ON THE VALUE OF SHORT-TERM WEATHER FORECASTS IN SCHEDULING SUPPLEMENTAL IRRIGATION OF POTATOES IN THE UNITED KINGDOM

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ABSTRACT

Many agricultural activities can be adversely affected by the weather. Effects may impact on farm-level production economics and/or the wider environment. Developments in weather forecasting have led to improvements in spatial and temporal resolution, but does the information meet the needs of UK farmers in making day-to-day operational decisions? In this study, a farm-level production economics model was used to investigate the value of short term weather forecasts in scheduling irrigation of potato crop. Irrigation scheduling was simulated over a range of irrigation costs for potatoes under conditions representing wet, dry and average years. The results demonstrate that the use of weather forecast in scheduling can deliver increased economic benefit when compared to the strategies not using weather forecasts. In the wet year the value of weather forecast (i.e. the increased economic benefit compared to alternative strategies) derives from increased profits due to cost savings from unnecessary irrigation. In the average and dry years the value of weather forecast would be in terms of greater profit per unit of water application and would derive from improved efficiency in the use of limited or expensive water supply.

Results from simulations using perfect knowledge of short-term weather to estimate the value of potential improvement in weather forecast suggest that profit would increase with improvements in quality and lead-time of weather forecast. The increase in profit would be due to further cost savings from unnecessary irrigations in the wet year and more rational use of limited or expensive water supply in the dry and average years.

KEYWORDS: Weather forecast; irrigation scheduling; value of information; potato.

1. INTRODUCTION

In the UK supplementary irrigation has become an essential component of a competitive crop production system on approximately 175,000 ha of arable land. Potatoes (*Solanum Tubersorum*) constitute the main irrigated crop and account on the average, for over 40% of the irrigated area and over 50% of water application. Irrigation water constitutes only about 1% of all surface and ground water abstraction nationally but because of its temporal and spatial distribution, the impact on water resources is far greater than the low percentage would indicate. Demand is concentrated in the Southeast region of England and over a relatively short period of 8 to 12 weeks in the summer months when water resources are scarcest. Irrigation is therefore a very significant consumptive user of water in the catchments at this period (Evans, 1994; University of Newcastle Upon Tyne, 1990). Widespread public concern about water scarcity and its environmental effects (e.g. Royal Society for the Protection of Birds, 1995) and the growing pressure from other competing users are limiting irrigatorsô access to water. A real need therefore exists for irrigators to use water more wisely through proper irrigation scheduling.

A major difficulty in scheduling supplemental irrigation is rainfall uncertainty. The irrigator faces the risk of excessive water stress that could potentially reduce crop yield and quality when irrigation is delayed and the anticipated rainfall fails to occur. On the other hand, if there is an unexpected rainfall soon after irrigation, over watering may occur with a possibility of crop damage, trafficabilty problems, erosion, excessive leaching of pesticides and fertilisers, and the wastage of water, labour and energy.

Water application in the UK is mainly by the overhead (spray) method using mobile hosereel-raingun irrigators. An irrigation cycle typically lasts for several days due to constraint of equipment capacity and/or of labour. This results in a queue of fields or farm sections waiting for irrigation. In the special circumstance of supplemental irrigation an important aspect of improved irrigation scheduling would be the use of weather forecast information, if available, for daily decisions on whether or not to initiate irrigation.

Existing irrigation scheduling models used by several commercial scheduling services in the UK are based on the ñtrigger levelò concept of available water. They do not consider weather forecasts or attempt to optimise returns from timing of irrigations. Gowing and Ejieji (2000) reviewed the models and others developed elsewhere based on dynamic programming frame work (e.g. Wilks and Wolf, 1998). They noted the constraints to the practical application of the dynamic programming approach, in particular the large size of the state space which occurs i.e. the so called curse of dimensionality and the associated computational cost. Adapting the free-form simulation approach of Swaney et al. (1983) therefore, Gowing and Ejieji (2000) proposed a model which utilises short-term weather forecasts and a decision model in scheduling supplemental irrigation. They applied the method to potato irrigation. The short-term weather forecasts utilised in the model are produced by the UK Meteorological Office for farmers through a commercial service. The weather forecast is provided for several regions of the country on daily basis for the current day and five days ahead. Information is provided on several weather variables including rainfall amount, rainfall probability, sunshine hours and, maximum and minimum temperatures.

The decision on whether or not to utilise the weather forecast information is however ultimately at the discretion of individual irrigators who may have their own perceptions regarding the value of this information.

The objective of this paper therefore is to present an objective assessment of the value of weather forecasts in relation to two irrigation scheduling strategies which may reasonably be considered as reflecting sensible alternatives to dealing with the scheduling problem without the use of weather forecasts. The first bases irrigation decision only on projected soil water deficit while the second combines the projection of soil water deficit with a simple assumption of short term weather persistence. The value of potential improvement in short-term weather forecasts was also evaluated using simulations assuming perfect knowledge of short-term weather.

2. MATERIALS AND METHODS

2.1 The Simulation Procedure

The simulation model of Gowing and Ejieji (2000) divides the entire season into three time segments all of which are taken into consideration in each irrigation decision. The time segments are termed the past, forecast and future periods. The past period represents the time from the beginning of the season to the day on which irrigation decision occurs and actual weather data are utilised in this period to describe the state of the crop-soil system. The forecast period represents the short-term horizon for the irrigation decision and is set at seven days in the model. The weather data input in this period is mainly from the available weather forecast. The future period refers to the time from the end of the forecast period to the end of the season. Since in a real time situation, information on weather conditions is unavailable beyond the forecast period, a projection of the state of the system to the end of the season is achieved in the forecast period by averaging the results from repeated simulations using several years of historical weather data.

The simulation model considers a farm made up of several fields which are defined as a zone of the farm that can be irrigated in one day. The irrigatorôs equipment and labour constraints are accounted for by specifying a minimum irrigation interval for the fields. For the description of the crop-soil interaction the model incorporates a dynamic physiologically-based crop model capable of simulating the growth of potato from planting to harvest (Ejieji and Gowing, 2000).

The simulation model updates the state of the crop-soil system on each day of the season by simulating for the current day the soil water balance and the crop growth and development. In order to reduce the possibility of excessive water stress in the last field to receive water in an irrigation cycle, a projection of the soil water deficit in all the fields is made to the end of the forecast period. If the largest or smallest projected soil water deficit is in excess of the allowable value and the minimum irrigation interval of the driest field would be equalled or exceeded by the next day, the irrigation criterion is applied. If irrigation is favoured, the driest field is flagged as the first to receive water in an irrigation cycle which would be initiated the next day. Irrigation decision is therefore essentially taken a day in advance. The decision is revised on daily basis taking advantage of the most recent weather forecast information. An irrigation cycle once started can therefore be terminated on any day without necessarily completing it.

The irrigation decision criterion is stated as follows

$$I_{t+i} = d, \quad i = 1, 2, ., ., ., \eta \qquad (1.\ a)$$

$$\text{if} \quad E[\varphi(I,t)] > E[\varphi(I^0,t)] \qquad (1.\ b)$$

else

$$I_{t+i} = 0, \quad i = 1, 2, ., ., ., \eta \qquad (1.\ c)$$

Equation 1.a represents the decision on day ñtò, to apply an irrigation depth d on each of the next η days i.e. from day t+1 to t+η where η is the number of days required to complete an irrigation cycle. In Equation 1.b $E[\varphi(I,t)]$ represents the expected profit estimated on day t for initiating irrigation on day t+1 , $E[\varphi(I^0,t)]$ is the expected profit of not initiating irrigation, φ denotes profit while I and I^0 denote the cases of irrigation and no irrigation respectively. Profit is computed as return from crop sale less variable cost of irrigation. Fixed cost is not considered because it is assumed that the irrigation system is already in place and the irrigatorôs concern is how best to use it.

The expected profit of irrigation is computed from the expression

$$E[\varphi(I,t)] = \sum_{k=1}^{m} P_{Tk} \frac{1}{n} \sum_{j=1}^{n} \varphi(R_{Tk}, W_j, I) \qquad (2)$$

where P_{Tk} is the probability of experiencing a rainfall event sequence in the first three days of the forecast period, R_{Tk} is the resulting sequence of rainfall amounts and m is the number of all possible rainfall event sequences. W_j is one of the years the historical daily data of which is used to describe the future period and n is the number of the years. Similarly, $E[\varphi(I^0,t)]$ is computed by substituting I with I^0 in Equation (2) i.e. making I_{t+i} , (i = 1, 2, ., ., ., η) identically zero (Equation 1.c). In the first three days of the forecast period there are eight possible rainfall event sequences ranging from three consecutive wet days to three consecutive dry days. There are 8n number of simulations required, from the first day after the forecast period to the end of the season, for the computation of an expected profit. For each of the simulations, a different weather year W_j is utilised.

It should be noted that the estimated event probabilities of the rainfall event sequences are based on the assumption of independence and ignores persistence. The deficiency of the assumption has been considered by Ejieji(1998) who suggested that the deficiency would be less severe in the summer months when the convective storms are common than in the winter period when precipitation in the UK is predominantly due to frontal systems.

Although the short term horizon (i.e. the forecast period) for irrigation decision is 7 days ahead, the model assumes that weather forecast is available for a lead-time of five days. Only the first three days

however explicitly influences irrigation decision because the forecast quality deteriorates with lead-time (Golding, 2000). The fourth and fifth days are categorically assumed to be dry or wet depending on whether the forecast rainfall probability for the days were high (≥ 0.8) or low (< 0.80). If the day (i.e. fourth or fifth day) was considered to be wet, the rainfall amount for the day was taken to be the expected rainfall given by the product of the forecast amount and the forecast probability. In order to simulate as closely as practicable a realistic rainfall situation for the last two days (i.e. sixth and seventh days) of the forecast period, the rainfall occurrence is generated stochastically as first order Markov process while the rainfall amount for a wet day is obtained by sampling from a gamma distribution the parameters of which are derived from historical daily rainfall data. The algorithm of the process is similar to that of Geng et al. (1986).

The main features of the simulated strategies are described in Table 1. Irrigation assuming perfect knowledge of short-term weather is not a practical proposition but only indicates the upper

Table 1. Main features of the irrigation strategies simulated

*Strategy	Use of the irrigation decision criterion	Description of the time segments		
		Past Period	Forecast period	Future period
With forecast (IRWF)	Yes	Uses actual weather data	Uses forecast weather data	Average of repeated simulations using several years of historical weather data
Perfect knowledge (IRPK)	Yes	Uses actual weather data	Uses actual weather data	Same as in IRWF
No Forecast (IRNF)	No	Uses actual weather data	Weather forecast not considered. 10-day moving averages of weather variables of the past period used to project soil water deficit	Not considered
Persistence (IRPSS)	No		Same as in IRNF but persistence of short-term weather is also assumed	Not considered

*IRWF = irrigation with weather forecast (The model of Gowing and Ejieji, 2000)

IRPK = irrigation with perfect knowledge of short-term weather

IRNF = irrigation without weather forecast

IRPSS = irrigation assuming persistence of short-term weather

bound of performance that could be expected with improvement in the quality and lead-time of the forecasts. In the case of irrigation without weather forecast, only water deficit projection to the end of the forecast period influenced irrigation decision. It did not consider any possible rainfall during the forecast period. Irrigation assuming short-term weather persistence followed the same procedure as irrigation without weather forecast except that short-term persistence of wet weather was assumed. Thus irrigation decision on a wet day was deferred to the next day. Since irrigation is taken a day in advance, the incidence of rainfall effectively postponed irrigation by at least two days. Irrigation without forecast was considered to represent the extreme attitude of an irrigator who gives no

consideration for the uncertain rainfall within the short-term horizon while irrigation assuming persistence of short-term weather was assumed to approximate to a moderate attitude of an irrigator with local knowledge of the long-term average rainfall characteristics.

2.2 Estimation of the Value of Weather Forecast and the Value of Potential Improvement in Weather Forecast

The estimation of the value of short-term followed a conventional approach in which the estimate of the value of information is taken in a relative sense as the difference in benefit obtained when using information optimally and that achieved under some basic information level. The value of short-term weather forecast in relation to each of the evaluated strategy (i.e. with the strategy as the basic level) was therefore estimated as the amount by which the profit was less than that of irrigation with weather forecast. In the case of value of potential improvement in short-term weather forecast however, it was evaluated as the amount by which the profit of irrigation assuming perfect knowledge of short-term weather exceeded that of irrigation using the available short-term weather forecast.

2.3 Input Data and Simulated Conditions

The data used in this study and the simulated conditions are representative of Cambridgeshire, East Anglia. They are the same as those that have been described elsewhere by Gowing and Ejieji (2000). The meteorological data comprised the relevant weather forecast data obtained from the Norwich Weather Centre of the Meteorological Office and twenty-six years (1970 ï 1995) of historical weather data from the UK Meteorological Office. The historical data include rainfall, potential evapotranspiration of grass, soil temperature, maximum and minimum air temperatures and sunshine hours; they are required to drive the crop growth simulation model.

The growing seasons considered were 1992, 1994 and 1995 representing a wet year, an average year and a dry year respectively. The average year has about average seasonal rainfall while the wet and dry years respectively have seasonal rainfalls above and below the average. Twenty years (1970 - 1989) of historical weather data were used to describe the future period. The soil water deficit situations triggering irrigation in the field were as discussed by Gowing and Ejieji(2000). All simulations were carried out at seven values of variable cost of irrigation of £1.7/ha mm, £3.4/ha mm, £5.8/ha mm, £9.2/ha mm, £12.6/ha mm, £14.3/ha mm and £17/ha mm. The crop prices of £58.4/t, £186/t and £150/t representing the actual crop prices for the 1992, 1994 and 1995 seasons respectively were used in the computation of profits for the respective seasons.

3. RESULTS AND DISCUSSION

3.1 Rainfall Characteristics

The growing season (April to September) rainfall showed marked variability in the seasonal amounts. The seasonal rainfall for a 26-year (1970-1995) period averaged 285.4mm with a coefficient of variability of 21.3%. The long-term daily rainfall pattern indicate that for each month of the growing season, the chance of a wet day being followed by another wet day is on the average more than 50% and is more than double that of a wet day following a dry day (Table 2.). The high variability of actual daily values of the transitional probabilities as reflected in the range of daily values (also shown in Table 2) however limit the validity of any generalised assumption regarding wet weather persistence especially for the short-term.

Table 2. Monthly averages of the daily transitional probabilities of wet day to wet day (P(W/W)) and dry day to wet day (P(W/D)), and monthly proportion of wet days during the growing season**.**

Month	*Average of daily transitional probabilities		Proportion of rainy days
	P(W/W)	P(W/D)	
April	0.69 (0.88 - 0.36)	0.28 (0.56 ï 0.08)	0.48
May	0.71 (1.00 ï 0.40)	0.25 (0.45 ï 0.00)	0.46
June	0.70 (1.00 ï 0.38)	0.23 (0.38 ï 0.00)	0.43
July	0.59 (1.00 ï 0.25)	0.26 (0.54 ï 0.00)	0.38
August	0.59 (1.00 ï 0.11)	0.28 (0.55 ï 0.07)	0.39
September	0.63 (1.00 ï 0.25)	0.25 (0.50 ï 0.00)	0.39

* The ranges of actual daily values in the respective months are shown in brackets

The amount of rainfall for the 1992, 1994 and 1995 seasons were 377.1mm, 276.9mm and 187.1mm respectively. The intra-seasonal rainfall distribution for the three seasons was characterised by dry spells with varied frequency of occurrence among the seasons. There were 87, 59 and 43 wet days in the 1992, 1994 and 1995 seasons respectively. Dry spells of two days duration or more occurred 16, 19 and 18 times in the 1992, 1994 and 1995 seasons respectively. The average duration of the dry spell was 4 days in 1992, 5 days in 1994 and 9 days in 1995 season while the maximum duration in the respective seasons was 8, 11, and 36 days. The longest duration spells tended to occur between June and mid August (i.e. between Julian days 151 - 230). The daily rainfall amounts ranged from 0.1mm to 26mm with rainfall amounts in the range of 0.1mm - 5mm predominating. The average rainfall depth per precipitation event was 3.4mm, 3.0mm and 2.2mm for the 1992, 1994 and 1995 seasons respectively.

3.2 Reliability of Rainfall Forecasts

The comparison between the forecast rainfall probabilities and the actual relative frequency of rainfall occurrence are shown in Fig.1 representing the pooled result from 1992 to 1995 seasons. To obtain the relative rainfall frequencies, the daily forecast rainfall probabilities for each of the 5 days ahead were assigned to given classes of equal rainfall probabilities. To calculate the relative frequency for each class, the number of rainfall occurrences was divided by the number of days having forecast rainfall probabilities in that class.

Within the range of probability values of 0.4 - 0.70 for the first day ahead and 0.5 - 0.70 for the second day ahead, the forecast probabilities agreed closely with the relative rainfall frequencies with an average absolute deviation of less than 0.03. A similar situation obtained only at the probability value of 0.70 from the third to the fifth days ahead. Forecast rainfall probabilities below the stated value or range of values for the respective days ahead were less than the relative rainfall frequencies implying that rain occurred more frequently than forecast. The reverse was generally the case for forecast rainfall probabilities above the stated value or range of values. The average absolute deviation of the forecast rainfall probabilities from the relative rainfall frequencies were 0.096, 0.126, 0.131, 0.150, and 0.136 for the first, second, third, fourth and fifth days ahead respectively confirming that the quality of forecast deteriorated with lead-time.

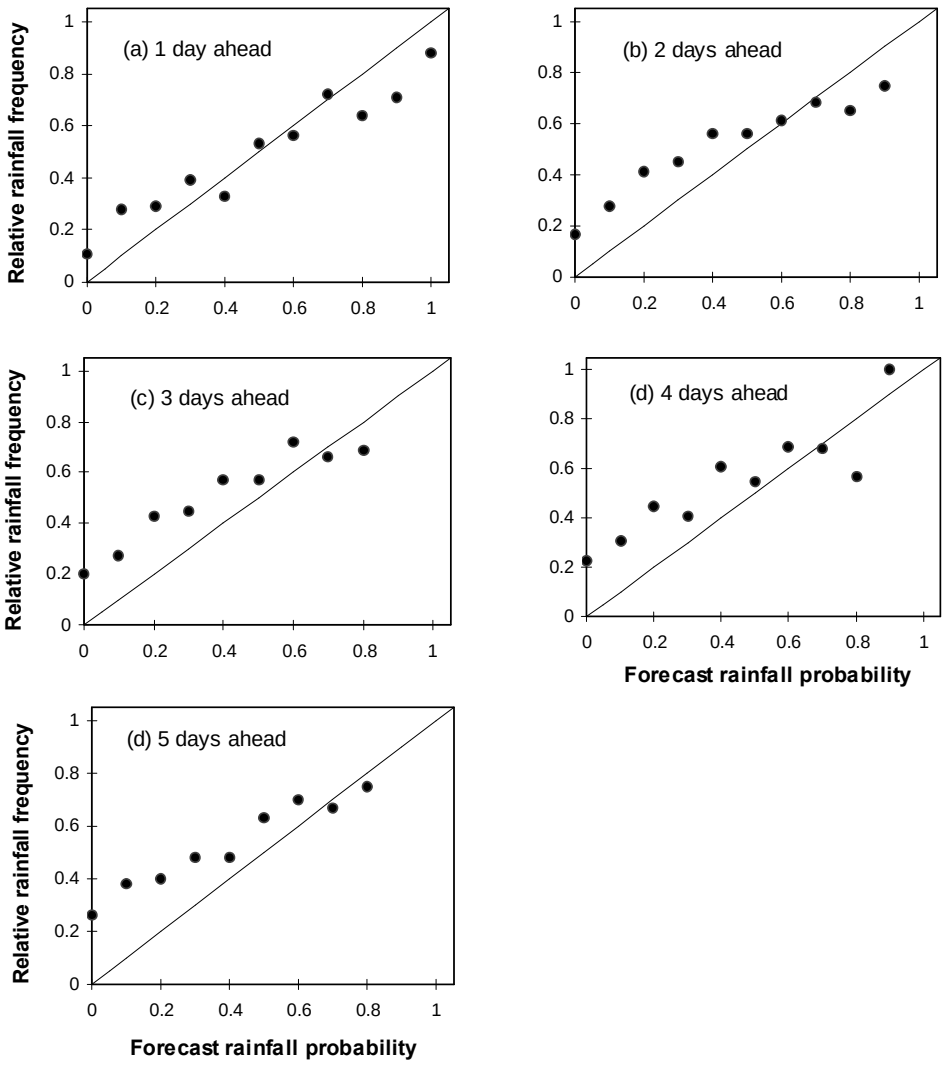


Fig.1. Comparison between forecast rainfall probabilities and relative rainfall frequencies for 1992 to 1995 seasons.

A comparison of the daily forecast and actual rainfall amounts during the growing seasons showed that rainfall amounts of less than 5mm were more frequently forecast and generally were, on the average, more closely predicted (Fig. 2). Actual rainfall amounts higher than this value were generally under predicted. The closest predictions were for rainfall amounts of 2.5mm or less. Golding(2000) has also found that larger events (10mm threshold) are less well predicted than small events(1mm threshold). It should be noted that except in the case of the forecasts of zero amount, actual forecast rainfall amounts are given as a range of values with the lower and upper values of the range provided. For this study the average of the upper and lower values was taken as the forecast amount.

During periods of extended dry spells, there was a tendency to erroneously predict the occurrence of rainfall over a greater part of a dry spell duration thus forecasting non-zero rainfall amounts for the dry days.

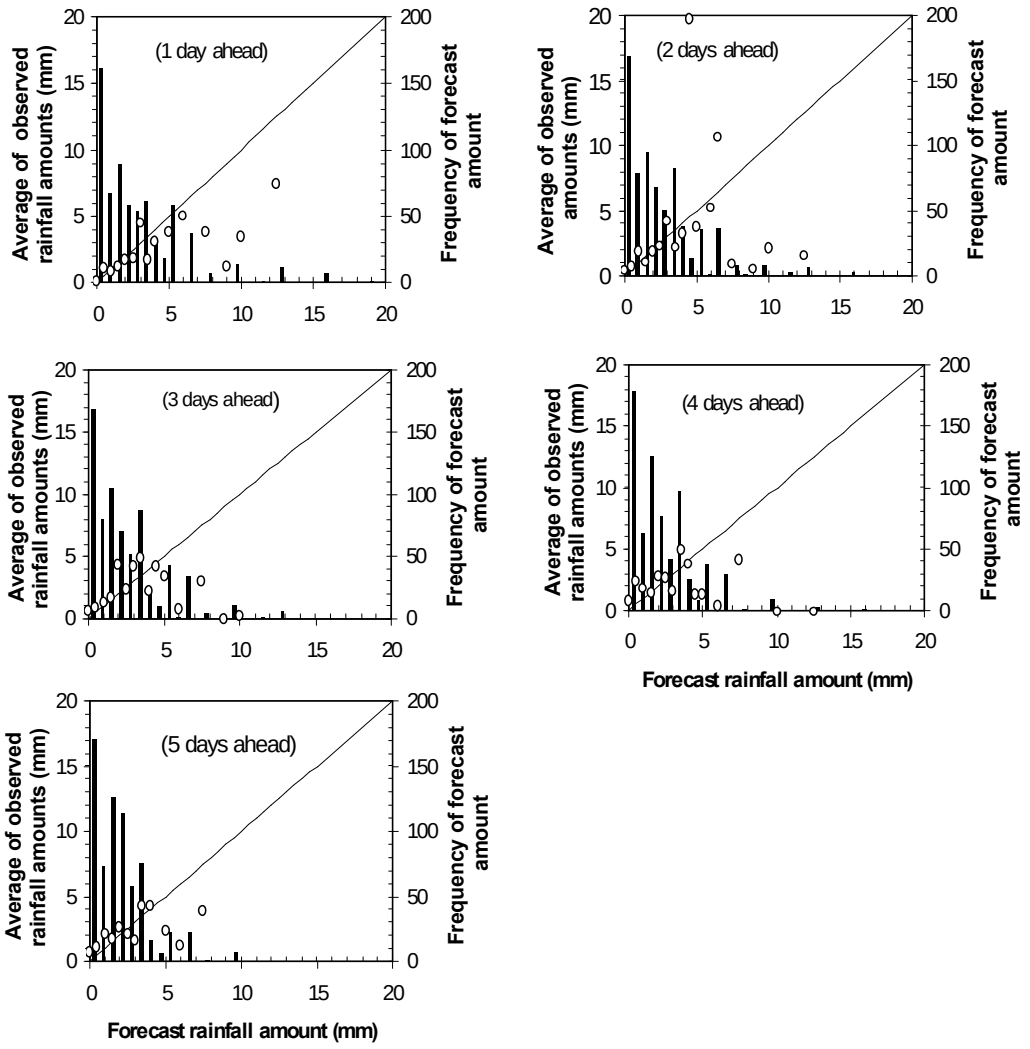


Fig 2. A comparison between forecast rainfall amounts and the average amounts observed (circles) for the respective forecast amounts in the 1992 to 1995 seasons, at March, Cambridgeshire,. Frequencies of the forecast amounts (columns) are also shown. (— = 1:1 line between the forecast and average observed amounts)

3.3 Water Application in Relation to Irrigation Cost and Yield

The average irrigation amounts and the average yields obtained for the simulated strategies are presented in Table 3. Actual number of irrigation events per field varied among the fields at each irrigation cost. The average irrigation amounts and average yield represent respectively the mean seasonal water application and mean crop yield for the seven fields.

Table 3. Average irrigation amounts and average crop yield obtained for the wet, average and dry years

	*IRNF	*IRPSS	IRPK and IRWF at various irrigation costs (£/ha mm)													
			1.7		3.4		5.8		9.2		12.6		14.3		17	
			IRPK	IRWF	IRPK	IRWF	IRPK	IRWF	IRPK	IRWF	IRPK	IRWF	IRPK	IRWF	IRPK	IRWF
(a) Wet year																
Average irrigation amount (mm/ ha)	207	143	96	114	96	111	75	104	0	86	0	61	0	57	0	57
Average yield (t/ha)	51.4	50.9	50.7	50.7	50.7	50.7	49.7	50.1	38.2	49.6	38.2	47.7	38.3	47.1	38.2	47.1
(b) Average year																
Average irrigation amount (mm/ ha)	296	218	282	214	282	214	282	193	282	182	43	177	29	164	21	161
Average yield(t/ha)	52.1	34.5	51.3	34.7	51.3	34.7	51.3	33.0	51.3	31.9	28.8	31.0	28.3	30.0	27.8	28.9
(c) Dry year																
Average irrigation amount (mm/ ha)	321	275	318	279	318	239	318	207	214	182	50	104	43	96	32	86
Average yield(t/ha)	40.6	36.7	41.1	37.9	41.1	36.1	41.1	35.8	38.0	34.6	31.1	31.2	30.5	31.1	30.0	30.9

* IRNF and IRPSS correspond to the cases of irrigation scheduling without weather forecast and with assumption of short-term weather persistence respectively and are therefore independent of irrigation cost.

For irrigation with weather forecast (IRWF) and irrigation assuming perfect knowledge of short-term weather (IRPK), the total seasonal irrigation application was generally sensitive to irrigation cost decreasing as irrigation cost increased. Stepped sensitivity to irrigation cost was however exhibited by IRWF over some ranges of irrigation cost and has been discussed elsewhere (Gowing and Ejieji, 2000). IRPK equally showed stepped sensitivity over the two lowest irrigation costs of £1.7/ ha mm and £3.4/ ha mm in 1992 (i.e. wet year) and 1995 (i.e. dry year), and over the irrigation cost range of £1.7/ ha mm to £9.2/ ha mm in 1994 (i.e. the average year). The water application was constant over the respective cost ranges. The fixed application depth per irrigation not adjusted to actual field soil water deficits is a contributory factor to the stepped sensitivity. The fixed application adopted in the simulation however reflects the normal UK practice, as it is not practical to adjust application to suit actual deficits.

In the cases of irrigation assuming short-term weather persistence (IRPSS) and irrigation without weather forecast (IRNF) where irrigation was not influenced by economic considerations, the corresponding results (also presented in Table 3) are independent of irrigation cost.

Crop yield generally increased with water application. IRNF applied the highest amount of water in all the years and except in the dry year had the highest yield.

3.4 Value of Weather Forecast and of Potential Improvement in Weather Forecast in terms of End of Season Profit

The values of weather forecast and of potential improvement in weather forecast in terms of end of season profit are presented in Fig. 3 for the three seasons at the various irrigation cost. The value of weather forecast for each strategy at a given irrigation cost is numerically equal to the profit for IRWF minus the profit for that strategy. The value of potential improvement in weather on the other hand is numerically equal to the profit for IRPK minus the profit for IRWF. In the wet year i.e. 1992 season, the value of weather forecast was positive for both IRNF and IRPSS and increased with irrigation cost (Fig. 3). The value of potential improvement in weather forecast also mostly increased with irrigation cost. The value ranged from £22 /ha at the lowest irrigation cost of £1.7/ ha mm to £445 /ha at the highest irrigation cost of £17/ ha mm or 8.0% to 25.6% of the profit of IRWF at respective irrigation costs. IRPSS saved some water from unnecessary irrigations relative to IRNF. The value of weather forecast was therefore higher for IRNF than IRPSS. Their difference in values of weather forecast ranged from £118 /ha at the lowest irrigation cost to £1065/ ha at the highest irrigation cost.

The water application by IRPSS was lower than that of IRNF by 30.9%. The largest water application by IRWF, which was at the lowest irrigation cost, was less by 20.0% and 44.8% than the seasons application by IRPSS and IRNF respectively but was 18.6% more than highest application by IRPK.

The value of weather forecast in the 1994 season i.e. average year was negative at all the irrigation costs for IRNF and at all but the two lowest irrigation costs for IRPSS. The negative values when expressed as absolute values (i.e. without the negative signs) represent the amounts by which the profits for the strategies exceeded those for IRWF. In the case of IRPSS the negative values averaged - £120/ ha or ï 3.1% of the profit for IRWF in the irrigation cost range of £5.8/ ha mm to £17/ ha mm. In that range of irrigation cost, the water application by IRPSS was 13.0% to 35.6% more than the applications by IRWF. For IRNF the negative values increased from - £3111/ ha at the lowest irrigation cost to - £2008 at the highest irrigation cost or ï 51.5% to ï 75.8% of the profit for IRWF at the respective irrigation costs. The water application by IRNF was however more than the applications by IRWF by 38.3% and 84.4% at the lowest and highest irrigation costs respectively.

It should be noted that the mainly negative values of weather forecast for IRWF and IRPSS in the 1994 season is attributable to the exceptional crop price in that year which was the highest crop price in 20 years (1975 ï 1994). Returns from higher yields from more generous applications of water by the strategies were therefore generally more than those achieved through more conservative

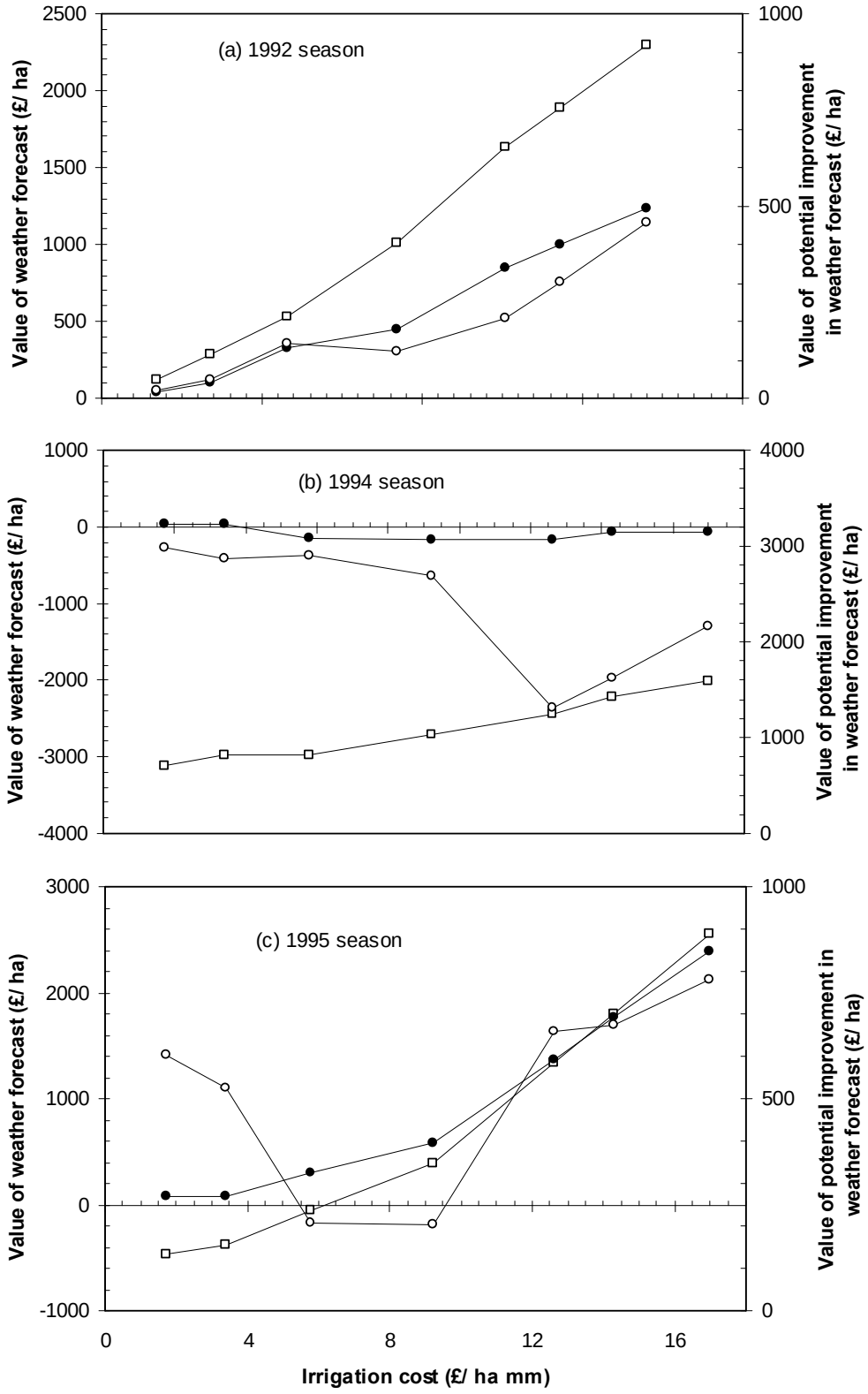


Figure 3. Value of weather forecast in relation to irrigation cost for the (a) wet season, (b) average season and (c) dry season with respect to the strategies of irrigation without weather forecast (□) and irrigation assuming short weather persistence (•). Value of potential improvement in weather forecast (o) in relation to irrigation cost is also shown.

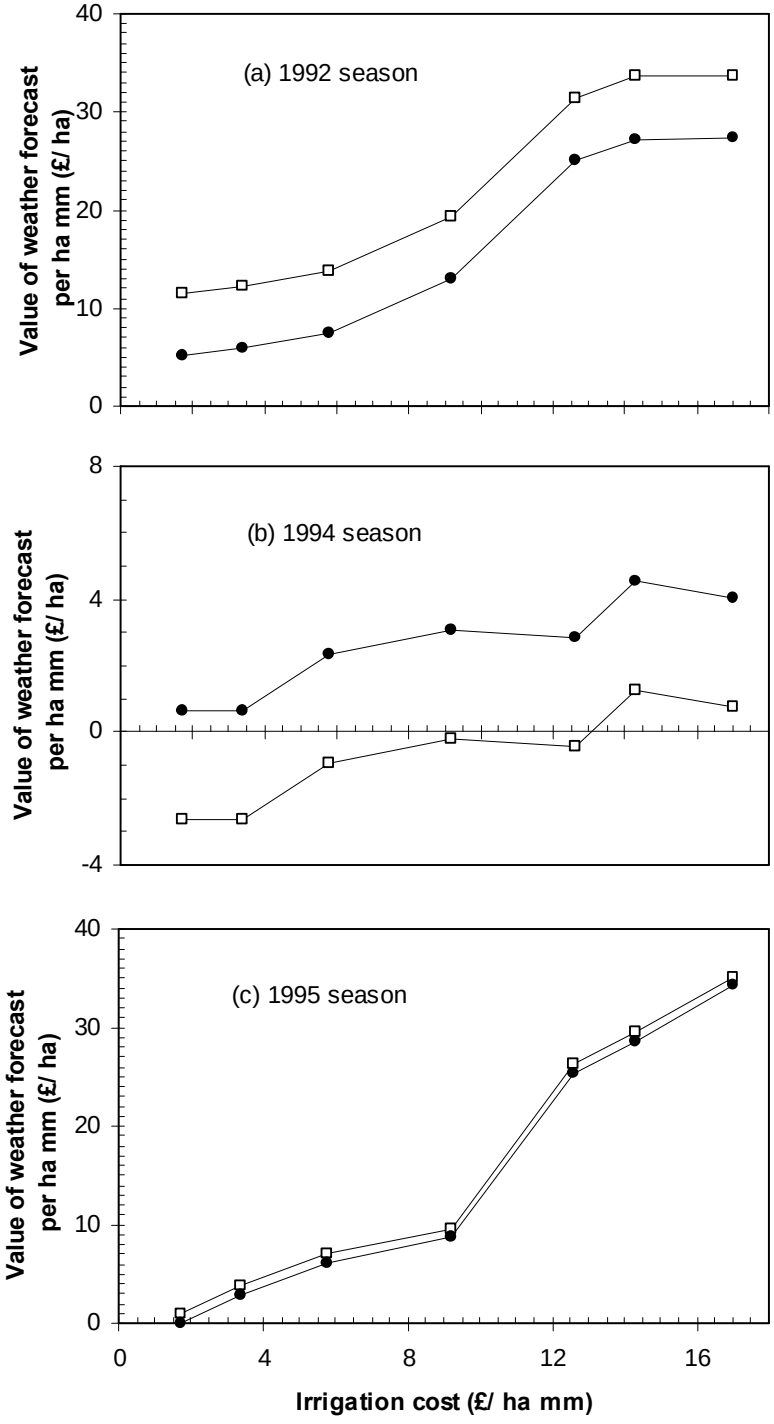


Figure 4. Value of weather forecast per ha mm of irrigation in relation to irrigation cost for the (a) wet season, (b) average season and (c) dry season with respect to the strategies of irrigation without weather forecast (□) and irrigation assuming short weather persistence (•).

irrigation by IRWF even at high irrigation costs. An analysis (not reported) of the simulation result obtained for the year by Ejieji (1998) with a lower projected crop price of £82/t showed that IRWF applied less water at corresponding irrigation costs and that the value of weather forecast was positive and increased with irrigation cost at the lower crop price.

The value of potential improvement in weather forecast was positive at all the irrigation costs. The values were between £1304/ ha and £2980/ ha. However the water application by IRPK was higher than by IRWF in the range of irrigation costs of £1.7/ ha mm to £9.2/ ha mm after which the water application reduced drastically below that by IRWF at higher irrigation costs. In the range of irrigation cost of £1.7/ ha mm to £9.2/ ha mm also, the amounts by which the profits for IRNF exceeded those for IRWF were higher than values of potential improvement in weather forecast by only an average of £84/ ha or less than 1% of the profits for IRNF. The water application by IRNF was however 5.1% higher than the applications by IRPK in that range of irrigation cost. This outcome suggests that at the lower irrigation costs in the average year, improvement in weather forecast may lead to increased water application by IRWF. Water savings would however be achieved compared to IRNF with marginal difference in their profits.

In the 1995 season i.e. the dry year, the values of weather forecast for IRNF and IRPSS increased with irrigation cost and were positive at all irrigation costs except in the case of IRNF where the value remained negative up to the irrigation cost of £5.8/ ha mm. The values were higher for IRPSS than IRNF at irrigation costs less than about £13.5/ ha mm. The difference in the values decreased from £545/ ha at the lowest irrigation cost to zero at irrigation cost of £13.5/ ha mm above which the values for IRNF were higher with the difference increasing to £165/ ha at the highest irrigation cost. This implies that the profits for IRNF were higher than for IRPSS at irrigation costs below £13.5/ ha mm. The water application by IRNF was however 16.9% more than that by IRPSS in the season.

At the irrigation costs of £1.7/ ha mm, £3.4/ ha mm and £5.8/ ha mm respectively, the negative values of weather forecast for IRNF were - £470/ ha, - £384/ ha and - £45/ ha or ï 9.3%, -8.35% and ï 10.47% of the profits for IRWF at the respective irrigation costs. However at the irrigation costs IRNF applied 15.4% to 55.2% more water than IRWF.

The value of potential improvement in weather forecast was positive at all the irrigation costs and ranged from £604/ ha at the lowest irrigation cost through a minimum £203/ ha at the irrigation cost of £9.2/ha mm to £781/ ha at the highest irrigation cost or 11.9% through 5.6% to 24.6% of the profit for IRWF at respective irrigation costs. In the irrigation cost range of £1.7/ ha mm to £9.2/ ha mm, the water applications by IRPK were 14.1% to 17.7% more than those by IRWF. The water application was below that of IRWF at higher irrigation costs. The potential value of improved weather forecast was more than the amounts by which the profits for IRNF exceeded those of IRWF at the irrigation costs of £1.7/ ha mm to £5.8/ha mm. The difference was on the average £145/ ha or 3.0% of the profit for IRNF. At the irrigation costs, IRNF water applied 1.1% more water than IRPK. The results suggest that in the dry year at the lower irrigation costs, the benefit of improvement in weather forecast would result in higher profits but through increased water applications by IRWF. The water applications would however, be less than by IRNF with the profits for IRWF also higher than for IRNF.

3.5 Value of Weather Forecast in terms of Efficiency of Irrigation Water Use

The values of weather forecast in terms profit per ha mm of applied water for IRPSS and IRNF in the three seasons are presented in Fig. 4. The values represent the amounts by which the profit per ha mm for IRWF exceeded those of the respective strategies. In the wet and dry years i.e. 1992 and 1995 respectively, the values were positive and increased with irrigation cost for both IRPSS and IRNF. The values for IRNF exceeded those for IRPSS by an average of £6.3/ ha mm and £0.9/ ha mm in the 1992 and 1995 seasons respectively showing that IRNF was less efficient than IRWF and IRPSS in the use of water in the two seasons.

In the 1994 season i.e. average year, the values were higher for IRPSS than for IRNF with the values being negative for IRNF at irrigation costs lower than £13.2/ ha mm. The difference in their values was £3.3/ ha mm on the average. The negative values obtained for IRNF despite its more generous water application is due to the very high crop price in that year.

3.6 Discussion

The results show that the use of weather forecasts in place of other scheduling strategies can enhance the returns from supplemental irrigation in terms of end of season profits and profit per unit of water application. There is however considerable variation between years as was also found by Fox et al. (1999a) in a similar evaluation of weather forecast information in winter wheat production.

In the 1992 season (i.e. the wet year), values of weather forecast in terms of end of season profit were positive for at all irrigation costs were achieved through greater cost savings from unnecessary irrigation. In contrast, the values of weather forecast were either very small or negative at all the irrigation costs in 1994 (i.e. the average year). In 1995 (i.e. the dry year) the value of weather forecast becomes positive only at relatively high irrigation cost assumptions. Clearly, the use of weather forecast does not always pay, as was also found by Fox et al. (1999b) in the case of alfalfa hay production. The negative values of weather forecast however occurred under significantly higher water applications that may not be feasible in practice due to the resource constraint typical of such years.

Under such resource constraint, the advantage of using weather forecast becomes apparent as shown in the positive values of weather forecast in the dry year when the values are in terms of profit per ha mm of irrigation (Fig. 4). This demonstrates the advantage of the use of weather forecast over IRNF and IRPSS in rational and efficient use of scarce or expensive water supply.

The value of weather forecast in terms of profit per ha mm of irrigation that was mostly negative for IRNF in the average year reflects the effect of the very high crop price for the year. An analysis (not reported) of a simulation result of Ejieji (1998) obtained with a reduced crop price of £82.6 /t for that year showed that the values of weather forecast for IRNF in terms of profit per ha mm followed a trend similar to that in the dry year.

The values of potential improvement in weather forecast obtained in this study suggest that the benefit in terms of higher profit from the use of weather forecast would increase with the improvement in the quality and lead-time of short-term forecasts. The benefits in the wet year would result from more cost savings from unnecessary irrigations. In the average and dry years the benefits would result from more rational use of water with increased water application at low irrigation costs and reduced water application at high irrigation costs. The increased water application would nevertheless still be less than water application by IRNF and, the efficiency of water use better than IRNF and IRPSS.

It should be noted that the analysis in this study did not explicitly consider environmental costs except in so far as they are represented by the use of excess water. Also, the incorporated crop model did not include any yield penalty function for excess irrigation and nutrient leaching. The soil profile was assumed to be freely draining. Inclusion of such cost and penalty factors may likely result in higher values of weather forecast than reported for the strategies especially at the lower irrigation costs in the average and dry years.

The threshold irrigation cost at which irrigation cost at which the end of season profit equalled that of the unirrigated crop for all the strategies (i.e. the threshold irrigation cost for beneficial irrigation) has been reported elsewhere (Ejieji, 1998). It was found to be highest for IRWF compared to IRNF and IRPSS except in the average year where the threshold cost of £16.5/ ha mm for IRNF was the highest. Based on the estimated actual variable cost of irrigation for 1994, the percentage contribution of water charges to the variable cost and the likely scenario for water charge escalation, Gowing and Ejieji (2000) concluded that for such average years, only real water-scarcity or institutionally limited

water supply rather than water price signal are likely to force the irrigator to use water more efficiently. Outright banning or restriction of water abstraction is however usual in a typical resource-stressed summer (Upton, 1995; University of Newcastle Upon Tyne, 1990). This study has demonstrated that compared to the alternative strategies of irrigation scheduling, the use of weather forecast under such conditions of resource constraint would increase the benefit per unit of applied water through improved efficiency of water use.

4. CONCLUSION

It has been demonstrated that the use of available weather forecast in irrigation scheduling could potentially yield increased benefit from supplemental irrigation over that from strategies which do not use the weather forecast but rely only on soil water deficit projection or on soil water deficit projection combined with a simple assumption of wet weather persistence. The value of weather forecast expressed as the increase in benefit over that of the alternative strategies would increase with irrigation cost.

The increased benefit of using weather forecast in the wet years would be more profit derived from cost savings from unnecessary irrigations. In the average and dry years the increased benefit would be in terms of higher profit per unit of water application resulting from improved efficiency in the use of limited or expensive water supply.

Improvement in quality and lead-time of forecasts would result in greater profit from the use of weather forecast in the wet year through more cost savings from unnecessary irrigations. In the average and dry years however, water application may increase with the use of weather forecast if the irrigation cost is low or decrease if the irrigation cost is high with increased profit in either case. The level of water in any increased application would nevertheless be lower than for irrigation without weather forecast with potentially higher profits for using weather forecast than for not using weather forecast. Efficiency of water use and the resulting benefit would also be higher for using weather forecast than for the strategies that do not.

It should be emphasised that the values of weather forecast reported for the various strategies were measured against a model that attempts to use the available weather forecast optimally in irrigation decisions. The actual economic value achievable in practice would therefore depend on the effective use of the available weather forecast information. It should be noted that the weather forecasts were taken at their face value in this study without consideration of their performance characteristics. The crop price uncertainty faced by the irrigator was also not considered. This study however demonstrates the advantage of the use of weather forecast in practical decision-making for supplemental irrigation scheduling based on simulated demand.

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HYDRAULIC MODELING OF BEGEMANN GATE FOR EFFECTIVE WATER MANAGEMENT SYSTEM IN HADEJIA VALLEY IRRIGATION PROJECT (HVIP), NIGERIA

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ABSTRACT

A mathematical model of Begemann gate was developed for Hadejia Valley Irrigation Project (HVIP) located in Sudan Savannah of Northern Nigeria. Begemann gate is an automatic check gate installed at the main canal of HVIP system with principal aim of regulating (maintaining) upstream water surface profile at constant depth under variable discharges passing through it. The hydraulic gate is made up of structures: a weir and a check gate which is simple to manufacture, easy to replace when damaged and self operational with the control of the discharge at off-take among other advantages. The principal hydraulic parameters considered in the modeling process include the total discharge (Qt) passing through the gate, discharge under the gate (Qd), sides discharges (Qc), and the pressure force acting on the gate plate.

Two mathematical models were developed based on principle and concept of trajectory of free over-fall; and energy conservation as well as the concept of real and virtual weirs. The models of trajectory of free over-fall given by Davis and Cavailhe were evaluated using a prototype model installed in the irrigation laboratory of ENSAM, Montpellier, France. The predicted flow equations (models) of Qt, Qc and Qd are statistically the same with the measured values at 5% level of significance. The covariance of the Cavailhe model (163.0) is twice that of Davis (82.27) when compared with the measured ones indicating that the latter is a better estimator of the hydraulic behavior of the Begemann gate model under real field situation.

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KEY WORDS: Begemann gate, side discharge, discharge under the gate, off-take, free overfall

1.0 INTRODUCTION

Water flow in irrigation canal of gravity system is usually maintained above certain hydraulic head for easy diversion into distributory canals or field channels. This is achieved by the use of hydraulic structures installed across the canals in forms of check gates, cross regulators, weirs and automatic control gates. They protect the canal against the erosive force of flowing water as it can be seriously damaged by a scouring water flow.

Generally, the flow in the main (or secondary) canal that feeds secondary or tertiary canals vary from 100 percent maximum design flow in the peak of irrigation to about 20% (Brouwer, 1987) when irrigation demand is low. Thus, seasonal or even daily variations occur as upstream turnouts are opened or closed according to the demand of the irrigation plots. While this variation in the canal flow is necessary for economic use of water, it is essential to reduce the variations in upstream water levels caused by variations in canal flow through the use of automatic check gates

Begemann gate is one of these automatic check gates. Its advantages are many: simple to manufacture, simple to adjust to the required/desired upstream water levels, easy to replace when damaged, practically maintenance free and self operational with the control of the discharge at off take. Despite its enormous advantages the gate is relatively unknown in the field of irrigation. Except in Bangladesh, Nigeria and USA, there are few other countries where this type of gate is employed in irrigation schemes (Litrico, 2001). Begamann gate has been a subject of research work to hydraulic Engineers for a long time. Vlugter (1940) studied diverse configurations of the gate and made modification for use in an area with a relatively small hydraulic head (gradient < 1%). Similarly, it

has been observed that the gate had become a subject of recent publications (Litrico 2000) with the reported works of De Graff, (1998), Raemy and Hager, (1998), Burt et al (2001) among others. The main research interests of the gate is the hydraulic modeling of the force exerted on the gate and the discharge passing through it. As rightly observed by Litrico (2000), the main problem in modeling the Begemann gate is the computation of the force exerted on the plate by the water. In closed position, the pressure distribution is hydrostatic but this pressure becomes more complicated to compute when the gate opens. The approach followed by Raemy and Hager (1998) and Burt et al (2001) was deriving an expression for determination of the pressure force experimentally. De Graaf (1998) used momentum on conservation of energy between the upstream and down stream to compute the pressure force on the plate. These methods are difficult to use in a real situation on the field where the channel geometry is complicated as in the case of unlined canals. On the modeling of the discharge passing through the gate, it can be observed that the gate function hydraulically different when the gate is slightly open with a small angle of opening as compared to when it opens with maximum angle of opening (Cavailhé, 2001). In a small angle of opening, the gate functions as an orifice while with a maximum angle of opening the gate functions as weir due to minimum interference of the gate on the water profile passing through. Consequently, the modeling of the discharge passing through the gate must take into consideration these different hydraulic behaviors of the gate as it functions. It is therefore imperative that the structures are studied more closely to explore their full potentials for wider applications in the country. Therefore, the objective of the study is to develop hydraulic models that take into account the discharge passing through the gate and thus, exert force on the plate of the gate, which can be used to analyze the performance of the distribution system among other usages.

2.0 MATERIALS AND METHODS

The methodology was divided into two: the first part was the theoretical development of the gate equations and the second part was the experimental evaluation of the developed equations using physical model of the gate

2.1 Theoretical Development of Discharge and Pressure Force Equations of the Gate

The working principle of Begemann gate is simple. It is made of a steel plate rotating around a horizontal axis to a pivot located above the upstream water level. In a closed position, the plate closes along the broad crested weir, where water at the upstream of the gate forces the gate to open while the counterbalance weight tends to keep it in a closed position. At a given water depth (full supply level FSL or a desired hydraulic head) at the up stream of the gate, the moment due to the weight of the counterbalance plus the weight of the gate is in equilibrium with the moment due to the force of the flowing water acting on the plate. A small rise in the water level above FSL pushes the gate further open and increases the flow through the gate while a drop in the water level is checked by the closing of the gate (Othman, 2002). Thus, the FSL at a depth ñhò in the canal is maintained with variable flow rate (Fig. 1 and 2).

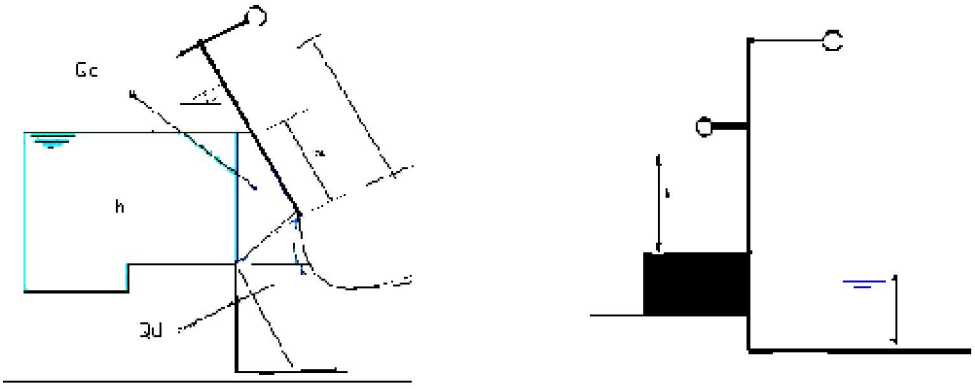


Figure 1 and 2 Schamatic Diagrams of Begemann Gate in opened and closed positions

Hydraulically, the gate is made up of two different hydraulic structures, weir and the gate plate and arms. Each of these structures plays important role for the operation of the gate. As mentioned earlier ,the gate functions as weir structure when it is open at maximum angle, at this position the gate gives a minimum disturbance to the surface water profile passing on the weir. When it functions with a small angle of opening (as orifice) it has tremendous effect on the discharge passing through it. Consequently, the discharge through the gate depends principally on the angle of opening and depth of the gate opening. Similarly, the pressure force that is exerted on the gate plate also depends on the discharge, angle of opening and the design upstream head (FSL).

2.1.1 Discharge equations

There are two different discharges passing through the gate: the discharge directly, under the gate (Q_d) and the discharge through the two sides (Q_c) of the gate (Figures 2 and 3). Q_d is directly proportional to the gate opening while Q_c increases proportionally with the gate opening up to a point where it begins to decrease with the increase of the angle of opening.



Fig. 3 Physical model of Begemann gate

Thus, the total discharges Q_t:

$$Q_t = Q_d + 2Q_c \qquad \text{..... (1)}$$

It is apparent that there are two discharge limits; the lower limit when the gate is closed, the discharge is zero and the upper limit when the gate is completely opened; the discharge is at maximum level Q_{max}.

2.1.2 Side Discharge Equation

Considering figures 1 and 2 which show the surface area where the side flows Qc passes through the gate, it can be said that Qc is a function of some parameters of the gate. Hence:

$$\mathbf{Qc = f (S, C_d, K, g, h)} \qquad \text{é é é . (2)}$$

Where S = surface area in which side discharge passes through (m^2)
C_d = Coefficient of discharge (no unit)
K = Multiplier depending on the angle of opening.
g = Acceleration due to gravity m/s^2
h = Upstream head (m)

Experimentally, it can be observed that, as the angle of opening δ starts from zero to maximum value: the value of Qc starts from zero, reaches its maximum at angle between zero and maximum and then decline to zero level at the angle δ maximum. Therefore; a multiplier K was chosen to take care of this phenomenon. Thus, K is given as;

$$K = \left(1 - \frac{\delta}{\delta_{max}}\right) \qquad \text{é é é .. (3)}$$

Where
δ = A given angle of opening.
δ_{max} = maximum angle of opening at which the gate just touches the surface water profile passing over the Broad-crested weir of the gate.
In order to determine δ_{max} it is necessary to consider the equation of surface water, profile passing on the weir (trajectory of free over-fall). Two equations of water surface profile were chosen, those given by Davis et al (1999) and Cavailhé (2001). Thus;

$$Y = \frac{2}{3}y_c - x\tan\alpha - \frac{1}{2y_c}\left[\frac{x}{\cos\alpha}\right]^2 \qquad \text{..... (4)}$$

$$Y = h_e - x\tan\beta - \frac{g}{2}\left[\frac{x}{V\cos\beta}\right]^2 \qquad \text{..... (5)}$$

Where
y_c = critical depth, the upstream depth above the weir
It is given by Cavailhé, (2001) as

$$y_c = \left[\frac{Q^2}{gL^2_a}\right]^{1/3}$$

Q = discharge in m^3/s passing over the weir
g = acceleration due to gravity in m/s^2
L_a= width of the canal in m

$$\alpha = \tan^{-1}\left[\frac{\frac{1}{3}y_c}{L}\right]$$ Refer to figure 4

L = length of the weir in m
$h_o = y_c$

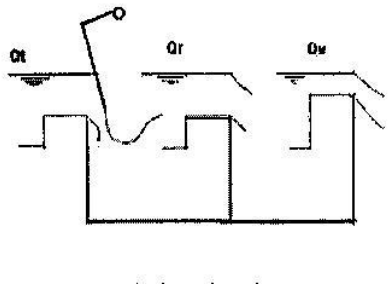


Fig. 4. The concept of real and virtual weirs

$$h_e = \frac{2}{3} y_c = \frac{h_o f^2}{f^2 + \frac{2}{5}}$$

f = Froude Number

The two equations were experimentally evaluated as discussed in 2.2. It can be noted that the two equations are in form of quadratic equation ($y = ax^2 + bx + c$). As the gate swings to open/close, it makes an arc of a cycle with a equation in the form of $R^2 = x^2 + y^2$

When resolved using trigonometry δ_{max} is found as:

$$\delta_{max} = \sin^{-1}\left(\frac{x+p}{R}\right) - \sin^{-1}\left(\frac{p}{R}\right) \quad \text{..... (6)}$$

$R^2 = L^2 + p^2$

Therefore,

$$Y = (ax^2 + bx + c) - (-\sqrt{R^2 - (x-p)^2} + L \quad \text{é é é (7)}$$

Where the parameters a, b and c are given below:

Case I. Equation of Cavailhe

$$a = -\frac{1}{2y_c(\cos\alpha)^2}; \quad b = -\tan\alpha; \quad c = \frac{2}{3} y_c$$

Case II. Equation of Davis

$$a = -\frac{g}{2V\cos\beta}; \quad b = -\tan\beta; \quad c = h_e$$

Equations (6) and (7) are solved using computer software *Mat lab* thereby determining δ_{max} and thus, computing the multiplier K for a given (any) angle of opening

The surface area S is determined considering the geometry of the cross section in which the discharge passes through (figure 2)

The surface area (S) is determined as

$$S = (h - U^*)\left[Uh - (h - U^*\frac{\tan\delta}{2}\right] + \frac{UhU^*}{2} \quad \text{é é é (8)}$$

Thus, using energy Q_c is determined as (referring to equation 2)

$$Q_c = C_d K S\sqrt{2gh} \quad \text{é é é (9)}$$

Where C_d is the coefficient of discharge.

Having determined Q_c, what remains is either to determine Q_d or Q_t. Note that Q_t is the sum of Q_d and Q_c. It can also be observed that Q_t is equivalent to the discharge over the weir when the gate opening is at maximum level. In this position, Q_t can be computed using flow equation over weir but at any other position the equation of weir cannot be used to determine Q_t. Using equation (9) and a selected discharge coefficient, side discharges were determined from ñδò equal to zero up to maximum attainable angle of 17°. Similarly, side discharges were measured for the same angles of openings. Consequently, to determine Q_t, an assumption is made with two hypotheses using the concept of real and virtual weir

Referring to figure (4) above, it can be said that:

$$Q_t = Q_r - Q_v \quad \text{é é é (10)}$$

Where:

Q_t = Total discharge passing through the gate

Q_r = Discharge passing over the real weir
Q_v = Discharge passing over the virtual weir
Therefore
$Q_t (h, \delta) = Q_r (h)$ ï $Q_v (h_{sv}, \delta)$

Hypotheses:
i) if $\delta = 0$, then $Q_t = 0$ and $Q_r = Q_v$ gate is closed and there is no flow
ii) if $\delta = \delta_{max}$ then $Q_t = Q_{max}$ and $Q_v = 0$ flow at maximum discharge
Using energy equation, Q_v and Q_r can be obtained, thus,

$$Q_v = C_d b_v \sqrt{2g}(h - h_{sv})^{\frac{3}{2}} \qquad \text{é é é} \quad (11a)$$

$$Q_r = C_d b_v \sqrt{2g}(h)^{\frac{3}{2}} \qquad \text{é é é} \quad (11b)$$

Where b_v = width of the virtual weir
b_r = width of the real weir
h = hydraulic head on the real weir
h_{sv} = hydraulic charge on the virtual weir.
Hence, referring to equation 1

$$Q_t = Q_d + 2Q_c = Q_r - Q_v = C_d b_v \sqrt{2g}\left[h^{\frac{3}{2}} - (h - h_{sv})^{\frac{3}{2}}\right] \qquad \text{é é} \quad (12)$$

$$Q_d = C_d b_v \sqrt{2g}\left[h^{\frac{3}{2}} - (h - h_{sv})^{\frac{3}{2}}\right] - 2C_d KS\sqrt{2gh} \qquad \text{é é é} \quad (13)$$

and Qt can be determined using equation 10 at any given angle of opening.

2.1.3 Pressure Force Equation

When the gate is in closed position, the pressure distribution is hydrostatic but in opened position, it is no longer hydrostatic as it changes with the angle of opening. There are fundamentally two opposing forces, the one(s) pushing the gate to open and the other(s) pushing the gate back to remain in a closed position. The equation of the pressure force is determined based on the assumption that at any given angle of opening the two opposing forces must be in equilibrium.

$$F_1 + P_1 = F_2 + F_x \qquad \text{é é é} \quad (14)$$

Where
F_1 = force due to flow velocity at position 1
P_1 = hydrostatic pressure force at position 1
F_2 = force due to flow velocity at position 2
F_x = component force due to weight of the gate
Thus;

$$\ell Q_1 V_1 + \ell g \frac{h_1^2}{2} b = F_2 + F_x$$

F_2 is the sum of pressure force and force due to flow velocity at the down stream level. However, in reality F_2 doesnôt have any effect on the gate as the activities downstream level is quite below the plank of the gate in this case (Begemann gate) not like the situation with Vlugter gate. Consequently, F_2 is safely neglected.
Hence;

$$F_x = \ell Q_1 V_1 + \ell g \frac{h_1^2}{2} b \qquad \text{é é é} \quad (14b)$$

But;

$$V_1 = \frac{Q_1}{b h_1}$$

And

$$F_v = \frac{F_x}{\cos\delta}$$

Therefore

$$F_v = \frac{\ell}{\cos\delta}\left[\frac{Q_1^2}{bh_1} + \frac{gh_1^2 b}{2}\right] \qquad \text{é é é} \quad (14c)$$

At equilibrium the force(s) responsible for opening the gate is always equated to the force F_v trying to close it.

2.2 Laboratory Evaluation of the Developed Equations

A Laboratory experiment was conducted to evaluate the developed equations of discharges passing through the Begemann gate at the irrigation laboratory of ENSAM, Montpellier, France. A physical model was constructed based on dynamic similarity with a Begemann gate in operation at the irrigation scheme of HVIP, Hadejia, Nigeria, using ratio of Froude number as described by Yalin, (1971). The pysical model was installed in the irrigation canal of ENSAM (see fig.5). A regulator (modules à masques) was installed at the upstream, which supplies the canal with water for a desired discharge up to maximum of 65l/s. The gate angle of opening was measured using potential meter, which translates angle of rotations of the gate into resistance in ohms. Two small plastic canals were installed at the two sides of the gate for measuring the side discharges and thin-crested (calibrated) weir was similarly installed at the downstream level for measuring the total flow rate passing through the canal (gate). The water level at upstream of the gate was measured using meter rule installed at upstream position. Two set of data were measured. The first was water profile for different discharges passing over weir without the gate. Small alloy rods installed in a plastic frame following the pattern of the water trajectory was used to measure the water profile. This data was obtained to evaluate the two water profile equations developed by Davis et al. (1999) and Cavailhé (2001). The second set of data were angles of opening δ, side discharges Q_c, upstream water level h and total discharge Q_t for different flow rates ranging from 10 l/s to 60 l/s at 5 l/s interval. The experiment was repeated three times for statistical analysis.

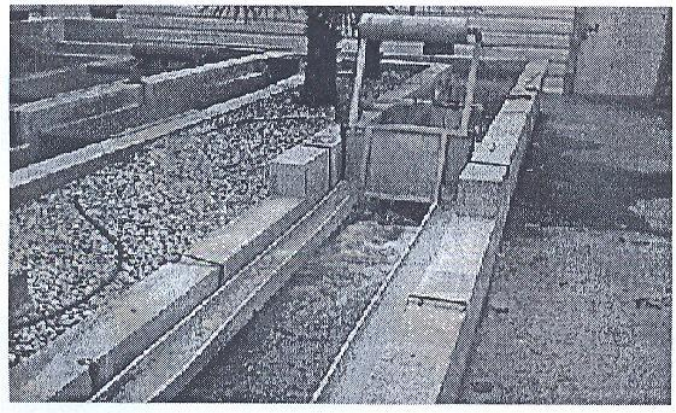


Figure 5 The prototype model installed in Irrigation lab. of ENSAM, Montpellier, France

3. RESULTS AND DISCUSSION

3.1 Comparison of Equations for Water Trajectory Lines

To measure the accuracy of the water profile equations (4) and (5) which describe the type of water profile which has direct relation with equation (1), the measured values were compared with the computed values.

Table 1 presents the water profile depths over the weir. The data is represented in Figure 6 (where the water profile depths were plotted against the horizontal distance from the edge of the weir). The line of trajectory estimated by Cavailhéôs equation was found to under estimate the profile depths when compared with those directly measured, while the Davis equation gave a relatively better estimation with the measured values in comparison with the equation of Cavailhé. This means that the Davis equation is more sensitive in measuring discharge over weir, taking into account the horizontal distance covered by its trajectory, as compared with Cavailhé equation. From Figure 6, the trajectory line from Cavailhé equation would terminate earlier than that of Davis for the same co-ordinate axis. It is to be noted that the value for maximum angle of gate opening depend heavily on the positions of the surface water profile shooting over the weir. Hence it is important to use an equation which gives a better prediction of the water surface profile. Thus, the equation of Davis was found to predict better values of water profile at different angles of opening compared with one given by Cavailhe as shown in table 1. Statistically, the covariance of Davisôs equation (82.27) is lower than that of Cavailhe (163.01). Consequently, the use of Davis equation is recommended for use of the developed model.

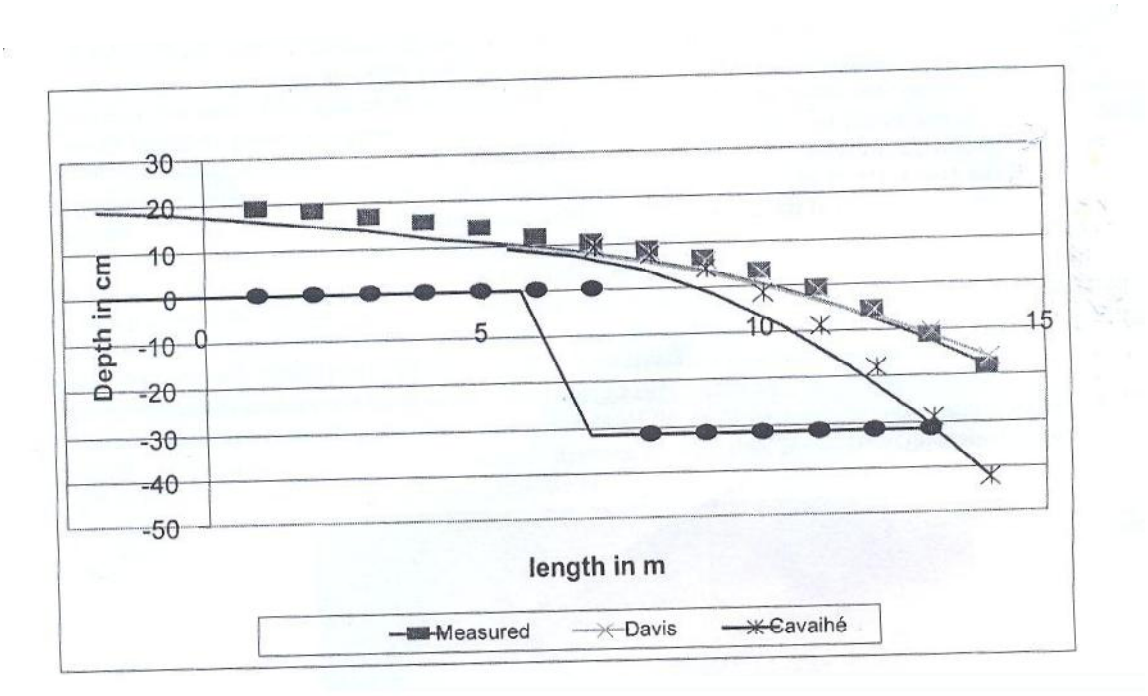


Fig. 6: Surface water profiles for measured and predicted equations of 0.01/sec discharge

Table 1 Water profile depths of measured and predicted values from Davis and Cavailhé equations. The reference point is on top edge of the broad crested weir

Distance From the edge of the weir(cm)	Depth (cm)		
	Measured X	Predicted using Davis Equation Y 1	Predicted using Cavailhé Equation Y2
0	10.20	9.75	9.10
5	8.50	8.08	7.40
10	6.10	5.72	3.83
15	3.20	2.68	-1.61
20	-0.70	-1.04	-8.93
25	-5.50	-5.45	-18.12
30	-11.50	-10.54	-29.18
35	-18.50	-16.32	-42.12
Covariance (X Y1, X Y2)		82.27	163.01

3.2 Sides and Total Discharge Equations

The predicted discharges were graphically compared with the measured sidesô discharges experimentally. Figure (7) shows predicted and measured discharges. It is to be noted that the predicted values reasonably agreed with the measured values at 5% level of significance. The predicted total discharge Q_t passing through the gate (The sum of the discharges passing under the gate Q_d and the two sides of the gate Q_c) and the measured discharge were similarly compared. Table 2 shows the predicted total discharge and the measured discharge, it also shows the discharge under the gate Q_d and sides discharges for the angle of openings used for the experiment. From figure 7, the estimated and measured sidesô discharges were reasonably within same range for the range of angle of opening. The curves for both estimated and measured show similar pattern; that the side discharges were zero at zero angle of opening and continued to increase to an optimal angle of opening therefore continue to decline until it approached zero at the max angle of opening. This pattern describes a normal distribution curve with the optional angle (in this case, figure 7) at 10^o, corresponding to a discharge of 8.4L/S. Table 2, however, presents two values for both predicted using the model and measured discharges which followed similar pattern with R2 value of 0.975. The pattern of these values were found to be different with those estimated for side discharge. They do not describe a normal distribution with the same range of angle of opening as in the case of side discharges. This dissimilarity is attributable to the effect of the discharge directly under the gate (Qa). As described by the relations, the higher the angle of opening the more the total discharge tend to equalize with the direct discharge under the gate ($Q_t \longrightarrow Q_d$) while the side discharges tends to zero value($Q_c \longrightarrow 0$). The optimization of the angle of opening for the gate is applicable to side discharges while a near to linear relation is the dominant feature of the curves for total discharges.

3.3 Optimization Angle of Gate Opening

The data presented in Table 1 and 2 as well as the curves in Figure 7 indicates that the value for the maximum angle of gate opening depend largely on the position of the surface water profile shooting over the weir. Hence, it is important to use an equation which give a better estimation of the water surface profile. Thus, Davisô equation (1999) was found to give higher values of angle of opening compared with one given by Cavailhe. Consequently, the use of Davis equation is recommended for use of the developed model.

Table 2 Predicted and measured discharges

Angle of Opening in Degrees	Total Discharges		Side discharge Qc	discharge Under Qd
	Qt measured l/s	Qt predicted l/s	l/s	l/s
0	0	0	0	0
1,35	15,01	7,41	3,19	4,23
2,84	21,59	15,48	6,59	8,89
4,00	29,61	21,69	9,16	12,53
5,26	34,33	28,26	11,79	16,47
6,47	38,70	33,99	13,73	20,26
8,10	43,31	41,24	15,88	25,36
9,82	48,86	47,91	17,16	30,75
12,99	52,48	56,79	16,13	40,66
15,78	60,08	60,73	11,33	49,40
17,27	61,66	61,53	7,46	54,07
R^2 value 0.975				

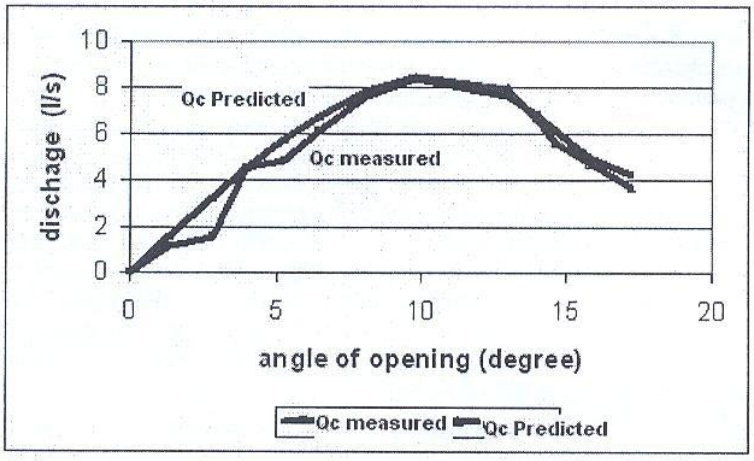


Figure 7 Graph of side discharges predicted and measured

4. CONCLUSION

The hydraulic modeling of Begemann gate for the discharge equation(s) and the pressure force acting on the gate were successfully developed and evaluated for incorporation into a procedure that form a model and the discharge equation which link upstream water level and angle of opening is a significant input in irrigation canal management. Principally, the aim of the Begemann gate is to maintain upstream water surface profile at a constant depth under variable discharges passing through it. In the development of this model the activities at the immediate down stream level of the gate were ignored as these activities practically do not influence the gate functioning. The model can be used in irrigation canal simulation when incorperated with appropriate equations (models) of various hydraulic structures found along irrigation canal network. This is a significant input in simplifying canal management.

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