rs.37,065/ha

Case II: Value of forest land as Rs. 111,200/ha

Case III: Value of forest land as Rs. 111,200/ha + minor forest produce as Rs 12,000/yr.

Case IV: (Standing biomass + value of land) as Rs. 2,250,000/ha

Case V: (Standing biomass + value of land) as Rs. 4,550,000/ha

Case VI: (Standing biomass + value of land) as Rs. 2.250,000/ha + environmental value as Rs. 14.130 million/ha

B/C computed for Case I is less than 1.5 for height H_1 (107 m), while for heights H_4, H_5 and H_6 it is greater than 1.5. B/C ratio computed for Case II has a value less than 1.5 for heights H_1 and H_2 and for other heights it is greater than 1.5. Data from various forest documents (timber, minor forest products, and other products) show the value of products from forest land as about Rs 12,000/ha/yr, and data from fuelwood depots at Kumta and Ankola shows fuelwood rate as Rs 250/t for local residents (heavily subsidised price for ration-card holders) and Rs 750/t for temples, hostels, etc. Quantity supplied to various sectors, such as households, for cremation (through depots), commercial organizations, temples and hostels were obtained from Forest Department (Canara circle). Incorporating this, Case III shows that for heights H_4, H_5 and H_6, B/C ratio is greater than 1.5. B/C ratios computed for various designs and various environmental values are shown pictorially in Figure 8. For Case IV, Case V and Case 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, hydroelectric generation through storage options (even for minimum submergence) becomes a less attractive option.

9. Conclusions

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

This analysis explains the upper limit on the height of 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

Parametric optimization technique is used to compute energy from hydro source at Magod If variation is allowed between P_1 (monsoon season) and P_2 (dry season), it reduces the storage capacity requirements. By allowing P_1 to P_2 ratio as 3, we notice that the submergence area saved is about 69.97 % and there is subsequent increase in electric energy generated. That is, when $P_1 = P_2$, electricity generated is 746.66 GWh and this increases to 810.82 GWh when $P_1 = 3 \times P_2$. This is mainly due to less evaporation and seepage loss due to less 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 That is, net energy increases from 522.66 to 896 35 GWh by hydro-thermal combined option in a land area of 95 03 km^2. Apart from the distinct reduction in submergence area, the overall reliability of a hydro-thermal combined system is much higher than that of a pure hydro system (which is very sensitive to fluctuation in rainfall). Fuelwood requirement in the region is about 312.05 GWh for domestic purposes Net energy computed for various dam heights indicates that a dam of height 67 m stores enough water to meet the region's lean season electricity requirement and area saved has bio-resource potential of 319 85 GWh which can cater for the thermal energy demand of 312.05 GWh

The cost per kWh for various designs of the dam shows 40.5 % reduction in cost (Rs 1 53/kWh to Rs 0.92/kWh) for a dam height reduction of 32.75 %. Benefit-to-cost ratio computed considering forest land value as Rs 111,200/ha is greater than 1.5 for dam height less than 87 m B/C is less than 1 5 for all dam heights incorporating tangible and intangible environmental factors in the cost-benefit analysis This means that by assigning environmental values taking all components into consideration, hydroelectric power generation through storage options (even for minimum submergence) becomes a less attractive option ■

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