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Large Irrigation Projects Water Reservoir Performance Assessment with the use of Remote Sensing and Hedging Rules– A New Concept

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Abstract—

The water reservoir operating rule provides guidance to the managers taking decisions of actual release. The reservoir performance characteristics are not assessed / published regularly for reservoirs in India as there is no standard methodology, procedure and format. The command area performance is measured with acres irrigated and crop production .The satellite remote sensing global datasets / local datasets from national satellites are being used for assessing spatial performance indicators like adequacy, uniformity, dependability and equity at distributaries' levels for command areas. The remote sensing based water contours of reservoirs are used for assessing actual amount of water available between two satellite overpasses on the area. The simulation and optimization techniques are not as flexible as hedging rules for a practicing engineer to perform efficient reservoir operations. The graphs of standard operating policy of a reservoir and its actual operations help us when and how to hedge. There will be enhancement of reservoir performance by conjunctive use of satellite remote sensing, field datasets, hedging rules and improved standard operating policy.

Keywords— reservoir performance, satellite water area contours, hedging, standard operating policy, daily water budget,

I. INTRODUCTION

The design and operation of surface water systems are the most typical watershed management problems. The fundamental components that make up surface water systems include reservoirs and their withdrawal structures and spillways, as well as pipelines, irrigation channels and hydropower units. With continuous increase in the demand for water in all regions, the need for planning for water resources development and management has become more important. Satellite remote sensing derived water spread area are used for filling gaps of re-capacity surveys of reservoirs using conventional hydrographic surveys [1].There are studies depicting water demand calculations in an irrigation command using remote sensing and geographic information sciences [2].However the water in an irrigation command will be supplied with less than the demand from engineering organizations for practicing protective irrigation in India. Nevertheless, the water demand using geoinformatics is effectively used for reservoir management/ reservoir operation analysis of the derived initial rule curves in Samrat Ashok Sagar Command project.[3]. This article highlights the personalized reviews of research based on body of published work on reservoir operations in general. It takes through the journey of research works related to reservoir system analysis, reservoir water management, reservoir management and highlights on new areas of analyzing the performance of water reservoir system using geoinformatics [4] and hedging rules policy guidelines. The components of reservoir water systems are explained in the first section.

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II. RESERVOIR SYSTEM ANALYSIS, RESERVOIR MANAGEMENT,RESRVOIR OPERATIONS VERSUS WATER RESOURCES CONFLICTS

Reservoir System Analysis

Reservoir system analysis models are developed to support: (a) in sizing of reservoir storage capacities and establishing operating policies during preconstruction planning of new projects, (b) in evaluation of the operating plans of existing reservoir systems, (c) in administration of water allocation systems involving water rights and agreements between water suppliers and users, (d) in operation planning for developing management strategies for the next year or season, (e) real time operations. Analysis includes a host of simulation and optimization models like linear programming, dynamic programming, neural networks, fuzzy model etc.

Real time reservoir operation implies the optimal operation of an existing reservoir system and decisions regarding releases for various purposes are made on a considerably shorter time period. [5] The operation planning for developing management strategies for the next year or season can be implemented after doing hedging as explained in next section on hedging rules.

Reservoir Management

Reservoir management is done for managing the sediments coming into it from upstream catchments. The catchments contributing to the reservoir need to be monitored and managed for their soil erosion and sediment deposition, and water storage aspects. Soil conservation and reforestation in the upper catchments can help in substantially reducing sedimentation. There are several models like USLE, CREAMS, HEC-1 WEPP and ANSWERS which are used frequently to estimate soil erosion and transport for different agricultural systems. Reservoir sedimentation reduces water into reservoir and more rainfall (because of increased forest) increases water into reservoir. This has a bearing on reservoir operations.

Reservoir Water Management

Reservoir water needs to be appropriately managed with costs of operations involved to cater to multi-purpose needs of the water users.

In India, reservoir level-area-capacity curves at 1feet or 1 meter elevation are generated by topographic surveying (block leveling) in the initial construction stages of the Dam. The scale of reservoir map is usually 1:10000. Sedimented reservoirs are resurveyed periodically once in five years (3 to 10 years in average) depending on rates of sedimentation. Two methods of recapacity surveys are in vogue. (1) range method of contouring (2) hydrographic surveys. Remote sensing techniques are an alternative to conventional methods of data acquisition and processing. They have advantages of revisit and synoptic coverage of satellite water contours.

Water Resources Utilization Conflicts

The water utilization analysis in watersheds, catchments, sub-basins and basins is complex because of hydrology and climate change. Small watersheds generally have small single purpose water reservoir / tank systems. The economic evaluation of multipurpose systems can be obtained by combining the marginal benefits of different purposes and the marginal costs. A large river basin consists of several sub-basins / sub systems. Influence of the higher-level sub-systems is binding on the lower-level subsystems. Water stored in minor tanks and reservoirs in watersheds/ sub systems need to be assessed for their timely reliable water access to resolve water conflicts and generate efficient reservoir operation policies.

Reservoir operation

It includes a set of rules or guidelines to store and release water depending on the purposes it is required to serve. The operating rule provides guidance to the water managers taking decisions of actual releases. A typical daily water budget table which is used for reservoir operation is given in Table I.

Table I. Daily Water Budget Tables for a typical major Project Reservoir

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Daily water recording of the T.B.Reservoir

Rainfall (mm) , Date 30 Oct 2008

A. RESERVOIR
1.Yesterday (Level, Area , Capacity)
2.Today (Level, Area , Capacity)
3.Net (a) depletion
(b) filling
4.Evaporation Losses
5.Gross depletion = (3a-4)
Filling (3a+4)

B. DRAWALS WORKING TABLE ACTUAL
(LEFT BANK) M.Cum , M.Cusecs M.Cum. M. Cusecs
1. PH
2. IS
3. HLC

C. DRAWALS
(RIGHT BANK)
1. PH
2. River Sluice
3. RB Channel
4. HLC

D. TOTAL DRAWALS

E . RIVER DISCHARGE AT DAM
1.Spilling on Dam
2.ROFS (Left)
3.ROFS (Right)

F . Miscellaneous
a. Head Regulator M (LB)
b. ---do----- P (RB)
c. Gundlakere escape
d. LLC Head Regulator
e. TB board limit of LLC
f. -----do---- HLC

FRL of TBR + 1633 ft Capacity at FRL = 115681 Mcft-

PH- Power House , M-Million ,IS-Irrigation Sluice ,HLC-High Level Canal,RB-Right Bank, RB-Right Bank, , ROFS-Reservoir Over Flow Spillway, LLC-Low Level Canal, FRL-Full Reservoir Level

Source: Tungabhadra Project Reports ,PWD ,Karnataka, India

The civil / construction engineer who is in charge of distributory releases only demands more from head side of the main canal and goes on *adhoc* water rotations in different sub-distributaries based on first sown first served basis, most of the times. There exist crop violations, unauthorized irrigation, political pressures and rent seeking which makes the irrigation system a happening and not an enterprise. Civil engineer concerned instead of concentrating on rational water distribution concentrates on maintaining and building structures. The rule curve (which specifies the desired storage to be maintained in a reservoir as closely as possible during different times of the year while trying to meet various demands) based reservoir water regulation takes a back seat and reservoir performance sees lows and highs from season to season and never gets recorded in the work books of project performance. Then reservoir non- working tables rule the roost.

The Overview of Parameters for Reservoir Water Management in a multi-purpose project.

The factors rainfall, temperature , number of degree days in a crop season, water vapor, soil moisture, humidity , surface water storage and ground water storage; type of crops , soil-water-plant relationships, crop evaporation, leaching , seepage, etc. affect water management.

The distinction in scheduling of irrigation is (i) scheduling for sole crops (based on ratio of irrigation water and cumulative pan evaporation) (ii) scheduling of irrigation for intercropping and other cropping systems.

The following factors have to be considered in planning irrigation for an area, from the reservoir of water (irrigation source) : (a) water supply demands for domestic purposes (as sanctioned in project), (b) upstream use demands , (c) irrigation demands (type of crop , growth stages , soil moisture , temperature , ground water status etc), (d) hydropower demands ,(e) lower riparian uses ,(f) existing reservoir storage, (g) current rainfall .

The methods of water distribution are generally (a) as per shares according to landholding,(b) methods of rotation and allocation, (c) partial demand system, (d) supply demand,(e) farmer managed water storage,(f) farmer organization of warabandi etc.

The design of reservoir operation policies takes into account all the above parameters into consideration.

Reservoir Operation Policies

These are developed in few reservoirs of India after studying the lacunae of equitable or efficient water distribution possibilities in using reservoir working tables.

Most of the available methods of operation of reservoirs (in literature and reports) have become academic exercise in Indian scenario and less taken up by practicing engineers. The real time operations of reservoirs by computers and models would have been a remedy for all inter-state water disputes, if the authorities accept/ practice the method of simulation and optimization discussed earlier and smart water grids would have been built.

The reservoir authorities never keep the performance parameters of a reservoir to be viewed by public at large. They do not even get published in technical journals. There is no way in which reservoir performances can be compared like pump / turbine performances. This paper, hence, builds on standard operating policy details and uses concepts of hedging (both calculus and geometry based ones) to understand the dynamics of reservoir operations to cater to practical engineers in charge of reservoirs who can understand a non-complex aspect (geometric ones) of hedging to support their decisions.

The simplest of the reservoir operation policies is the standard linear operating policy (SLOP or SOP) See Fig.1.

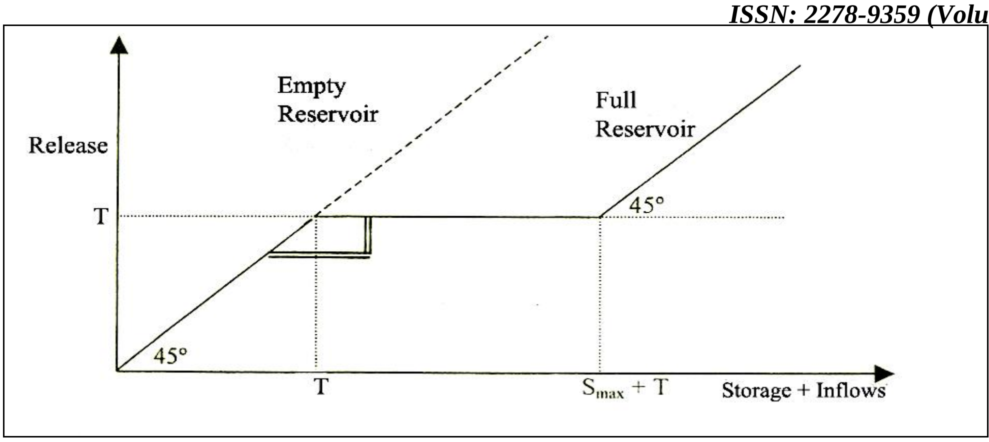

Fig. 1 Graphical Representation of the Standard Linear Operation Policy

Let A_w represent the available water and T the target demand. Mathematically, the SLOP or SOP can be expressed as :

If $A_w \leq T$, Release = A_w
If $T \leq A_w \leq S_{max} + T$ Release = T
If $A_w > S_{max} + T$ Release = $A_w - S_{max}$

A SLOP/SOP is one under which the seasonal release is equal to the target release or all the available water, whichever is less.

A brief literature survey of the Hedging Rules is done and methodology for assessing reservoir performance is explained below.

III. RESERVOIR HEDGING RULES

Release and carryover storage decisions should be made to maximize the sum of immediate use and carryover storage benefits. In reservoir operations for irrigation water supply, water can be either released for beneficial uses or retained in the reservoir for possible future use. The simple choice becomes complex in the presence of uncertain future inflows and economic benefits for released water. The problems of how much water to withhold from immediately beneficial deliveries, retaining that water in storage, are known as “hedging”. The so called SOP is perhaps the simplest reservoir operating rule for water supply systems. It aims to best meet the demand in each period based on the water availability in that period. The parameters that affect hedging are already discussed in detail in earlier sections of this paper.

Hedging rules normally used for rationing operation to smooth the deficit fluctuation of water shortage.(see Fig.2) Hedging operating policies reduce the intensity of a more severe shortage which likely occurs in future by only providing portion of the target yield in advance. Releases are apportioned among reservoirs by the space rule, and among time intervals by the pack and hedging rules.[6] However the inherent uncertainty of reservoir operation complicates the decision making of hedging. Following a procedure similar to Rippl's method, the SOP [7] is to be developed for reservoir operation under a fixed water delivery target. SOP releases water as close to the delivery target as possible, saving only surplus water for future delivery. SOP is practical during periods of operation when inflow is plentiful. However, it neglects potential shortage vulnerability during later periods. Most recently, hedging was again addressed in the context of economic water operation due to increasing water stress over the world. Draper and Lund expanded the objective of hedging from reducing gross loss to increasing net benefit by replacing water supply deficit with water use benefit.

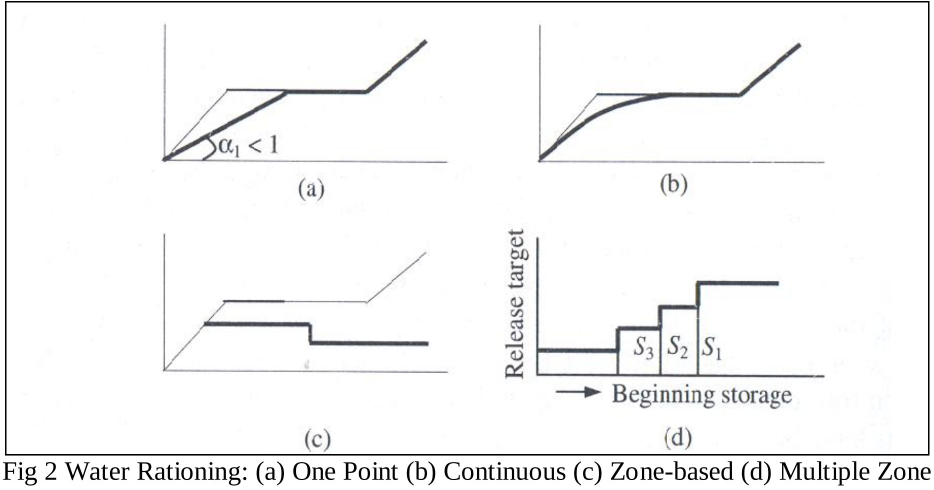

Fig 2 Water Rationing: (a) One Point (b) Continuous (c) Zone-based (d) Multiple Zone

One point hedging, two point hedging, three point hedging, continuous hedging etc. are some examples analytically investigated by Draper & Lund.(see Fig.ii) [8]

The condition for the optimal hedging is stated as *"at optimality the marginal benefit of storage must equal the marginal benefits of release":*

$$\frac{\partial B(D)}{\partial D} = \frac{\partial C(S)}{\partial S} \qquad 1)$$

Where *B(.)* is the current water delivery benefit, *D* is the water delivery, C(.) is the Carry over storage value function representing the expected value of water stored now *(S)* for all future time periods. Both *B (.)* and C (.) are non-linear utility functions. Note that when the utility or loss function is linear, SOP is the optimal operating policy.

The sum of *D* and *S* represents the current water availability A:

$$A = S+D \qquad .2)$$

Eq. (2.2) does not explicitly account for future inflow to the reservoir but implicitly considers this information *in C(S).* The benefit from carryover storage value (C) can be a nonlinear function of the second and future periods of inflow too. According to the principle of decreasing marginal utility, the marginal value of carryover storage will decline with additional water availability. Therefore, neglecting future water availability may not lead to an optimal total benefit over two periods. To account for the effect of the second-period inflow, the model is to be modified by introducing the second period inflow (I_f). The total water availability in two periods is:

$$A_{total} = A + I_f \qquad .3)$$

in which *A* represents water availability in the current period, which is a known item in the two-period model.

In reservoir sizing, one common method extensively used in practice, is to determine the active storage capacity using the Rippl diagram or the mass diagram by plotting cumulative inflow with time.. This method is cumbersome compared to a simple analytical technique, known as sequent peak (SP) method **[9]** which can be applied for constant or varying demands in time. The SP algorithm is as follows:

Let t denote the time period, Q_t the inflow, and R_t, the required release or demand in period t. Let K_t be defined as follows:

$$K_t = K_{t-1} + R_t - Q_t \quad \text{if positive} \qquad 4)$$
$$= 0 \quad \text{otherwise,}$$

With K_0 set equal to zero (K_0= 0)

Or , K_t may be expressed conveniently as the maximum of zero and $K_{t-1} + R_t - Q_t$,as

$$K_t = \max\{0, K_{t-1} + R_t - Q_t\} \qquad .5)$$

The values of K_t are computed for each period t for two cycles or successive inflow sequences.

But the SP procedure suffers from few limitations. Two algorithms that improve upon the sequent peak procedure for reservoir capacity calculations are presented by Lele. **[10]**

Direct problem is to determine the minimum required storage for given inflow, outflow, precipitation and evaporation rates. *Reverse problem* is to determine the maximum uniform firm yield that can be withdrawn from a reservoir having a given storage. It is possible to determine the maximum uniform monthly firm yield to fully utilize the available volume of water.

In a case study on water supply reservoir **[11]** two types of hedging are explored: the first uses water availability defined as storage plus inflow, while the second depends on the potential shortage conditions within a specific future lead-time period. One of the *drawbacks* which can be realized here is that frequent hedging increases the total deficits over the study horizon. The hedging, one for the short- term and another for the long-term, leads to derive the optimal hedging rules.

IV. REMOTE SENSING FOR RESERVOIR PERFORMANCE ASSESSMENT

Remote sensing based reservoir capacity estimation uses data of *satellite water areas* of different dates (of different reservoir levels) pertaining to an irrigation year. It uses the fact that water-spread area of the reservoir reduces with the sedimentation at different levels. The water spread area and the elevation information is used to calculate the volume of water stored between different levels. These capacity values are then compared with the previously calculated capacity values to find out the change in capacity between different levels**. [12]**

In another study, satellite water areas of reservoir from remote sensing were used for estimating water volumes between two satellite overpasses in an irrigation season for several dates. (say eight or nine).These volumes were used interactively in a water balance approach near a large reservoir site for an irrigation season. Generally, the carry over storage is not practiced in these upstream reservoirs. Reservoir will be empty at the end of the season. This is taken as ground truth / field observation and water balance was carried out at reservoir site to arrive at actual amount of water available at each time period. A comparison was made by using WSA contours obtained from field surveys and that from remote sensing. In a reservoir capacity of 115 TMC the discrepancy in volume of water at the end of an irrigation season is around 15 TMC in one irrigation year and 2 TMC in another year**.[13]** Such quantifiable discrepancies in all reservoirs of a basin bring forth the utility pattern and performance assessment of the reservoirs. This gives better inputs for improved *basin* water accounting, reservoir operation and regulation scenarios. Irrigation projects command area performance using remote sensing is explained next.

V. REMOTE SENSING BASED PERFORMANCE ASSESSMENT OF COMMAND AREA WATER UTILISATION

In a project, the quantity of water which is beneficially used during one irrigation season enables useful analysis of command area irrigation performance. The water quantity variable delineated from Indian satellite data [14] is the crop water use zone (CWZ) for a rabi / summer season; it is basically the area getting converted into crop water use (by using appropriate coefficients) in one season at different parts of the command area irrigation system . CWZ has been used to arrive at spatially depicted (on a map) irrigation performance parameters like uniformity, adequacy, equity, and dependability of irrigation water distribution management.**[15]**. Ninety percent of irrigation projects in India do not have measurement devices beyond distributory head points. Spatial depiction of performance of irrigation helps in better future management decisions. Global croplands obtained from constellation of satellites too have the ability to monitor performance of command areas and food security analysis**.[16]**

VI. DISCUSSIONS AND CONCLUSIONS

The following conclusions can be drawn:

1. The water reservoir performance assessment needs to be emphasized in Indian context, as no performance indicators are regularly practiced by field project professionals. The use of remote sensing based water volume estimates and water demand needs to be practiced for assessing water reservoir performance.
2. The space rule and pack rule suggested by Maas et.al. are heuristic and define the desired storage and release targets in terms of some state variables. Their aim is to reduce losses due to spills and for encourage framing hedging rules.
3. It is recommended that Decision Support Systems be developed by using hedging rules and geo-informatics based solutions.
4. Routinely used techniques, using neural networks, queuing theory etc once implemented in field offices , are applicable for decision making in structured environments only and techniques using hedging , geoinformatics can be used for unstructured environments. See Table II.

Table II Structured and Unstructured Decisions

Structured	***Unstructured***
Stable context	Volatile context
Common Place	Atypical unique
Recurrent	Discrete
Programmable	Intuitive, Creative
Easily accessible information	Problematic access to information
Decision Criterion understood	Decision Criterion unclear
Focused decision strategy	Multiple decision strategies

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