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Performance assessment of irrigation water management of heterogeneous irrigation scheme: 2. A case study

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Abstract: The non-uniformity of soils, weather, fields, cropping pattern and canal systems in most surface irrigation schemes makes irrigation water management complex, but optimum performance is important particularly in irrigation schemes with limited water supply. This paper focuses on the performance of irrigation water management during the area and water allocation with a case study of an irrigation scheme in the semi-arid region of India. Often the irrigation managers or authorities of these heterogeneous irrigation schemes also need to deal with different allocation rules. The allocation plans and the corresponding water delivery schedules during the allocation process were estimated with the help of a simulation-optimisation model for different allocation rules based on cropping distributions (free and fixed), water distributions (free and fixed-area proportionate), irrigation depth (full, fixed depth and variable depth irrigation) and irrigation interval (from 14 to 35 days). The performance measures of productivity (in terms of net benefits and area irrigated), equity (in water distribution), adequacy and excess were assessed for these different allocation plans and schedules. These were further compared with the performance measures of the existing rule (fixed depth irrigation at a fixed interval). The analysis revealed that these performance measures are in some cases complimentary and in other cases conflicting with each other. Therefore it would be appropriate for the irrigation managers to understand fully the nature of the variation in performance measures for different allocation rules prior to deciding the allocation plans for the irrigation scheme.

Keywords: irrigation water management, performance assessment, allocation plans, water delivery schedules.

Introduction

Irrigation water management (IWM) can be considered under three processes which are undertaken on an irrigation scheme: area and water allocation, operation and evaluation (Gorantiwar and Smout, 2003). The success of irrigation water management depends on these processes being performed according to the objectives of the irrigation scheme. Therefore irrigation authorities need to measure the performance of different processes in irrigation water management for determining and improving irrigation water management performance in the irrigation scheme. Gorantiwar and Smout (2003) developed a framework for the performance assessment of irrigation water management during these processes. This paper focuses on the measurement of performance indicators during the planning process of irrigation water management. The planning consists of using the set objectives/targets for the scheme to prepare an allocation plan for distribution of land and water resources to different crops up to tertiary level, together with water delivery schedules giving the timing and amount of water delivery for the allocation plan.

Several methodologies have been developed in the past to prepare the allocation plans during the planning process. Depending on the objectives, the allocation plans were based on optimising the use of land (Windsor and Chow 1971; Matanga and Marino 1977; Maji and Heady 1978; Gulati and Murty 1979; Morales et al. 1987; Singh et al. 1987; Afshar and Marino 1989; Mayya and Prasad 1989; Prasad and Mayya 1989; Salokhe and Raheman 1989; Paudyal and Gupta 1990 Afshar et al. 1991; Thandaveswara et al. 1992; Shyam et al. 1994; Onta et al. 1995 and Balasubramamiam et al. 1996), or water (Trava et al. 1977; Loftis and Houghtalen 1987; Abderrahman et al. 1989; Hiessl

and Plate 1990; Rao et al. 1990; Vedula and Mujumdar 1992; Akhand et al. 1995 and Wardlaw and Barnes 1999) or both land and water (Matanga and Marino 1979; Yaron and Dinar 1982 and Bernardo et al. 1988; Mannocchi and Mecarelli 1994; Mainuddin et al. 1996; Sunantara and Ramirez, 1997, Paul et al. 2000 and Sahoo et al. 2001). In these models the land and/or water resources were optimised for obtaining maximum crop production or monetary return or for irrigating maximum land. Hence the performance measure of productivity was addressed. The models used in most of these studies were of the single field type and hence the water delivery schedules for the allocation plans were not discussed. Those studies which used the multi-field type of model produced water delivery schedules for the given allocation plan or plans and hence discussed other performance measures such as equity and adequacy (Sritharan et al. 1988; Shyam et al. 1994 and Onta et al. 1995). However these allocation plans were not necessarily optimum.

According to the objectives of the irrigation scheme there may be several allocation rules and a number of possible allocation plans may be produced. Therefore to decide between these in the planning process it is necessary to assess the performance of all the allocation plans which are optimum for an allocation rule and the performance of their respective water delivery schedules. In this paper the four performance measures: productivity, equity, adequacy and excess are compared for the allocation plans and water delivery schedules obtained for different allocation rules for an irrigation scheme in a semi-arid region of India.

Model used for obtaining the allocation plans

To evaluate the performance indicators it is necessary to simulate the response of different allocation rules in terms of output (net benefits/crop yield), considering the heterogeneous nature of the typical irrigation scheme in semi-arid regions (different crops, soils, temporal and spatial variation of weather parameter, multiple field with varying characteristics, complex water delivery network). As land and water resources may be scarce in the irrigation scheme, it is essential that these resources be optimally allocated. Estimation of some performance measures (equity, adequacy, excess) needs information on the spatial and temporal distribution of the resources. For this it is appropriate to use a model based on a simulation-optimisation approach and able to produce the allocation plans for different allocation units in the command area of the irrigation scheme and corresponding water delivery schedule for each irrigation. This study used the Area and Water Allocation Model (AWAM) (Gorantiwar, 1995 and Gorantiwar and Smout, 1995^a) which satisfies these requirements. The model is described briefly below.

The AWAM model has the following four phases and is executed for each set of irrigation interval over the irrigation season.

1. Generation of irrigation strategies
2. Preparation of irrigation programmes
3. Selection of irrigation programmes
4. Optimum allocation of resources

1. Generation of irrigation strategies: The area of the irrigation scheme with similar climate (Region), soil (Soil group) and crop is termed a Crop-Soil-Region (CSR) unit, but this is not a physical division of the irrigation scheme. The optimum allocation of water

needs estimates of the output obtained from several possible ways of irrigating the crop. These several ways (irrigation strategies) are generated in Phase 1 for each Crop-Soil-Region unit and for a given set of irrigation intervals.

2. Preparation of irrigation programme: The irrigation programme which consists of information on yield/benefits and irrigation requirement (depth) per irrigation is prepared for each irrigation strategy generated in Phase 1, from the following two sub-models.

- **SWAB:** This sub-model simulates soil moisture in the soil root zone and estimates the actual crop evapotranspiration and the other related parameters and the irrigation requirement (depth) per irrigation.
- **CRYB:** This sub-model estimates crop yield and net benefits.

Irrigation programmes are prepared for each Crop-Soil-Region unit for the given irrigation strategy such as full irrigation (irrigation to fill the root zone to field capacity) or a given irrigation depth for each irrigation.

3. Selection of irrigation programmes: Phases 1 and 2 may generate many irrigation programmes. Not all of them are important and all cannot be considered in the fourth phase due to computational limitations. Therefore this phase selects a specified number of irrigation programmes, which are optimal and efficient according to certain criteria for each Crop-Soil-Region unit. This step is skipped if a single irrigation strategy is given for each Crop-Soil-Region unit or irrigation scheme.

4. Optimum allocation of resources: The entire irrigation scheme is physically divided into a number of smaller units called “Allocation Units” (AU) over which land and water

resources are allocated. The climate is assumed to be uniform over the allocation unit, but the allocation unit may include different soils and crops. The climatic conditions may be different for different allocation units. The need to divide the irrigation scheme into several allocation units arises due to the heterogeneous nature and large extent of the irrigation scheme and in order to make allocation of resources, water delivery schedules and management of the irrigation scheme efficient. The largest possible size of the allocation unit is equivalent to the size of the irrigation scheme itself. The smallest size of the allocation unit is the individual farm. The intermediate sizes are the command areas of the secondary, tertiary and quaternary canals or groups of these canals. This phase of the model allocates land and water resources optimally to different crops grown on different soils in different allocation units, with the help of the irrigation programmes obtained for different Crop-Soil-Region units from Phases 1, 2 and 3 for different objectives. This is done through the following three stages.

- Preparation of irrigation programmes for each Crop-Soil (CS) unit (a unit in allocation unit with similar Crop and Soil) of each allocation unit by modifying the irrigation programmes of the corresponding Crop-Soil-Region unit considering the distribution and conveyance efficiencies.
- Allocation of the resources to each Crop-Soil unit of each allocation unit with chosen objective(s) and constraints with the Resource Allocation (RA) sub model. Thus this stage gives optimum allocation plan.
- The preparation of a water release schedule for the canal system for the selected allocation plan.

Study area

The “Nazare Medium Irrigation Scheme” in Maharashtra State of India was selected as a case study for performance assessment of irrigation water management. The irrigation season of this irrigation scheme starts from the 15th October and ends on 14th October of next year. There are three distinct crop seasons within the irrigation season. These are winter (Rabi), summer (hot weather) and rainy (Kharif). As little rainfall is received in Rabi season, the crops grown in this season are supplied with irrigation water for their growth. In the summer season no rainfall is received and evapotranspiration is high so cropping is limited and requires irrigation. Most of the rainfall is received in Kharif (monsoon) season. Therefore crops grown in this season need one or two irrigations (protective irrigations) only but these are of little interest in this study as the reservoir fills during the Kharif season. Therefore for this scheme in this study, the irrigation season was considered to spread over Rabi and summer crop seasons. Normally the irrigation interval in Rabi season is 21 days and in summer season is 14 days.

The gross reservoir capacity and dead storage capacity of the reservoir are 22.313 and 5.684 Mm³, respectively. One main canal originates from the headworks. The full supply discharge and length of the main canal are 1.53 m³/s and 3.05 Km, respectively. The main canal supplies one distributory canal, 11.75 Km long and also with a carrying capacity of 1.53 m³/s. The conveyance losses are estimated as 2% per 1000 m for both these lined canals, based on a study conducted by the Irrigation Research and Development (IRD), Department of Irrigation, Maharashtra State.

The cultural command area (CCA) of the irrigation scheme is 3539 ha. There are 28 direct outlets (4 on the main canal and 24 on the distributory canal) and four minors (all on the distributory canal). There are 9 outlets on the minors but the details of these outlets could not be obtained. Therefore the culturable command areas of the 28 outlets and 4 minors were considered as allocation units, resulting in 32 allocation units. The allocation unit numbers 5, 9, 12, and 20 are related to minors and the others to direct outlets. The details are shown in Figure 1.

Previous studies found the conveyance efficiency of field channels below the outlet was 86% (Stofkoper and Tilak, 1992 and IRD, 1992) and therefore the distribution efficiency of each allocation unit related to a direct outlet was considered as 86%. The transmission efficiency of minors was found to be 80% (Stofkoper and Tilak, 1992 and IRD, 1992) and therefore the distribution efficiency of those allocation units which are the culturable command area of minors, was considered as 68.8%. These distribution efficiencies were assumed the same for all the irrigations for particular allocation units. A field application efficiency of 75% was assumed for all the crops on all soils and for all irrigations (including presowing irrigation, if any).

The climatological data was collected from the daily records of the Meteorological Observatory of the nearest agricultural university (Mahatma Phule Agricultural University, Rahuri). The same data series was used for the reservoir (for estimating the water evaporation) and command area (for estimating the reference crop evapotranspiration and bare soil evaporation). The climate over the entire command area was assumed as uniform, and thus there was only one 'Region'. The command area is characterised with four different types of soils. In the present study as two crop seasons

formed the irrigation season, the Rabi crops gram, sorghum, onion and wheat and the summer crops groundnut and sunflower were considered in the analysis (Figure 2 (a)).

Allocation rules

The allocation rules assessed for the performance are based on cropping distribution, water distribution, irrigation frequency and irrigation depth. These are discussed below. Optimum allocation plans and water delivery schedules were obtained for different combinations of these allocation rules with the help of the Area and Water Allocation Model (AWAM) for the study area (“Nazare Medium Irrigation” Scheme in Maharashtra State of India).

Cropping distribution rule

Allocation plans were obtained for two cropping distributions: free cropping and fixed cropping. In a free cropping distribution, no restrictions are imposed on the crops to be irrigated and hence land and water resources are allocated to those crops which maximize the total net benefits. In a fixed cropping distribution there is some restriction on the area to be allocated to different crops, depending on requirements in the scheme. The land and water resources are then allocated to the crops according to these restrictions and then to obtain the maximum total net benefits from the scheme. Based on the previous history and trend in this irrigation scheme, the following fixed cropping distribution was considered while obtaining the allocation plans: gram-25%, sorghum-20%, onion-10% and wheat-15 % in Rabi; and Sunflower–10 % and groundnut-20% in summer season (Figure 2(b)).

Water distribution rule

The performance of the allocation plans is highly dependent on how the water is distributed amongst various users in the irrigation scheme. Plans were obtained for two types of water distribution: free water distribution and fixed water distribution. In a free water distribution, the water distribution to different users is not predefined and hence the allocation plans for this water distribution consist of the allocation to those units which are productive from a water utilisation point of view. In a fixed water distribution the water allocation to different users or allocation units is fixed, depending on certain criteria. In the present study water distribution proportionate to the culturable command area of the users was followed to obtain allocation plans for the fixed water distribution.

Irrigation interval rule

The frequency of irrigation influences the output and hence the allocation plans. Therefore allocation plans were obtained for seven sets of irrigation interval. These are 14 (I-14), 21 (I-21), 28 (I-28) and 35 (I-35) days both in Rabi and summer season and 21 in Rabi and 14 in summer (I-21-14), 28 in Rabi and 21 in summer (I-28-21) and 35 in Rabi and 21 in summer (I-35-21).

Irrigation depth rule

The applied irrigation depth will vary between different crops grown on different types of soils on different climate zones and considering the soil, water and plant relationships.

However this heterogeneity is often not considered and allocation plans are based on a fixed depth of water. When water is scarce, using deficit irrigation may be beneficial compared to full irrigation (English and Nuss, 1982; Hargreaves and Samani, 1984; Trimmer, 1990 and Keller et al., 1992). As the degree of deficit for different crops during different periods may be different, deficit irrigation results in variable depth irrigation (Gorantiwar and Smout, 1995^b). Based on these findings the following three irrigation rules were considered for obtaining the allocation plans.

(1) Full irrigation: Full irrigation is the application of the irrigation depth needed to bring the soil moisture in the root zone to field capacity at the time of irrigation. When the irrigation interval is large, full irrigation may still cause stress to the crop and reduce the crop yield below its maximum level.

(2) Fixed depth irrigation: Fixed depth irrigation is the application of a fixed depth of irrigation to each crop grown on different soils in different climatic zones during the entire crop season. However the fixed depth of irrigation is optimised for a particular set of irrigation interval and crop season.

(3) Variable depth irrigation: In a water-limiting situation, it may be beneficial to apply less depth than full irrigation (deficit irrigation) and spread water to a larger area. However the amount and duration of the deficit will vary according to the crop and growth stage. In variable depth irrigation the optimal combination of deficit is selected to decide the depth of irrigation for a particular crop grown on different soils in different climatic regions and during different crop growth stages by following the approach of Gorantiwar and Smout (1995^b).

Results

AWAM was used to obtain the allocation plans and water delivery schedules for different combinations of allocation rules. For each of these allocation plans and water delivery schedules, the following performance measures were estimated. The details of the methods are presented by Gorantiwar and Smout (2003):

- ***monetary productivity (based on net benefits):***

$$Pr_g = \frac{OB_a}{OB_t} \quad (1)$$

where,

Pr_g = monetary productivity (gross)

OB_a = actual output (total net benefits in currency-unit estimated for the optimum allocation plan corresponding to the selected combination of the allocation rules)

OB_t = output of management strategy with maximum output (total net benefits in currency-unit estimated for the optimum allocation plan obtained for the combination of free cropping distribution, free water distribution, variable depth irrigation and irrigation interval of 21 days in Rabi and summer seasons)

- ***area productivity (based on area irrigated):***

$$Pr_g = \frac{OA_a}{OA_t} \quad (2)$$

where,

Prg = area productivity (gross)

OAA = actual output (total area estimated for irrigation in ha for the optimum allocation plan corresponding to the selected combination of the allocation rules)

OAT = targeted output (culturable command area of Nazare Irrigation Scheme i.e. 3539 ha)

- *equity (based on the allocation proportion by area):*

$$E_i = \frac{\overline{Ra^{pq}}}{\overline{Ra^{bq}}} \quad (3)$$

where

E_i = equity for the irrigation scheme

$\overline{Ra^{bq}}$ = average of allocation ratios of the best quarter

$\overline{Ra^{pq}}$ = average of allocation ratios of the poorest quarter

$$Ra_i = \frac{\lambda a_i}{\lambda d_i} \quad (4)$$

where

Ra_i = allocation ratio of i^{th} allocation unit

λa_i = actual allocation proportion for i^{th} allocation unit

λd_i = desired allocation proportion for i^{th} allocation unit

$$\lambda d_i = \frac{\Delta d_i}{\sum_{i=1}^{na} \Delta d_i} \quad (5)$$

where

Δd_i = the value of the parameter to which equity should be proportional, assigned to i^{th}

allocation unit (culturable command area of i^{th} allocation unit in ha.)

na = total number of allocation units (32 for Nazare Medium Irrigation Scheme)

$$\lambda a_i = \frac{\Delta a_i}{\sum_{i=1}^{na} \Delta a_i} \quad (6)$$

where

Δa_i = value of parameter (water allocated in ha-m at allocation unit level) by which equity

is measured, computed for i^{th} allocation unit

$$\Delta a_i = V_i * A_i$$

A_i = Area allocated for irrigation or irrigated of i^{th} allocation unit

V_i = Volume of water allocated or delivered to the i^{th} allocation unit

- *adequacy (based on the ratio of supply to crop water requirements):*

$$AQS = \left(\frac{\sum_{i=1}^{na} \sum_{j=1}^J \min(Va_{ji}, Vs_{ji})}{\sum_{i=1}^{na} \sum_{j=1}^J Vs_{ji}} \right) \quad (7)$$

where

AQS = Adequacy for the irrigation scheme

$V_{a_{ji}}$ = volume of water allocated to i^{th} allocation unit during j^{th} irrigation

$V_{s_{ji}}$ = deliverable volume of water needed according to maximum demand to i^{th} allocation unit during j^{th} irrigation

- *excess (based on supply surplus to requirements):*

$$EX = \left(\frac{\sum_{i=1}^{na} \sum_{j=1}^J \max(V_{a_{ji}} - V_{r_{ji}}, 0)}{\sum_{i=1}^{na} \sum_{j=1}^J V_{r_{ji}}} \right) \quad (8)$$

where

EX = Excess for the irrigation scheme

$V_{r_{ji}}$ = volume of water needed according to maximum demand to i^{th} allocation unit during j^{th} irrigation

The results for each of the performance measures are presented in Tables 1 to 5 and discussed below.

Results for different cropping distribution rules

Both free cropping distribution and fixed cropping distribution rules were combined with other distribution rules and some of the results are discussed in the following sections. The cropping distribution rules themselves however have a major effect, as can be seen

from the monetary productivity (net benefits) (Table 1) and area productivity (irrigated area) (Tables 2 to 5) of both the cropping distributions. In all cases the productivity of the free cropping distribution is considerably higher than the productivity of the fixed cropping distribution, for example the total net benefits with free cropping are approximately 2 to 3 times higher than for the fixed cropping distribution. The drastic reduction in net benefits by adopting the fixed cropping distribution is due to compulsory irrigation of those crops which give lower monetary returns (such as sorghum) and to the crops needing more water (such as sunflower and groundnut). The free cropping distribution resulted in an allocation plan with fewer selected crops (onion mainly and gram some times) in the command area, but the effect of the reduction in local market prices due to over production of a particular crop was not considered in the model. The crops with high water requirements also appeared in the allocation plan in the fixed cropping distribution, but not for the free cropping distribution, so the area productivity (area irrigated) is also higher for the free cropping distribution than for the fixed cropping distribution.

Tables 2 to 5 show that the cropping distribution also influenced the equity when the water distribution was free. The equity is higher with a free cropping distribution than with the fixed cropping distribution. In a free cropping distribution, as the most profitable crops (onion and gram) are not the crops needing more water (sunflower and groundnut), the benefits of irrigation were spread to the larger area. In the fixed cropping distribution however, due to the compulsory allocation to crops needing more water, the irrigations were limited to a smaller area. However this may not be the case when the most profitable crops are also the crops needing more water. As would be expected, adequacy and excess were constant for full irrigation. For fixed depth or variable depth irrigation however, the

adequacy was higher for free cropping than for the fixed cropping distribution. This was because the crops which appeared in the free cropping distribution gave greater benefit in this study when irrigation allocations approached full irrigation. This is not necessarily a general trend, but its basis in crop growth models suggests that similar findings can be anticipated in other irrigation schemes with limited water supply.

Results for different irrigation interval rules

Tables 2 to 5 show that irrigation interval influenced the monetary productivity (net benefits). However the trend of influence depends on the irrigation depth rule. In general for full irrigation, the monetary productivity increased with the irrigation interval (up to 21 days) and then decreased. A similar trend is observed for fixed depth irrigation, except for the fixed cropping distribution where the monetary productivity increased up to I-21-14 and then decreased. In variable depth irrigation, the monetary productivity is almost constant for the lower irrigation intervals (up to 21 days) and then decreased. This was due to the flexibility to skip a scheduled irrigation. The higher monetary productivity at an irrigation interval of 21 days is attributed to the fact that deficit irrigation is beneficial in some form i.e. either by prolonging the irrigation interval with full irrigation or by prolonging the irrigation interval and applying less water than at full irrigation (fixed depth or variable depth irrigation). However deficit irrigation only in the form of reducing the depth of irrigation may not be beneficial, as can be seen from the monetary productivity for the lowest irrigation interval considered in the study i.e. 14 days.

The influence of irrigation interval on area productivity (area irrigated) depends on the irrigation depth rule and cropping distributions (Tables 2 to 5). Area productivity

increased with the irrigation interval for full irrigation. This was because prolonging the irrigation interval minimised the losses associated with each irrigation and in turn irrigated more area. However the increase in irrigated area due to the reduction in these losses could not compensate for the reduction in crop yield beyond the irrigation interval of I-21-14 days as seen from the monetary productivity (net benefits) which decreased when irrigation interval was increased beyond I-21-14 days. For variable depth irrigation, area productivity (area irrigated) increased with irrigation interval when the cropping distribution was free, and the irrigation interval did not influence the area productivity when the cropping distribution was fixed. The main cause of this trend is the flexibility to adjust the water delivery interval in variable depth irrigation and to allocate resources to only a few crops in fixed cropping distribution.

In fixed depth irrigation the area productivity (area irrigated) increased with irrigation interval when cropping distribution was free. However when the cropping distribution was fixed, the area productivity decreased with the irrigation interval. In fixed depth irrigation, the irrigation depth is optimised for all crops (i.e. the depth giving maximum productivity) for each irrigation interval, separately. This optimised depth was higher for larger irrigation intervals (to minimise the effect of excessive deficit due to the large irrigation interval) than for smaller irrigation intervals (where the deficit was less). This phenomenon was not pronounced in the free cropping distribution due to the predominance of onion which needs a lower optimised depth even at larger irrigation intervals compared to summer crops like groundnut and sunflower. Tables 2 to 5 show that the irrigation interval has no specific impact on the equity, adequacy and excess.

Water distribution rules

Monetary productivity (net benefits) obtained with free water distribution is higher than with the area proportionate fixed water distribution. This is due to the objective function of maximization of total net benefits, allocating water to the most productive units such as units with more suitable soils and units closer to the head of the system, when the water distribution is free. In the fixed water distribution all the allocation units were allocated with water in proportion to their culturable command area. However in some cases e.g. for larger irrigation intervals, the area productivity (area irrigated) is higher with fixed water distribution than with free water distribution. This was because in such cases when water distribution was area proportionate, the allocation units with less productive soils were also allocated water. These units needed less water, producing also lower benefits, but in this process water was spread to a greater area than with free water distribution.

The equity indicator measures water distribution compared to the area proportionate water distribution. When the water distribution was free, the equity reduced drastically to around 0.5 for most cases in a free cropping distribution. Reduction in equity was due to productive allocation units getting more water when the water distribution was free. When the cropping distribution was fixed, the equity was zero with free water distribution. The further reduction in equity in the fixed cropping distribution is due to allocation of water to the crops needing more water and hence fewer allocation units getting water. Thus free water distribution gives maximum productivity while area proportionate fixed water distribution gives maximum equity. The adequacy and excess were not influenced by the water distribution.

Irrigation depth rule

Amongst all the three irrigation depth rules, the monetary productivity (net benefits) was highest with variable depth irrigation (VDI) followed by full irrigation and fixed depth irrigation (Tables 2 to 5). The higher total net benefits with variable depth irrigation is due to deficit irrigation by skipping a scheduled irrigation and/or by applying lower irrigation depths than the full irrigation depths and spreading the irrigation water to a greater area. With fixed depth irrigation, the same depth of irrigation is applied to all crops and soils. Though this fixed depth is optimised, it may not meet the requirements for all crops and soils. Therefore the monetary productivity (net benefits) is the lowest with the fixed cropping distribution. The difference in the monetary productivity of different irrigation rules in a free cropping distribution is not as pronounced as in the fixed cropping distribution, because only a few crops are included in the optimal allocation plan with free cropping distribution (mainly onion with irrigation close to full irrigation).

The area productivity (area irrigated) was highest in variable depth irrigation followed by fixed depth irrigation and full irrigation. The inclusion of appropriate deficit in variable depth irrigation could spread the irrigation over a larger area, while obtaining the maximum total net benefits. As in case of fixed depth irrigation, the depth was not according to the full irrigation for all crops and soils, the deficit irrigation was induced to some extent and hence a greater area could be irrigated with fixed depth irrigation than with full irrigation. However as the deficit applied was not optimum for all allocation units and systematic as in case of variable depth irrigation, the total net benefits were lower.

The highest adequacy of one was obtained with full irrigation, as in full irrigation water was applied to fill the root zone at every irrigation. In variable depth irrigation, the approach was to optimise the deficit either by skipping irrigation or applying less water than full irrigation or by both and this process gives reduced adequacy but increased productivity. Full irrigation and variable depth irrigation gave zero excess but there was generally some excess with fixed depth irrigation. In fixed depth irrigation, the optimised depth may prove excess for some crops and inadequate for some crops. The equity was not influenced by the irrigation depth rules.

The allocation rules influencing different performance measures considered in this study are shown in Figure 3. Figure 3 indicates that in some cases different performance measures are complimentary to each other whereas in others they conflict with each other. For example, both productivity and equity are higher for free cropping distribution than for fixed cropping distribution. However in the case of water distribution, productivity is higher and equity is less when the water distribution free and productivity is less and equity is higher when the water distribution is fixed (proportional to culturable command area of each allocation unit).

Comparison with existing practice

The monetary productivity (net benefits) obtained for the irrigation interval of 21 days is highest for a free cropping distribution. For the fixed cropping distribution, the maximum monetary productivity was obtained for an irrigation interval of I-21-14 for full and fixed depth irrigation and for 21 days for variable depth irrigation. However the monetary

productivity for irrigation interval of I-21-14 is close to the maximum monetary productivity values for these different scenarios. The existing practice in the irrigation scheme is to adopt the irrigation interval of I-21-14, and to apply a fixed depth of 70 mm at every application. Hence the different performance measures are compared for the irrigation interval of I-21-14. The comparison amongst full, fixed depth, variable depth and existing practice of irrigation for the area productivity (area irrigated), monetary productivity (net benefits), equity, adequacy and excess for free and area proportionate water distribution is shown in Figure 4 for free cropping distribution and in Figure 5 for fixed cropping distribution. Figure 4 shows that there are no major differences amongst the performance measures of the three different irrigation depth rules. However the productivity and equity for the existing practice are much lower than for these three rules. Similarly the excess with existing practice is higher. Thus for a free cropping distribution wherein the resources are allocated to a few crops or in a monocrop situation, if the resources are allocated optimally the irrigation depth rules did not influence the performance measures.

However the results are different for the fixed cropping distribution. Variable depth irrigation produces 22 % and 27 % more monetary productivity (net benefits) and 25 and 14 % more area productivity (area irrigated) over full and fixed depth irrigation, respectively for free water distribution and 21 % and 27 % more monetary and 28 and 17 % more area productivity for area proportionate fixed water distribution. When compared with existing practice, variable depth irrigation produces 27 % and 14 % more monetary and area productivity for free water distribution and 27 % and 17 % more monetary and area productivity for area proportionate fixed water distribution. Equity values are zero for free water distribution and one for area proportionate fixed water distribution for all

the irrigation rules and existing practice for fixed cropping distribution. The adequacy is one for full irrigation followed by fixed depth irrigation and existing practice. The adequacy is less in the case of variable depth irrigation than for existing practice. Excess is zero in full irrigation whereas highest in fixed depth irrigation and existing practice.

Conclusions

This study analysed the different allocation rules against which the irrigation managers or the irrigation authorities in the irrigation scheme with limited water supply need to take decisions. This is done firstly by obtaining the allocation plans and water delivery schedules with simulation-optimisation models and secondly by estimating the performance measures of these allocation plans and schedules. The study did not analyse the allocation rules for entire range of the performance measures described by Gorantiwar and Smout (2003), but the results of the analysis of productivity (area and monetary), equity (in water distribution), adequacy and excess provided the information on how these measures are in some cases complimentary and in others conflict with each other. While free cropping distribution maximises the productivity, this does not consider the traditional crop mix developed in the command area of the irrigation scheme over the years which is represented by the fixed cropping distribution. The free water distribution gives the maximum productivity by ensuring that the most productive allocation units get water, but it reduces the equity to zero in the case of fixed cropping distribution. The fixed water distribution in a prescribed form (in this study the area proportionate water distribution) can achieve equity objectives (in this study the equity in water distribution) but at the cost of lower productivity. Full irrigation assures adequate water supply but deficit irrigation (in this study the variable depth irrigation) may be more productive in a

water scarce situation. Thus it would be useful for irrigation managers to appreciate the nature of this variation in performance measures for different allocation rules prior to deciding the allocation plans for the irrigation scheme. The proposed framework for assessment of the performance measures (Gorantiwar and Smout, 2003) is useful tool to analyse the performance of the allocation plans and water delivery schedules.

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Table 1. The monetary productivity (net benefits) for the allocation plans obtained with different allocation rules for free and fixed cropping distributions.

Allocation rule	Irrigation interval	Free cropping distribution		Fixed cropping distribution	
		Free water distribution	Water distribution proportionate to area	Free water distribution	Water distribution proportionate to area
Full irrigation	I-14	0.821	0.747	0.311	0.271
	I-21-14	0.918	0.850	0.315	0.276
	I-21	0.962	0.895	0.320	0.279
	I-28-21	0.768	0.693	0.293	0.249
	I-28	0.799	0.724	0.276	0.238
	I-35-28	0.715	0.634	0.242	0.192
	I-35	0.721	0.641	0.203	0.166
Fixed depth irrigation	I-14	0.842	0.762	0.277	0.244
	I-21-14	0.927	0.868	0.294	0.257
	I-21	0.971	0.913	0.245	0.219
	I-28-21	0.756	0.689	0.247	0.201
	I-28	0.783	0.721	0.203	0.174
	I-35-28	0.658	0.576	0.193	0.150
	I-35	0.663	0.582	0.169	0.139
Variable depth irrigation	I-14	0.978	0.909	0.410	0.360
	I-21-14	0.956	0.887	0.401	0.351
	I-21	1.000	0.933	0.388	0.335
	I-28-21	0.829	0.766	0.357	0.289
	I-28	0.858	0.798	0.340	0.279
	I-35-28	0.736	0.666	0.296	0.000
	I-35	0.742	0.673	0.000	0.000
Existing practise	21-14	0.779	0.700	0.294	0.257

Table 2. The performance measure for the allocation plans obtained with different allocation rules for free cropping distribution with free water distribution.

Allocation rule	Irrigation interval	Performance measures				
		Productivity (Area)	Productivity (Monetary)	Equity	Adequacy	Excess
Full irrigation	I-14	0.471	0.821	0.000	1.000	0.000
	I-21-14	0.595	0.918	0.175	1.000	0.000
	I-21	0.623	0.962	0.226	1.000	0.000
	I-28-21	0.610	0.768	0.281	1.000	0.000
	I-28	0.634	0.799	0.424	1.000	0.000
	I-35-28	0.718	0.715	0.498	1.000	0.000
	I-35	0.725	0.721	0.502	1.000	0.000
Fixed depth irrigation	I-14	0.485	0.842	0.000	0.972	0.000
	I-21-14	0.676	0.927	0.641	0.858	0.000
	I-21	0.709	0.971	0.678	0.860	0.000
	I-28-21	0.689	0.756	0.682	0.849	0.021
	I-28	0.717	0.783	0.760	0.851	0.021
	I-35-28	0.655	0.658	0.441	0.974	0.126
	I-35	0.662	0.663	0.473	0.974	0.126
Variable depth irrigation	I-14	0.600	0.978	0.426	0.753	0.008
	I-21-14	0.639	0.956	0.511	0.912	0.000
	I-21	0.671	1.000	0.615	0.912	0.000
	I-28-21	0.685	0.829	0.567	0.869	0.000
	I-28	0.714	0.858	0.582	0.863	0.000
	I-35-28	0.764	0.736	0.435	0.771	0.061
	I-35	0.770	0.742	0.439	0.779	0.059
Existing practise	21-14	0.499686	0.778646	0	0.987	0.213

Table 3. The performance measure for the allocation plans obtained with different allocation rules for free cropping distribution with water distribution proportionate to area.

Allocation rule	Irrigation interval	Performance measures				
		Productivity (Area)	Productivity (Monetary)	Equity	Adequacy	Excess
Full irrigation	I-14	0.429	0.747	1.000	1.000	0.000
	I-21-14	0.552	0.850	1.000	1.000	0.000
	I-21	0.581	0.895	1.000	1.000	0.000
	I-28-21	0.588	0.693	1.000	1.000	0.000
	I-28	0.614	0.724	1.000	1.000	0.000
	I-35-28	0.718	0.634	1.000	1.000	0.000
	I-35	0.725	0.641	1.000	1.000	0.000
Fixed depth irrigation	I-14	0.440	0.762	1.000	0.974	0.000
	I-21-14	0.636	0.868	1.000	0.864	0.000
	I-21	0.669	0.913	1.000	0.864	0.000
	I-28-21	0.654	0.689	1.000	0.865	0.026
	I-28	0.684	0.721	1.000	0.865	0.026
	I-35-28	0.712	0.576	1.000	0.923	0.073
	I-35	0.720	0.582	1.000	0.923	0.073
Variable depth irrigation	I-14	0.563	0.909	1.000	0.752	0.007
	I-21-14	0.604	0.887	1.000	0.911	0.000
	I-21	0.636	0.933	1.000	0.911	0.000
	I-28-21	0.760	0.766	1.000	0.754	0.005
	I-28	0.791	0.798	1.000	0.755	0.005
	I-35-28	0.790	0.666	1.000	0.760	0.058
	I-35	0.798	0.673	1.000	0.767	0.056
Existing practise	21-14	0.454	0.700	1.000	0.988	0.221

Table 4. The performance measure for the allocation plans obtained with different allocation rules for fixed cropping distribution with free water distribution

Allocation rule	Irrigation interval	Performance measures				
		Productivity (Area)	Productivity (Monetary)	Equity	Adequacy	Excess
Full irrigation	I-14	0.412	0.758	0.000	1.000	0.000
	I-21-14	0.427	0.768	0.000	1.000	0.000
	I-21	0.454	0.780	0.000	1.000	0.000
	I-28-21	0.440	0.716	0.000	1.000	0.000
	I-28	0.475	0.673	0.000	1.000	0.000
	I-35-28	0.453	0.591	0.000	1.000	0.000
	I-35	0.490	0.494	0.000	1.000	0.000
Fixed depth irrigation	I-14	0.552	0.676	0.000	0.755	0.000
	I-21-14	0.494	0.718	0.000	0.793	0.061
	I-21	0.561	0.599	0.000	0.768	0.055
	I-28-21	0.472	0.603	0.000	0.847	0.052
	I-28	0.498	0.495	0.000	0.849	0.073
	I-35-28	0.380	0.471	0.000	0.969	0.210
	I-35	0.422	0.411	0.000	0.966	0.174
Variable depth irrigation	I-14	0.576	1.000	0.000	0.675	0.024
	I-21-14	0.573	0.979	0.000	0.693	0.028
	I-21	0.567	0.948	0.000	0.725	0.034
	I-28-21	0.542	0.871	0.000	0.753	0.029
	I-28	0.600	0.829	0.000	0.745	0.030
	I-35-28	0.584	0.722	0.023	0.730	0.036
	I-35					
Existing practise	21-14	0.494	0.718	0.000	0.793	0.062

Table 5. The performance measure for the allocation plans obtained with different allocation rules for fixed cropping distribution with water distribution proportionate to area.

Allocation rule	Irrigation interval	Performance measures				
		Productivity (Area)	Productivity (Monetary)	Equity	Adequacy	Excess
Full irrigation	I-14	0.354	0.660	1.000	1.000	0.000
	I-21-14	0.375	0.672	1.000	1.000	0.000
	I-21	0.399	0.681	1.000	1.000	0.000
	I-28-21	0.412	0.609	1.000	1.000	0.000
	I-28	0.452	0.581	1.000	1.000	0.000
	I-35-28	0.465	0.468	1.000	1.000	0.000
	I-35	0.516	0.406	1.000	1.000	0.000
Fixed depth irrigation	I-14	0.489	0.596	1.000	0.762	0.000
	I-21-14	0.434	0.627	1.000	0.790	0.068
	I-21	0.501	0.535	1.000	0.793	0.051
	I-28-21	0.413	0.491	1.000	0.855	0.113
	I-28	0.494	0.424	1.000	0.829	0.080
	I-35-28	0.346	0.365	1.000	0.973	0.310
	I-35	0.486	0.340	1.000	0.874	0.129
Variable depth irrigation	I-14	0.535	0.878	1.000	0.649	0.036
	I-21-14	0.523	0.856	1.000	0.692	0.034
	I-21	0.496	0.816	1.000	0.762	0.041
	I-28-21	0.477	0.706	1.000	0.779	0.031
	I-28	0.531	0.680	1.000	0.798	0.033
	I-35-28					
	I-35					
Existing practise	21-14	0.434	0.627	1.000	0.790	0.068

Figure 1. Schematic map of allocation units and their details

Figure 2 (a) . Crop period for different crops

Figure 2 (b). Cropping distribution

Figure 3. The allocation rules influencing different performance measures

Figure 4. The performance measure for the allocation plans obtained with different allocation rules for free cropping distribution.

Figure 5. The performance measure for the allocation plans obtained with different allocation rules for fixed cropping distribution.