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Optimal estimation of storage-release alternatives for management of surface water- logged area

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Abstract
Surface water logging over a depressed land of 1062 sq. km., - known by Mokama Group of Tals, in Central Bihar created every year from the accumulation of monsoon runoff, and its drainage problem are serious concern in terms of loss acquire in agricultural productivity and due to flooding. A number of high level committees felt the seriousness of the problem, and had suggested some remedial measures on ad-hoc basis without assessing the in-sight of the problem. The study presented here is quantification of storage-release pattern of monsoon water addresses through development of a management model aimed at minimization of the waterlogged area which is equivalent to maximizing the cropped area in the Tal under the constrains of check over inflows entering into the tal. The check over inflows has been demonstrated keeping in view the beneficial uses of water require at the different irrigation commands of the respective tributaries. A two-tier maximization problem has been envisaged and solved setting 164 numbers of constraints both for Rabi and Kharif seasons. Different scenarios of check over inflows and corresponding benefits have been analyzed.

INTRODUCTION

Accumulation of monsoon runoff and thereby stagnation of water over the depressed lands create storage. The rate of storage of water or alternately the drainage capacity of accumulated water depends upon its inflow and outflow conditions. Restriction of natural passage of water due to inadequate drainage outlet or blockage of water by the higher water level elevation at the outlet would aggravate the accumulation instead of emptying the storage. This eventuality is termed here as *surface waterlogging.* Waterlogging and drainage problems of such nature not only cause flooding in areas suitable for kharif crops (crops grown during monsoon season, June through September) but also result in loss of agricultural productivity. Stagnation of water for a longer period besides damaging agricultural activities of subsequent season due to the rise of sub-soil water table, also effects the socio-economic aspects of a region.

The problems of surface waterlogging and drainage over a depressed land of 1062 sq. km. in Mokama tal area of Central Bihar are a long standing issue to the water resources planners in terms of complexity of the problem, and loss incurring in achieving the requisite agricultural return. The entire Tal area, which lies in the Kiul-Harohar river basin undergoes submergence every year during the monsoon period occurring from June through September. During this period, no crops can be grown in the Tal area due to waterlogging. These areas can only be put under cultivation when accumulated water recedes at the mid of October. Reasons of submergence and stagnation of water have been reported to be due to the inadequate drainage system and blockage of water discharges by the different tributaries joining the Tal area. On the other hand, at the end of monsoon, the agricultural activities in the upper catchment of Kiul-Harohar suffer due to scarcity of irrigation water. This clearly indicates an existence of dimensionally opposite problem in the catchment viz., (i) surface water logging in the lower catchment (the Tal area) and; (ii) scarcity of irrigation water in the upper catchment.

Keeping this in view and the drainage problem in Tal area, an optimisation model with the objective of minimisation of waterlogged area in the Mokama group of Tals under the constraints of storage of inflows based on the irrigation requirement at the upper catchment, and subsequent release according to the requirement of water in the tal area, has been developed. Various scenarios of storage-release patterns and its benefits in terms of intended objective have been analysed and presented.

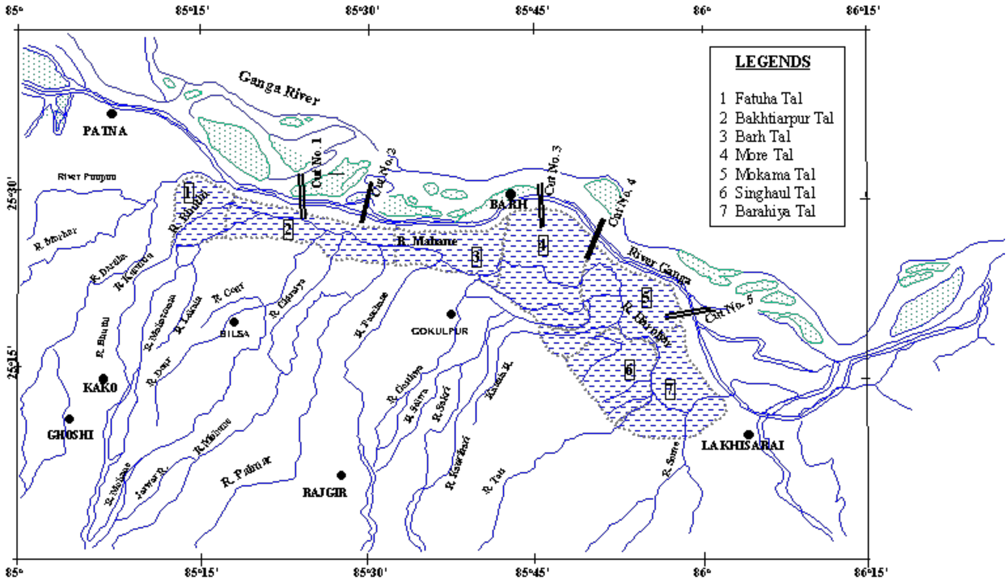

Figure 1. Index map of Mokama group of tals.

STATEMENT OF THE PROBLEM

Tal is a local name of impounded waterbody created naturally by the abnormalities of topographical variation. Mokama group of Tals consisting of 7 tals which are connected in series and known by different names in different stretches (Figure 1), is a combination of naturally created and man-made obstructed water barriers with its sustenance of about 4 to 5 months in a year. The tal area is located in a linear stretch of 100 km along the right bank of the river Ganga within Central Bihar. Several north flowing rainfed rivers of South Bihar have their outfalls in the Mokama group of Tals. However, the only drainage of the Tals' water is to the river Ganga through river Harohar. During monsoon period, inflow from north flowing river and the higher water level at the outlet point often delay the drainage of tals' water. Tal area also receive flood water at its upstream end from the river Ganga through its tributary, the Punpun. Construction of embankment as a remedial measure to encounter the back water pressure of the Punpun river is in progress. Most of the Tals remain under submergence almost with a frequency of 8 to 9 times in every 10 years, with a degree of submergence more than 50 % of the Tal area. This is obviously a very unique situation. Due to submergence of the Tal area, land resources are under utilized resulted in loss of crop productivity, particularly; Kharif crops. The Rabi crops (crops grown after monsoon season) also suffers when the drainage of the Tal is delayed beyond mid of October.

Generally, the Tal area faces two types of extreme problems: flood and famine; the former one is due to the inadequate drainage while the later one is due to the shortage of irrigation water needed for cultivation of Rabi crop. A common concern among the users and beneficiaries is that the drainage problem of the Tal area is required to be solved to ensure timely drainage after the monsoon flooding in order to make efficient Rabi cultivation. Water logging effects Rabi cultivation during the years when; (a) the Ganga water level at the out fall point remains persistently high after the end of September, and/ or, (b) there is heavy runoff contribution from the north flowing rivers draining into the Tal. Tal area being prone to frequent inundation, the agricultural activities and productivity during the wet season is very low. On the other hand, for the successful Rabi crop in major portion of the Tal which remain submerged in monsoon period, drainage of Tal area by the 15th October is very crucial. Delay in getting drained the Tal water adversely affects the Rabi crop.

MODEL FORMULATION

The problem has been conceptualized as a management model considering water logged area as a storage reservoir whose drainage area is the total Kiul-Horahor basin, and during monsoon period the upstream runoffs are to be so regulated that storage would have no danger towards flood rather would be able to meet the irrigation water requirement in the tal area and also at the upstream commands. For formulation of the model, two assumptions are made; i) no overflow from the river Punpun to the waterlogged area , and ii) seepage from the river Ganga to the water logged area, if any, is insignificant.

The objective of minimising the waterlogged area in the monsoon season, in other words, is equivalent to maximising the cropped area in the Tal. This is possible by minimising the inflow into the Tal, ensuring that crop water requirement in the Tal area is met. Again, minimising the inflow into the Tal area is equivalent to maximising the water stored in the upstream reaches. The storage of water in the upstream reaches would subequently be utilized to meet the irrigation water requirement at the upper reaches and in the Tal area. The minimisation problem thus reduces to maximisation of cropped area both in the upstream reaches as well as in the Tal area.

The model is formulated taking into account the crop factors, the monthly reservoir storage values in the upstream catchment and the area expected to be exposed in the Tals. The tal area being irregular (saucer) in shape, its area-capacity and stage-capacity form a non-linear curve. Thus, a non-linear programming technique is used in model formulation.

Objective Function

$$Maximise \sum_{i=1}^{m} \sum_{j=1}^{n1} SBAK_{ij} + \sum_{j=1}^{n1} TAK_j + \sum_{i=1}^{m} \sum_{j=1}^{n2} SBAR_{ij} + \sum_{j=1}^{n2} TAR_j \quad (1)$$

in which m = number of sub-basins in the river catchment; n1 and n2 = number of crops grown in kharif and rabi seasons respectively; $SBAK_{ij}$ = area of i^{th} sub-basin allocated to j^{th} crop in kharif season in sq. km.; TAK_j = tal area allocated to j^{th} crop in kharif season in sq. km.; $SBAR_{ij}$ = area of i^{th} sub-basin allocated to j^{th} crop in rabi season in sq. km.; TAR_j = tal area allocated to j^{th} crop in rabi season, sq. km.

The factors of the objective function (eq.1) are subjected to the constraints of: i) storage requirement in the upper catchment and in the Tal area both for Kharif and Rabi crops, ii) storage requirement, on the other hand, depends upon the cultivable area available and their irrigation requirement in both the seasons, and iii) affinity of farmers towards cultivation of crops is another important factor which further demonastrate the storage requirement. Making use of all these considerations, constraints have been formulated.

STORAGE CONSTRAINTS - UPPER CATCHMENT

Based on the water balance, the storage constraints in the upper catchment for kharif and rabi seasons are as follows:

For kharif season

$$S_{ik} = \sum_{k=1}^{k} I_{ik} - \sum_{k=1}^{k} O_{ik} - \frac{1}{\eta} \sum_{k=1}^{k} \sum_{j=1}^{n1} WR_{kj}.SBAK_{ij} - \sum_{k=1}^{k} (E_k + P_k).SA_{ik} \quad (2)$$

in which s = number of months in kharif season; S_{ik} = cumulative water storage in the reservoir of i^{th} sub-basin in k^{th} month in sq. km. m (It is assumed that there is no dead storage at the beginning of Kharif season); I_{ik} = inflow (Runoff) from the i^{th} sub-basin to the reservoir in k^{th} month in sq. km. m; O_{ik} = outflow from the reservoir in the i^{th} sub-basin in k^{th} month in sq. km. m; η = irrigation efficiency; WR_{kj} = water requirement of j^{th} crop in k^{th} month in m; E_k = evaporation loss from reservoir in k^{th} month in m; P_k = percolation loss from reservoir in k^{th} month in m; SA_{ik} = water spread of the reservoir in the i^{th} sub-basin in k^{th} month in sq. km and i = 1 to m and k = 1 to s.

The irrigation water requirement of a crop is a function of the evaporation, the crop coefficient, the percolation loss and the effective rainfall. Doorenbos and Pruitt (1977) recommended the following equation to estimate the irrigation water requirement in the k^{th} month of growth stage of the crop.

$$WR_{kj} = E_k.Kc_{kj} + P_{kj} - \mathrm{Re}_k \quad (3)$$

in which WR_{kj} = irrigation water requirement of the j^{th} crop in the k^{th} month in m; E_k = Evaporation in the K^{th} month; Kc_{kj} = crop coefficient of j^{th} crop in k^{th} month; P_{kj} = percolation loss for j^{th} crop in k^{th} month in m; Re_k = effective rainfall in k^{th} month in m.

For rabi season

$$S_{ik} = \sum_{k=1}^{s} I_{ik} - \sum_{k=1}^{k+s} O_{ik} - \frac{1}{\eta} \sum_{k=1}^{s} \sum_{j=1}^{n1} WR_{kj}.SBAK_{ij} - \frac{1}{\eta} \sum_{k=1}^{k} \sum_{j=1}^{n2} WR_{kj}.SBAR_{ij} - \sum_{k=1}^{k+s} (E_k + P_k).SA_{ik} \quad (4)$$

in which r = number of months in rabi season; i = 1 to m and k = 1 to r.

AREA CONSTRAINTS

The area constraints for crops in the upper catchment and Tal area mean the total cultivable area available both in kharif and rabi seasons. The crop rotation, the soil texture, topography and the affinity of the farmers towards a specific crop in a season have been considered as characterizing factors for estimating the cultivable area. The area under waterlogged conditions governs the area constraints for the Tal.

Area constraints - Upper catchment

For kharif season

$$\sum_{j=1}^{n1} SBAK_{ij} \le CA_i \quad (5)$$

in which CA_i = total cultivable area available for canal irrigation in ith sub-basin, sq. km and i = 1 to m.

For rabi season

$$\sum_{j=1}^{n2} SBAR_{ij} \le CA_i - \sum_{j=1}^{p} SBAK_{ij} \quad (6)$$

in which p = number of perennial crops which are sown in kharif season but are harvested only after rabi season. However, these crops do not require water during rabi season.

Area constraints - Tal area

For kharif season

As mentioned earlier, the Tal area gets waterlogged during the monsoon season. Hence, the total cropped area in kharif season in the Tal should be less than or equal to the exposed Tal area, which is free from waterlogging. Thus,

$$\sum_{j=1}^{n1} TAK_j \le TEA_k \quad (7)$$

in which TEA_k = exposed tal area in kth month in sq. km and k = 1 to s.

The exposed Tal area is a function of the amount of water stored in the Tal during that month. The function is of the form

$$TEA_k = a + b.V_k + c.V_k^2 + d.V_k^3 + e.V_k^4 + f.V_k^5 + g.V_k^6 \quad (8)$$

in which a, b, c, d, e, f and g = coefficients of sixth order polynomial regression equation for exposed area versus volume of water in Tal; and V_k = Volume of water in Tal area at the end of k^{th} month in sq. km.m.

The volume of water in the Tal area at the end of a particular month is governed by the water balance of : inflow (runoff) from the Tal, outflow from the sub-basins of the upper catchment, irrigation water requirement in the Tal area and evaporation and percolation losses from the waterlogged area in the Tal. The expression for volume of water is thus given by

$$V_k = \sum_{k=1}^{k} IT_k + \sum_{k=1}^{k}\sum_{i=1}^{m} O_{ik} - \frac{1}{\eta}\sum_{k=1}^{k}\sum_{j=1}^{n1} WR_{kj}.TAK_j - \sum_{k=1}^{k}(E_k + P_k).WL_k \quad (9)$$

in which IT_k = runoff from Tal area in k^{th} month in sq. km.; O_{ik} = outflow from the reservoir in the i^{th} sub-basin in k^{th} month in sq. km.m;WL_k = waterlogged area in Tal in k^{th} month, sq. km.

$$WL_k = TTA - TEA_k \quad (10)$$

TTA = total tal area

For rabi season

The total cropped area in rabi season in the Tal should be less than or equal to the difference of the total cultivable area and the area occupied by the perennial crops.

$$\sum_{j=1}^{n2} TAR_j \le TA - \sum_{j=1}^{p} TAK_j \quad (11)$$

in which TA = Total cultivable area in Tal in sq.km.

Water Requirement Constraints

The water requirement constraints are formulated based on the consiseration that the monthly requirement of water for a command area should be less than or equal to the monthly availability of water which, in other words, can be stated that in any given month, the cumulative water requirement should be less than or equal to the cumulative water available at that month.

Water requirement constraints - Upper catchment

For kharif season

$$\frac{1}{\eta}\sum_{k=1}^{k}\sum_{j=1}^{n1} WR_{kj}.SBAK_{ij} \le \sum_{k=1}^{k} I_{ik} - \sum_{k=1}^{k} O_{ik} - \sum_{k=1}^{k}(E_k + P_k).SA_{ik} \quad (12)$$

in which i = 1 to m and k = 1 to s.

For rabi season

$$\frac{1}{\eta}\sum_{k=1}^{k}\sum_{j=1}^{n2} WR_{kj}.SBAR_{ij} \le \sum_{k=1}^{s} I_{ik} - \sum_{k=1}^{k+s} O_{ik} - \frac{1}{\eta}\sum_{k=1}^{s}\sum_{j=1}^{n1} WR_{kj}.SBAK_{ij} - \sum_{k=1}^{k+s}(E_k + P_k).SA_{ik} \quad (13)$$

in which i = 1 to m and k= 1 to r.

Water requirement constraints - Tal area

For kharif season

$$\frac{1}{\eta}\sum_{k=1}^{k}\sum_{j=1}^{n1} WR_{kj}.TAK_j \le \sum_{k=1}^{k} IT_k + \sum_{k=1}^{k}\sum_{i=1}^{m} O_{ik} - \sum_{k=1}^{k}(E_k + P_k).WL_k \quad (14)$$

in which k = 1 to s.

For rabi season

During rabi season, water from tubewells can also be utilised in Tal area in addition to the outflow from the sub-basins in the upper catchment, to meet the crop water requirements. Thus the water requirement constraint can be expressed as follows:

$$\frac{1}{\eta}\sum_{k=1}^{k}\sum_{j=1}^{n2} WR_{kj}.TAR_j \le \sum_{k=s+1}^{s+k}\sum_{i=1}^{m} O_{ik} + \sum_{k=1}^{k} TU_k \quad (15)$$

in which TU_k = water available from tubewells in k^{th} month in sq.km.m and k = 1 to r.

Further, it is required that the outflow from the upper catchment be totally utilised for meeting the crop water requirements in the Tal area in rabi season. This ensures that waterlogging in Tal area in rabi season does not aggravate. The resulting constraint can thus be expressed as follows:

$$\frac{1}{\eta}\sum_{k=1}^{k}\sum_{j=1}^{n2} WR_{kj}.TAR_j \ge \sum_{k=s+1}^{s+k}\sum_{i=1}^{m} O_{ik} \quad (16)$$

Affinity Constraints

Farmers of the region have tendency to grow paddy during kharif season. Keeping this in mind, the lower limit of the area under paddy cultivation is kept as 60% of the total irrigated area.

$$SBAK_{i1} \ge 0.6\sum_{j=1}^{n1} SBAK_{ij} \quad (17)$$

in which $SBAK_{i1}$ = Area of i^{th} sub-basin under paddy cultivation; and i = 1 to m.

Similarly, for rabi season, the minimum area under wheat cultivation is kept as 55% of the total irrigated area.

$$SBAR_{i1} \geq 0.55 \sum_{j=1}^{n1} SBAR_{ij} \tag{18}$$

in which $SBAR_{i1}$ = Area of i^{th} sub-basin under wheat cultivation and i = 1 to m

Cropping Pattern Constraints

Keeping in view the cropping pattern of the area, the lower and upper limit of the area under different crops have been fixed.

Formulation of Non-linear Optimisation Model with Constrained Outflow

Creation of number of storage reservoirs at the upper catchment is again a limiting factor guided by the topography of the area. Partial storage of water in the upstream catchment and its effect on the waterlogged area and also in the upper catchment are considered as a constraint . The constraint of outflow thus is set as :

$$O_{ik} \geq c(I_{ik}) \tag{19}$$

in which c = a fraction, which may take values ranging from 0.1 to 0.9; i = 1 to m and k = 1 to s.

INPUT DATA

Based on the drainage patterns, the Kiul-Harohar river basin is classified into four major sub-basins excluding the waterlogged portion in the Tal area. The cropping pattern of those sub-basins and Tal area have been considered based on statistical record of those area, soil and topographic maps, and also detailed conversations with a number of farmers and local people. The crops usually grown during kharif season are: Paddy, Maize, Vegetables, and Arhar while rabi season's croprs are: Wheat, Gram , Mustard, Potato, and Vegetables. Arhar is a perennial crop usually sown in kharif season but is harvested only after rabi season.

Hydrological data pertaining to the Mokama group of tals were based on the data collected by the Water Resources Department, Government of Bihar. The irrigation water requirement of a crop from its sowing to the harvesting period has been estimated monthwise using eq. (3). The monthly values of evaporation has been estimated using Christiansen's method (Michael, 1978). Percolation loss has been used for paddy crop only at a rate equal to 3 mm per day. The irrigation system efficiency has been considered to be 70 percent. Dependability of storage has been decided based on analysis of available rainfall and runoff pattern.

Remote sensing technique in integration with ancillary data such as soil map, contour map, rainfall in the catchment, runoff entering the Tal, submergence level and control structures etc. have been used to delineate the water logged areas (Lohani et al 1999). Figure 2 shows the Digital Elevation Model (DEM) of Mokama group of Tals. Using GIS, the waterlogged areas (hence, the exposed area) for various storage values in the Tal have been estimated. From the correlation of exposed area versus water storage values, the following relationship has been evolved:

$$E_a = 1010.5 - 1374.4V + 1252.4V^2 - 596.7V^3 + 145.5V^4 - 17.4V^5 + 0.8V^6 \quad r^2 = 0.99 \tag{20}$$

in which E_a is the exposed area in km^2 and V is the storage volume in km^3.

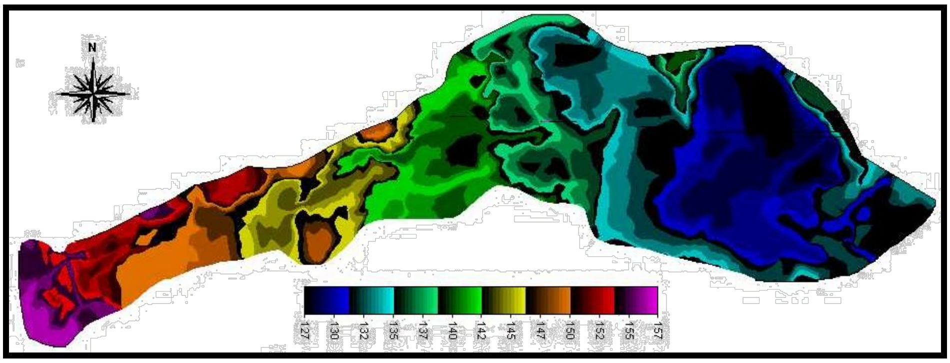

Figure 2. Digital Elevation Model (DEM) of Mokama Group of Tals.

RESULTS AND DISCUSSIONS

The objective of the total frame work being maximization of cropped area both in the Tal area and in the upstream reaches under the constraints of check over inflows, the solution of the model is said to be optimum if for given inputs the outputs are in the expected line. Using all possible combinations of estimated and given values of decision variables appeared in eqs.(2) through (20) which has given shape of 164 constraints, the objective function, eq.(1) is computed to achieve an optimal solution. The QSB package (Quantitative Systems for Business) – which is based on penalty function methodology, has been used to solve the constrained problem. Table-1 showing the areas allocated to different crops in kharif and rabi season in various sub-basins of the upper catchment and Tal area are an output of the optimized values of decision variables.

Cropped and waterlogged area in Mokama group of Tals

It is observed (Table 1) that in kharif season, out of a total area of 1062 km^2, only 137.38 km^2 remains waterlogged and the remaining area of 924.62 km^2 is allocated to different kharif crops. Similarly, in rabi season, only 137 km^2 remains waterlogged while an area of 925 km^2 is allocated to different crops. This leads to a increase in cropping intensity to the tune of 105% in the Tal area. Again, out of 925 km^2 of cropped area in rabi season, 883.39 km^2 is allocated to different rabi crops and the remaining area of 41.61 km^2 is allocated to Arhar crop, which is an annual crop. It is further noted that an area of approximately 137 km^2 remain waterlogged in the Tal in both kharif as well as rabi season when the solution is emerged as optimum. By restricting the inflows in accordance with the irrigation requirement at the upstream and at the Tal areas, the cultivable area in the vicinity of Tal can be substantially increased to 87% both in kharif as well as rabi season. This reduces the waterlogged area to a minimum of 13% (Fig. 3).

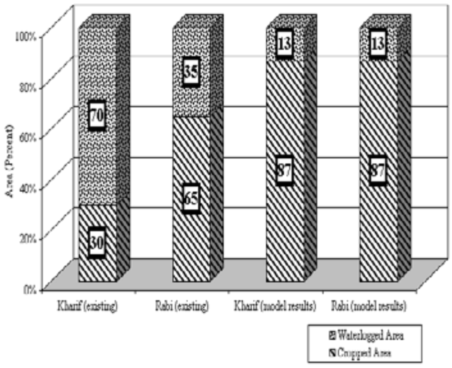

Figure 3. Comparison of existing cropped and waterlogged area.

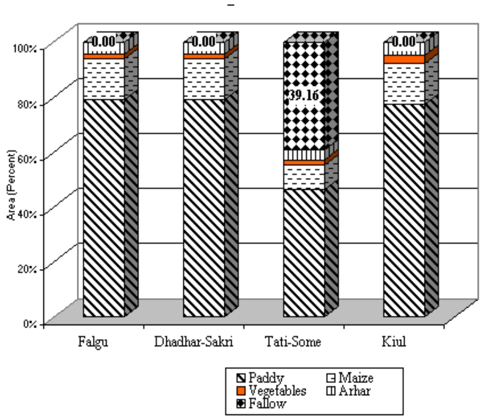

Figure 4. Percentage of cultivable area under different crops under kharif season.

Cropped area in the various sub-basins of the upper catchment

The area allocated to different crops in various sub-basins both for kharif and rabi season are also shown in Table 1. Figures 4 and 5 show plots of percentage of total cultivable area allocated to different crops in various sub-basins for kharif and rabi seasons respectively. It can be seen that in all the sub-basins except Tati-Some, the total cultivable area remains under cropping in both the kharif and rabi seasons. In Tati-Some sub-basin, 39.16% of the total cultivable area remains fallow only in kharif season. This is because of shortage of irrigation water. The cropping intensity of other sub-basins is about 195% except in Tati-Some where it is 157.19% (Table 1). The Figures 4 and 5, further demonstrate that the area allocated to paddy crop is maximum and in case vegetables it is minimum in kharif season, while in rabi season, area allocated to wheat is maximum, and minimum in case vegetables. These are in accordance with the affinity constraints.

Table 1. Crop Area Allocation in Various Sub-Basins under the Objective of Maximisation of Cropped Area, km^2.

Crop	Area Allocated in Different Sub-Basins (km^2)				
	Falgu	Dhadhar-Sakri	Tati-Some	Kiul	Tal Area
Kharif Season					
Paddy	1181.05	1100.47	458.67	960.56	804.42
Maize	224.25	208.95	90.53	186.60	64.72
Vegetables	22.43	20.90	18.11	37.32	13.87
Arhar	67.28	62.69	36.21	59.52	41.61
Rabi Season					
Wheat	1120.76	1044.30	573.47	710.69	693.46
Gram	107.08	99.77	143.37	177.67	66.25
Mustard	85.66	79.82	114.69	142.14	53.00
Potato	71.39	66.52	76.46	94.76	44.17
Vegetables	42.83	39.91	47.79	59.22	26.50
Total Area, km^2	2922.72	2723.31	1559.31	2428.48	1808.01
Total Cultivable Area, km^2	1495.00	1393.00	992.00	1244.00	925.00
Cropping Intensity (%)	195.50	195.50	157.19	195.21	195.46

Storage-Release Schedule

Fixation of number of storage reservoir and size has not been considered for study. However, the storage requirement is a function of cropping pattern. Hence, based on the monthly crop water requirements (including conveyance losses) in various sub-basins and Tal area, storages have been worked out and presented in Table 2. Considering quantity of water requires for irrigation in every month as the guidelines for release of water, the schedule of operation has been worked out. In order to ensure the irrigation requirements in Tal area, an additional release of 219.70 km^2m in September and 113.86 km^2m in rabi season from the Falgu sub-basin and 81.97 km^2m in October and 301.60 km^2m in rabi season from Dhadhar-Sakri sub-basin would be necessary.

Table 2. Monthly Crop Water Requirements in various Sub-Basins and Tal Area under the Objective of Maximisation of Cropped Area

Sub-Basins	Monthly Crop Water Requirements (Including Conveyance Losses), Km^2m.										
	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Total
Falgu	25.33	47.64	102.44	336.10	96.31	88.65	150.65	168.57	104.91	24.40	1145.01
Dhadhar-Sakri	23.61	44.39	95.45	313.17	89.74	82.60	140.37	157.07	97.75	22.74	1066.89
Tati-Some	9.84	18.50	39.80	131.82	37.57	55.05	95.21	109.84	73.53	15.89	587.05
Kiul	20.60	38.75	83.33	274.71	78.41	68.23	117.99	136.12	91.12	19.69	928.96
Tal Area	17.25	32.45	69.50	220.04	65.52	54.85	93.21	104.30	64.91	15.10	737.15

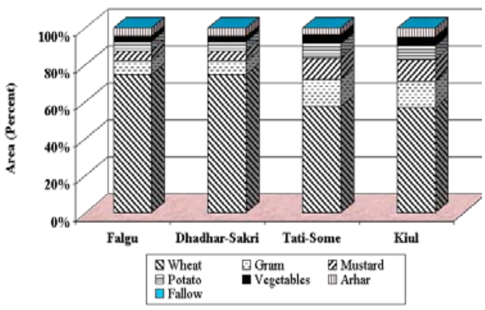

Figure 5. Percentage of cultivable area under different crops.

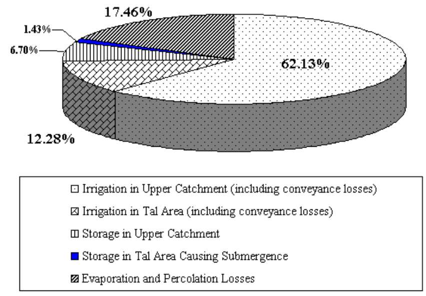

Figure 6. Water utilisation in Kiul-Harohar river basin.

Water Utilisation in the Tal and Various Sub-Basins

Water utilisation pattern (Fig. 6) indicates that 62.13% of the water is used for irrigation in the upper catchment while 12.28% is used for irrigation in the Tal area. Further, 6.70% of the water is stored in the upstream catchment, particularly in the Falgu and Dhadhar-Sakri sub-basins which means that more area can be brought under irrigation in these sub-basins. Around 1.43% of the water causes submergence in the Tal area whereas 17.46% of the water is lost in the form of evaporation and percolation from the upstream catchment and the Tal area.

Effect of Varying Outflow on the Waterlogging Conditions

The solution of the non-linear optimisation model has also been obtained for eight different cases, e.g., for the minimum value of outflow to the Tal area ranging from 10% to

80% of the inflow in upper catchment, at intervals of 10%. The upper limit is chosen as 80% (≠100%) because in the present circumstances, 75 to 80% of the inflow in the up-stream catchment is released to the Tal and the rest 20 to 25% is utilised in the upstream catchment.

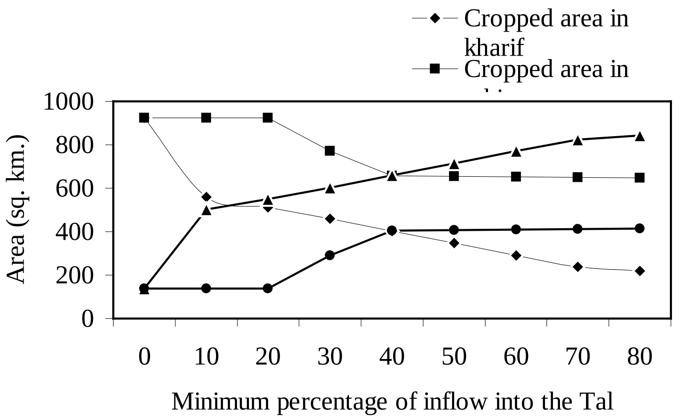

Figure 7. Variation of waterlogged and cropped areas with different percentages of inflows in Mokama group of tals (Model Results).

The extents of waterlogged and corresponding cropped area in the Tal for different inflow conditions are plotted as shown in figure 7 for both kharif and rabi seasons. It is observed (figure 7) that in kharif season, the waterlogged area in the Tal is minimum when inflow into the Tal is completely restricted. However, a gradual increase in the extent of waterlogged area in the Tal is observed as the percentage of inflow into the Tal is increased from 0 to 80%. The rate of spreading is more when the percentage of inflow into the Tal increases from 0 to 10%. This may be attributed due to the non-uniformity of topography of the Tal area. It is also observed from figure 7 that in rabi season, the waterlogged area in the Tal is minimum when there is no constrained of inflow into the Tal and remains constant up to the percentage inflow increases to 20%. This is due to the fact that the excess water at the end of kharif season is drained out into the river Ganga making the Tal area free from waterlogging. However, as the percentage inflow increases from 20% to 40%, the extent of waterlogging in the Tal gradually increases. This is because, as the percentage of inflow increases there is a decrease in water storage in the upstream catchment and hence the release of water from the upstream catchnment to the Tal area in rabi season also decreases. The deficiency of water in the Tal during rabi season is compensated by storing a part of the excess water at the end of kharif season. This leads to an increase in the waterlogged area in the Tal during rabi season. The increasing trend continues till percentage of inflow reaches 40% when the water availability in the upstream catchment decreases to an extent that no release of water from the upstream catchment to the Tal during rabi season is possible. The water requirement in the Tal in such condition is met by a part of the excess water in the Tal at the end of kharif season in addition to the water available from tubewells. Thereafter with further increase in the percentage inflow, the waterlogged area in the Tal in rabi season remains a constant.

CONCLUSIONS

From the analysis of results of optimization model and hydrological data, following conclusions are drawn:

Out of the total Tal area of 1062 km^2, during kharif season only 30 % of the area is possible to cultivate and balance 70% remain waterlogged, while, during rabi season, cultivable area increases to about 65% and balance 35% remain waterlogged.

Restricting monsoon inflows into Tal area, cultivable area in the Tal can be considerably increased to 87% both for kharif and rabi seasons, which in other words, will reduce the waterlogged area to a minimum of 13%. This can be achieved by storing part of inflows at the upstream catchment and judiciously using the stored water in the upstream catchment as well as in the Tal area according to the crop water requirement.

By optimal storage-release alternatives, the irrigation potential in the upstream catchment can substantially be increased. This could be in the order of 4735.52 km^2 during kharif season and 4898.30 km^2 during rabi season, against the existing total cultivable area of 2879.90 km^2 in kharif and 1231.39 km^2 in rabi season.
Different scenarios of upstream storages, for ranges from 10 to 80% and its effect on the waterlogging in the Tal both for kharif and rabi seasons have been studied. These results would provide a vital input to the decision making process.

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