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Research Paper

ASSESSMENT OF OPTIMAL YIELD AND CROP PLAN FOR A RIVER BASIN

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This paper presents application of Modified Integrated Yield Model (MIYM) for river basin development, which is an implicit stochastic screening model based on linear programming to assess optimal annual yields from reservoirs based on pre-specified annual release reliabilities with site specific yield failure years and failure fraction factors and also simultaneously optimizing the cropping pattern. The model is applied to Vedavathi basin of Krishna River in Andhra Pradesh, India. The study result showed that MIYM as a screening model performs well in achieving its intended purpose of determining yields from a system of reservoirs and barrages with optimal crop plan.

Keywords: Yield model, Failure fraction, Optimal yield

INTRODUCTION

Increasing demands for water emphasize the proper need for effective planning and development of river basin system. Determination of system yield is often a complex problem because it depends on factors like, physical configuration of the system; active storage capacities of the reservoirs; distribution of natural stream flows entering into the reservoirs; and reservoir operating policy (Loucks *et al.,* 1981). Techniques available to estimate the yield of a multiple reservoir system include simulation, optimization and, techniques that utilize both simulation and optimization (Loucks *et al.,* 1981; Chaturvedi and Srivastava, 1981; and Yeh, 1985). Screening models based on optimization techniques are very much useful for reasonable estimate of system yields in initial phase of planning. However, major limitation of the optimization model is its size using long period of historical river flows. Long time period is essential to include the critical period of flows and to capture the flow characteristics. The concept of yield model introduced by Loucks *et al.* (1981) overcomes these difficulties. The yield model is an approximation of full optimization model based on Linear Programming (LP) and capable of estimating the over-year and within-year reservoir capacity requirements to meet

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the specified release reliability targets. Stedinger *et al.* (1983) reviewed and compared deterministic, implicitly stochastic and explicitly stochastic reservoir models and concluded that the explicitly stochastic yield model introduced by Loucks *et al.* (1981) produced reasonable reservoir designs with release reliabilities near targets. The concept of the original yield model is employed through a combination of simulation and non linear optimization techniques for multipurpose multi reservoir systems (Lall and Miller, 1988; Lall, 1995; and Sinha *et al.,* 1999).

Dahe and Srivastava (2002) presented a multiple yield model for a multiple reservoir system in the upper basin of the Narmada River. The objective of their study was to achieve pre-specified reliabilities for irrigation and energy generation and to incorporate an allowable deficit in the annual irrigation target through a multiple yield model for a multiple reservoir system consisting of single-purpose and multipurpose reservoirs. Panigrahi and Srivastava (2005) presented Integrated Yield Model (IYM) for river basin development to assess optimal annual yields from reservoirs based on pre-specified annual release reliabilities with site specific yield failure years and failure fraction factors and also simultaneously optimizing the cropping pattern at each site and suggested optimization-simulation technique for system of reservoirs and barrages.The major limitation of yield models by Loucks *et al.*(1981), Dahe and Srivastava (2002), Panigrahi and Srivastava (2005), Dahe (2001) and Panigrahi (2006) is that these models could not be applied to the system comprising of reservoirs and barrages as a whole because these models do not work in case of barrages. Hence Panigrahi and Srivastava (2005) and Panigrahi (2006) recommended optimization-simulation model for system of reservoirs and barrages.

This paper presents application of MIYM which will be used for the river basin comprising of reservoirs as well as barrages to assess the various optimal integrated annual system yields with specified release reliabilities depending upon different water uses by simultaneously optimizing the cropping pattern for each project at the same time after the mandatory demands in each within-year time periods are fully met out of the within-year firm yields.

MODEL FORMULATION

In this, two yields; one firm yield with maximum reliability and the other secondary yield with reliability lower than the maximum reliability is considered. For the modelling purpose, three types of water uses are considered for a multipurpose project, viz., municipal demand, industrial demand, and irrigation. For finding the optimal yield from a multipurpose reservoir having mandatory release towards municipal and industrial demand in addition to the irrigation, the following assumption has been adopted, i.e., two types of reservoir yields, one firm yield with maximum possible annual release reliability, i.e., $n/(n+1)$ in a sample size of n and the other an incremental secondary yield with desired annual release reliability depending on the water use, are to be considered for all the single and multipurpose projects within the basin.

Consider a multipurpose reservoir with three purposes, i.e., municipal demand, industrial demand and irrigation. Fixed quantity towards municipal and industrial demands in each within-year time period is to be released even during the critical years with an intention to achieve the maximum possible annual release reliability, simultaneously satisfying its within-year distribution. Whereas irrigation demand will be met from the total annual yield less the mandatory releases. In addition, the model also determines optimal crop plans. The improved yield model having capability to assess optimal yields and simultaneously determining optimal crop plans of reservoirs as well as barrages is defined as Modified Integrated Yield Model (MIYM).

The objective of the model is either to maximize annual yield or maximize gross benefit from different water uses for known reservoir capacities. This model can also be used to find out required active reservoir capacity for desired demands. The concept and logic of yield model formulation by Dahe and Srivastava (2002) and Panigrahi and Srivastava (2005) is not repeated but only the equations which are essential and modified are presented here. The model is formulated below.

OBJECTIVE FUNCTION

Maximize annual system yield, i.e.,

$$\text{Max} \sum_{i}\sum_{t}\left(Oy_{it}^{fp} + Oy_{it}^{sp2} \right) \quad ...(1)$$

or

Maximize the gross benefit from different water uses, i.e.,

$$\text{Max} \sum_{i=1}^{NPI}\sum_{r=1}^{NC}\left(A_i \; \Phi_{ir} \; \Psi_{ir} \; B_{ir} \right)$$

$$+ \sum_{i=1}^{NMun}\left(\mu M_i \; B_i^{mun} \right) + \sum_{i=1}^{NInd}\left(\mu I_i \; B_i^{ind} \right) \quad ...(2)$$

where Oy_{it}^{fp} and Oy_{it}^{sp2} are the firm and secondary reservoir yields from reservoir *i* in period *t* with annual reliability *p* and *p*2, respectively; *NPI* = number of reservoirs having irrigation component; *NC* = number of crops; A_i = culturable command area (CCA) of reservoir *i*; Φ_{ir} = fraction of CCA under crop *r* of reservoir *i*; ψ_{ir} = yield of crop *r* per unit area of CCA under reservoir *i*; B_{ir} = gross return from unit weight of yield of crop *r* under reservoir *i*; *NMun* = number of reservoirs having municipal water supply component; *NInd* = number of reservoirs having industrial water supply component; μM_i = annual mandatory release for municipal water supply from reservoir *i*; μI_i = annual mandatory release for industrial water supply from reservoir *i*; ; and B_i^{mun} = gross benefit from unit volume of mandatory release for municipal water supply from reservoir *i*; and B_i^{ind} = gross benefit from unit volume of mandatory release for industrial water supply from reservoir *i*.

CONSTRAINTS

1. Over-year storage continuity for year *j* at reservoir *i*

$$S_{i,j-1}^{o} + \left[\sum_{k \in m} Sp_{kj} \right] + I_{ij} - Oy_i^{fp} - \theta_{ij}^{p2} \; Oy_i^{sp2}$$

$$- EV_{ij} - Sp_{ij} = S_{ij}^{o} \qquad \forall ij \quad ...(3)$$

$$\theta_{ij}^{p2} = \begin{cases} 0 & \text{for failure years} \\ 1 & \text{for successful years} \end{cases}$$

where $S_{i,j-1}^{o}$ = initial over year storage volume in year *j* of reservoir *i*; *m* = set of contributing reservoirs upstream of reservoir *i*; *k* = index for contributing reservoir upstream of reservoir *i*; Sp_{kj} = excess release (spill) from upstream contributing reservoir *k* in year *j*; I_{ij} = annual inflow at reservoir site *i* in year *j*; Oy_i^{fp} = annual firm reservoir yield with a reliability *p* for reservoir *i*; θ_{ij}^{p2} = factor to identify a successful or a failure year for secondary yield in case of a multiple yield model; Oy_i^{sp2} = annual secondary reservoir yield with a reliability *p2* for reservoir *i*; EV_{ij} = annual evaporation volume loss from reservoir *i* in year *j*; Sp_{ij} = excess release (spill) from reservoir *i* in year *j*; and S_{ij}^o = final over year storage volume in year *j* for reservoir *i*.

2. Within-year storage continuity for reservoir *i* in time *t*

$$S_{i,t-1}^w + \beta_{it}\left[\left(Oy_i^{fp} + Oy_i^{sp2}\right) + \sum_t Ev_{it}\right]$$

$$+\sum_{k\varepsilon m}\left\{\left[\delta_k^{irr}\left(Oy_{kt}^{fp} + Oy_{kt}^{sp2}\right) + \left(\delta_k^{mun} - \delta_k^{irr}\right)\mu_{kt}^{mun}\right.\right.$$

$$\left.\left. + \left(\delta_k^{ind} - \delta_k^{irr}\right)\mu_{kt}^{ind}\right] + \left(Ex_{kt}^{fp} + Ex_{kt}^{sp2}\right)\right\}$$

$$-Ev_{it} - \left(Oy_{it}^{fp} + Oy_{it}^{sp2}\right) - \left(Ex_{it}^{fp} + Ex_{it}^{sp2}\right) = S_{it}^w$$

$$\forall it \qquad ...(4)$$

where $S_{i,t-1}^w$ = initial within-year storage volume in period *t* for reservoir *i*; β_{it} = ratio of the inflow in period t of the critical year of record to the total annual inflow of that year; Ev_{it} = evaporation volume loss from reservoir *i* in period *t*; δ_k^{irr} = fraction of reservoir yield coming as regenerated flow from upstream contributing reservoir k after utilization for irrigation purpose; δ_k^{mun} = fraction of reservoir yield coming as regenerated flow from upstream contributing reservoir *k* after utilization for municipal water supply purpose; δ_k^{ind} = fraction of reservoir yield coming as regenerated flow from upstream contributing reservoir *k* after utilization for industrial water supply purpose; μ_{kt}^{mun} =total mandatory release towards municipal demand during period t from upstream contributing reservoir *k*; μ_{kt}^{ind} = total mandatory release towards industrial demand during period *t* from upstream contributing reservoir *k*; Ex_{kt}^{fp} = excess firm release from upstream contributing reservoir k during period *t*; Ex_{kt}^{sp2} = excess secondary release from upstream contributing reservoir *k* during period *t*; Ex_{it}^{fp} = excess firm release from reservoir *i* during period *t*; Ex_{it}^{sp2} = excess secondary release from reservoir i during period *t*; and S_{it}^w = final within-year storage volume in period *t* for reservoir *i*.

3. Over-year active storage volume capacity for year *j* at reservoir *i*

$$S_{i,j-1}^o \le Y_i^o \qquad \forall ij \qquad ...(5)$$

where Y_i^o = over-year storage capacity of reservoir *i*.

4. Total active reservoir storage capacity for reservoir *i*

$$Y_i^o + S_{i,t-1}^w \le Ya_i \qquad \forall it \qquad ...(6)$$

where Ya_i = total active storage capacity of reservoir *i*.

5. Continuity of annual yields at each reservoir site

(I) For firm reservoir yield

$$\sum_t Oy_{it}^{fp} = Oy_i^{fp}$$

$$+\sum_{k \in m}\left[\delta_k^{irr}\sum_t\left(Oy_{kt}^{fp}\right)+\left(\delta_k^{mun}-\delta_k^{irr}\right)\mu M_k\right.$$

$$\left.+\left(\delta_k^{ind}-\delta_k^{irr}\right)\mu I_k+\sum_t Ex_{kt}^{fp}\right]-\sum_t Ex_{it}^{fp}$$

$$\forall i \qquad ...(7)$$

where μM_k = annual mandatory release towards municipal demand from upstream contributing reservoir *k*; and μI_k = annual mandatory release towards industrial demand from upstream contributing reservoir *k*.

(II) For secondary reservoir yield

$$\sum_t Oy_{it}^{sp2} = Oy_i^{sp2}$$

$$+\sum_{k \in m}\left[\delta_k^{irr}\sum_t\left(Oy_{kt}^{sp2}\right)+\sum_t Ex_{kt}^{sp2}\right]-\sum_t Ex_{it}^{sp2}$$

$$\forall i \qquad ...(8)$$

6. Constraints for allowable annual deficit criterion

$$\sum_t Oy_{it}^{fp} \geq \rho_i^{p2}\left(\sum_t Oy_{it}^{fp}+Oy_{it}^{sp2}\right) \quad \forall i \qquad ...(9)$$

for $0 \leq \rho_i^{p2} < 1$

where ρ_i^{p2} = fraction of total annual yield desired to be released in the failure years for reservoir *i*.

7. Annual mandatory release towards municipal demand from reservoir *i*;

$$\sum_t \mu_{it}^{mun} = \mu M_i \qquad \forall i \qquad ...(10)$$

8. Annual mandatory release towards industrial demand from reservoir *i*;

$$\sum_t \mu_{it}^{ind} = \mu I_i \qquad \forall i \qquad ...(11)$$

7. Constraint to achieve maximum possible annual reliability for mandatory release

$$Oy_{it}^{fp} \geq \mu_{it}^{mun} + \mu_{it}^{ind}$$

8. Water availability/requirement Constraint

$$\sum_{r=1}^{NC_t}\left(A_i\ \Phi_{ir}\ \Delta_{irt}\right)+\mu_{it}^{mun}+\mu_{it}^{ind} = Oy_{it}^{fp}+Oy_{it}^{sp2}$$

$$\forall i \qquad ...(12)$$

where NC_t = number of crops in period *t*; Δ_{irt} = gross irrigation requirement (GIR) in depth by the crop *r* during period *t* of reservoir *i;*

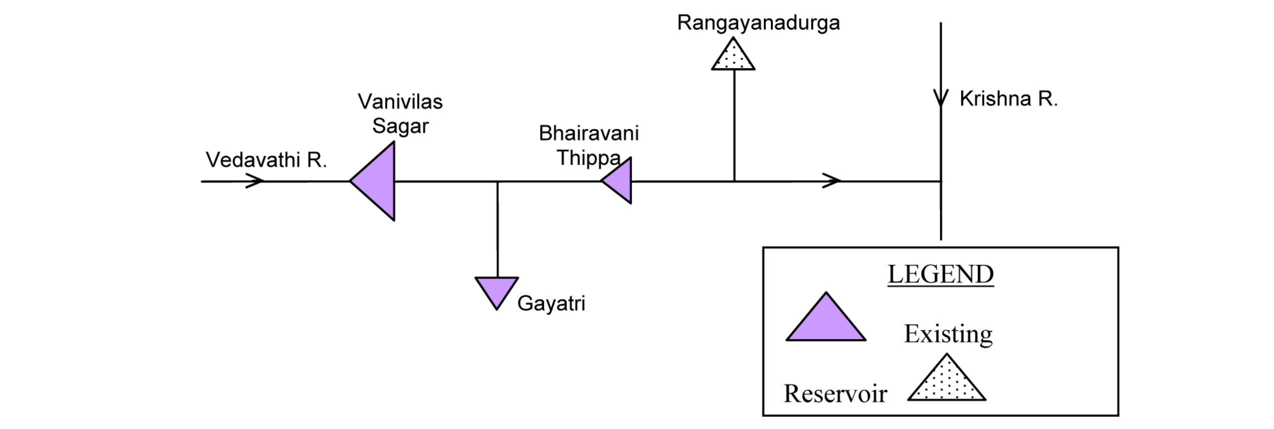
Other constraints like annual evaporation losses, within year evaporation losses, irrigation intensity limitation, area under crops, land availability, protein and calorie requirement are considered (Loucks *et al.,* 1981 and Panigrahi and Srivastava, 2005).

MODEL APPLICATION

The river Vedavathi is a right bank tributary of the river Tungabhadra and the river Tungabhadra is a right bank tributary of the river Krishna. The Vedavathi, also called, the Hagari, is formed by the union of the streams- the Veda and Avati originating in the Bababudanagiri range of hills of the Western Ghats in Karnataka. It traverses a length of 391 km before meeting the river Tungabhadra. The Vedavathi basin comprises the entire catchment of the Vedavathi from its source to its outfall in the Tungabhadra including the catchment of all its tributaries. The Suvarnamukhi, the Chinna Hagari and the Peddavanka are the principal tributaries of the Vedavathi river. The Vedavathi basin lies between east longitudes 75°43'00" to 77°25'00" and north latitudes 13°07'00" to 15°44'00". The basin has a catchment area of 23590 sq km and forms 9.11% of the Krishna basin. 77.23% of the catchment area of the basin lies in Karnataka and balance 22.77% in Andhra Pradesh. The basin mainly experiences the south-west monsoon which is generally from May to November. The mean monthly maximum temperature is found to be 38.1°C and minimum as 16.7°C. The maximum culturable area of the basin is 17.08 lac ha, which is 72.38% of the total geographical area of the basin. Projects in the basin are presented in Figure 1. Out of four reservoirs, Vanivilas Sagar is the only major existing project; Gayatri and Bhairavanithippa are the existing medium and Rangayana Durga is an ongoing medium project. All reservoirs are multipurpose with three purposes to serve, i.e., irrigation, municipal and industrial demand. MIYM is applied to assess the water resources potential of the system.

The inflow series of 28 years are considered for computation purposes. For the purpose of this study 28 over-year time periods, and 12 within-year time periods for the critical year only are considered with the water year starting from the month of June and ending in May. Annual reliabilities for the firm and secondary yields considered are 97% and 76%, respectively. The net inflow series at each project were calculated by the basin water balance method from the discharge data available at nearby river gauging site. At each site, Weibull's plotting position method is adopted for identifying failure years from the respective net inflow series. The inflow fractions in within-year time periods β_t are calculated for each reservoir considering inflow of the driest year. Storage area curves (linearized over dead storage) are used for computation of evaporation parameters. The gross irrigation water requirements at each within-year time period of the proposed crop plan under each project was estimated by FAO methodology (Allen *et al.,* 1998). Crop period, number of days in different growth stages and corresponding crop coefficient (K_c) are taken

Figure 1: Schematic Diagram of Vedavathi Basin



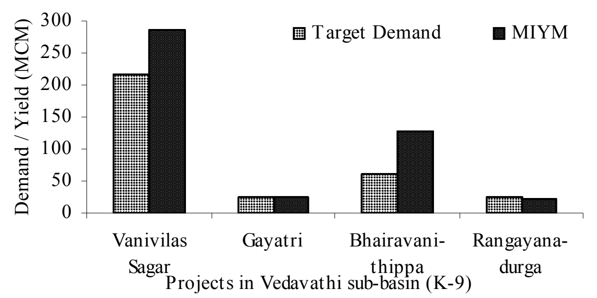
from different sources (Allen *et al.,* 1998; Doorenbos and Pruitt, 1997; and NWDA, 1987). Projected population of a basin is distributed proportionately among all the projects in proportion of their respective Culturable Command Area (CCA). Municipal and industrial water demand at each project is calculated for projected population. Site-specific values of allowable percentage yield (failure fraction) for satisfying the project specific demands as far as possible in successful years have been considered in the study. Data pertaining to crop yield, gross income from crop produce, and protein and calorie requirement of each crop are taken from different sources (Dahe, 2001 and Panigrahi, 2006). Protein and calorie requirements of the total as well as of the agricultural population have been computed. Regenerated flows are assumed to be 10 percent for irrigation projects having planned annual utilization of 85 MCM or above, 80% for municipal use and 97.5 % for industrial use (GOI, 1973). The LINDO software (LINDO, 2002) is used for solving the LP problem.

RESULTS AND DISCUSSION

MIYM was applied to major and medium projects in Vedavathi basin and their optimal yields were assessed. Optimal annual yields of Vanivilas Sagar, Gayatri, Bhairavanithippa and Rangayanadurga projects for an annual reliability of 76% for irrigation and 97% for municipal and industrial release are found to be 286.82 MCM, 23.64 MCM, 128.59 MCM, and 22.68 MCM with maximum failure fraction of 14.02%, 54.27%, 77.54%, and 89.36%, respectively. Optimal annual yield achieved through MIYM for Vanivilas Sagar and Bhairavanithippa would be more than target annual demands whereas Gayatri and Rangayanadurga projects would not be able to meet their target demands. Though Irrigation intensity achieved through MIYM is almost equal to the proposed intensity, re-crop planning is essential for Vanivilas Sagar project as it would not be able to irrigate perennial crops.

Estimation of the nutritional production and gross income from crop produces of the entire system was carried out for successful years. The basin would not be able to satisfy nutritional demands even for the agricultural population during successful years. However, Vanivilas Sagar and Bhairavanithippa projects would be able to meet the nutritional demands for agricultural population by the end of planning horizon, i.e., 2050 AD. As against target requirement of 0.24×10^{5} tons of protein and 6.61×10^{11} of calorie unit, the system can produce 0.06×10^{5} tons and 2.26×10^{11} calorie unit, respectively. Maximum gross returns of the system are estimated to be 725.10 million Indian rupees. Optimal annual yield assessed by MIYM at each project are shown in Figure 2.

Figure 2: Target Annual Demand vis-à-vis Model Assessed Annual Yield



CONCLUSION

The objective was to ass optimal yield at each project for attaining maximum failure fraction while satisfying target demand as far as possible under diverse hydrological conditions and to maximize annual gross benefit. Also the potential of the system to satisfy nutritional requirements of the population by the end of planning horizon was assessed. It is demonstrated that MIYM as a screening model performs well in achieving its intended purpose of determining yields from a system with added advantage of estimating optimal yield and simultaneously determining optimal crop plans while taking into consideration system specific demands and hydrological diversity in a large basin.

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