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Incorporation of rainfall into modelling for optimal water allocation on the Rio Cobre Irrigation Scheme, Jamaica

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Abstract A computer model has been applied to the planning and operation of the Rio Cobre irrigation system to determine optimal water allocation strategies, especially during periods of limited water supply. The model allows for the effect of rainfall by using historical rainfall data at prescribed probability levels to predict rainfall contribution to irrigation over a given planning horizon. The rainfall information together with other operational parameters such as evapotranspiration, crop growth data, water availability and system capacity are used to determine ways of allocation of water so that the value of crop production is optimized. The operation of the scheme was simulated over an entire season to determine optimal water allocation period by period. Each period the actual rainfall and irrigation depth for the previous was used to update the soil moisture content to the beginning of the current period. Historical rainfall data was then used to predict rainfall inputs over the planning horizon which may be from one to five periods. The optimal water allocation for the current period was then determined. For comparison, the runs were repeated with varying levels of predicted rainfall. The results show that considering the effect of rainfall in irrigation scheduling can improve effective rainfall by reducing runoff losses.

Incorporación de las precipitaciónes en modelamiento para optima Proyecto de Irrigación, Jamaica

Resumen Una modelo coputadora ha sido aplicada para el planeamiento y operación del sistema de irrigación en el Rio Cobre para determinar una estrategia óptima de distribucion de agua, especialmente durante periodos de limitado suministro de agua. El modelo tiene en cuenta los efectos de la lluvia usando datos historicos de la lluvia promedio en los niveles prescriptos de probabilidad para predicir la contribución de las precipitaciones sobre un horizonte de planeamiento. La información de las precipitaciones junto con otros parametros operacionales tales como evaporación, datos de crecimiento de las cosechas, disponibilidad de agua y capacidad del sistema son usados para determinar modos de distribución de agua asi como el valor de producción de la cosecha esta optimizado. La operación del proyecto fue simulada durante una temporada completa para determinar la distribución optima de agua, periodo pro periodo. En cada periodo las precipitaciones actuales y profundidad de irrigación para las periodos anteriores fueron usados para poner al día el contenido de humedad del suelo para el comienzo del periodo actual. Los datos historicos de precipitaciones fueron entonces usados para predecir suministros de lluvias sobre el horizonte de planeamiento el cual puede ser de uno a cinco periodos. La optima distribución de agua para el periodo actual fue entonces determinado. Por comparación, las carreras fueron repetidas variando los niveles de predicción de lluvia. Los resultados muestran que, considerar los efectos de la lluvia en los programas de irrigación, puede mejorar la lluvia eficaz por reducir las perdidas de desagues, de este modo reduce la distribución de agua por riego.

INTRODUCTION

Computer models are being increasingly applied to the management of irrigation schemes at the main systems level. The INCA model (Bird & Makin, 1992) facilitates the processing of scheme data with its graphical database interface while the CAMSIS model (Burton, 1992) allows the user to choose from several water allocation policies. The computer model *Irrigation Management and Optimisation System* (IRMOS) was developed (Hales, 1994) to facilitate optimal water allocation in irrigation systems. In 1992 the IRMOS model was applied to the Rio Cobre irrigation scheme, Jamaica to assess the scheme's actual performance and to evaluate simulated performance under various operational conditions. The objectives of this paper are to show how rainfall was incorporated into the IRMOS model and to demonstrate the impact of rainfall prediction on various performance indicators in the scheduling of water allocation on the Rio Cobre scheme (Fig. 1) during the study period.

BACKGROUND

The Rio Cobre scheme

The Rio Cobre Irrigation scheme is located in southern St Catherine, Jamaica and has a command area of 12 000 ha. The water is diverted from the Rio Cobre River into a canal network for distribution to over 400 users growing a variety of crops. Annual rainfall in the irrigated areas averages less than 600 mm, of which 40% falls in the months of September and October. Figure 2 shows actual rainfall during 1992 and average rainfall for the Innswood Station within the Rio Cobre scheme. The average class A Pan evaporation is 1865 mm year^{-1} with a peak of 7 mm day^{-1} in July. The discharge in the river is such that the water that can be diverted into the system is generally inadequate to meet the requirements of the crops during some months of the growing season, even during a wet year.

The scheme grows a variety of crops including sugarcane, pasture, vegetables and freshwater fish. Sugarcane is by far the predominant crop accounting for 67% of the cultivated area. The study period covers the calendar year 1 January-31 December 1992. The diversion structure on the river was breached in May 1991, resulting in its capacity being reduced from 6 to 3 m^3 s^{-1}. Consequently, during the study period, the average crop area irrigated by the scheme was only 4200 ha.

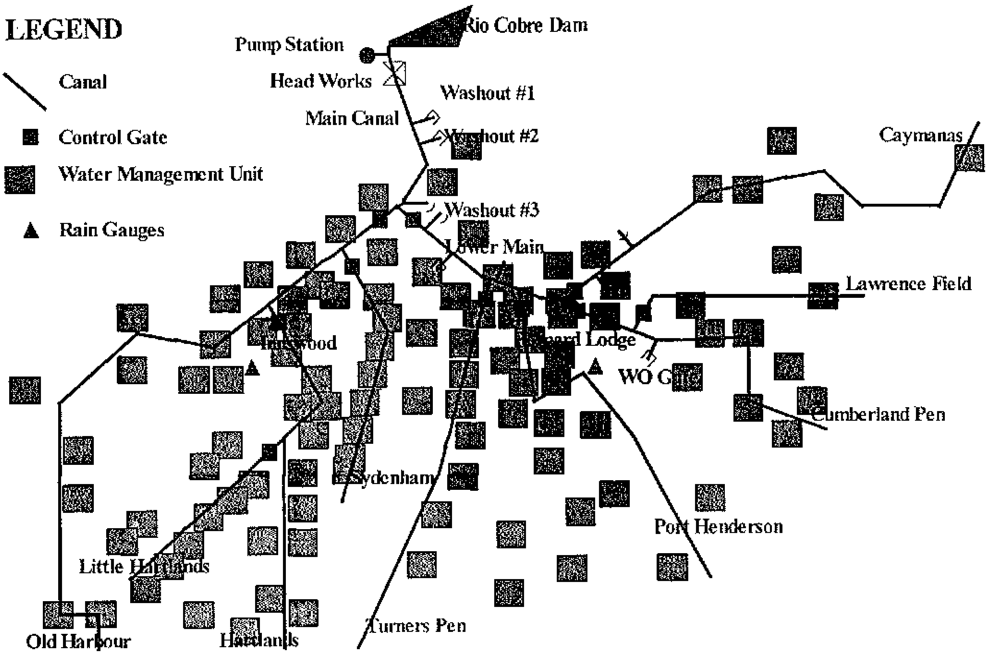

Fig. 1 Schematic layout of the Rio Cobre Irrigation System.

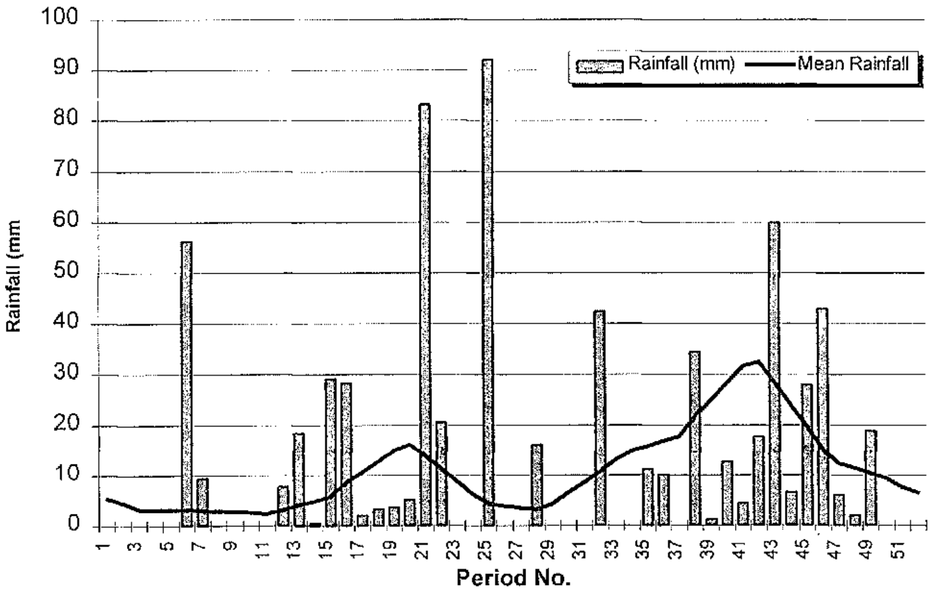

Fig. 2 Rainfall data at Innswood Station in the Rio Cobre scheme.

The IRMOS model

The IRMOS model is a tool for computer-aided management and optimal water allocation in an irrigation system. The model has two main modules, one mainly for data management and the other for water management and scheduling. The model is designed to allow optimal water allocation at the main systems level on schemes with one or more sources of water, several tertiary and quaternary units and complex cropping patterns.

The data management component of the model involves the processing of information that describes the physical characteristics of the scheme, climate history, seasonal information and periodic data. Crop coefficient and root depth for different development stages, yield response information, production costs and unit price are stored in the database for each crop. Seasonal data describe the season, period length, planned cropping pattern, expected water supply and other information required for preseason planning. Periodic data include planting, harvesting, water application, rainfall and evaporation.

A schematic layout of the Rio Cobre scheme (Fig. 1) is typical of a scheme that can be modelled by IRMOS. The scheme typically comprise a main and secondary canal network that supplies water at off-takes to Water Management Units (WMU). Each WMU may contain tertiary canals, farms and fields. For the purpose of the model each WMU contains a number of basic analytical units called a plot. A plot has a unique soil type and cropping pattern, so that at any point in time the plot's crop coefficient, yield sensitivity factor, root depth and status can be determined.

The water management module uses the information in the database to perform the analyses necessary for planning, operating and performance assessment of an irrigation system. During a normal run for planning or operation, IRMOS generally estimates available water supply, determines for each plot the crop water requirement and the expected input from rainfall. It then proceeds to allocate available water according to user selected water allocation policy. Two of the water allocation policies available in IRMOS are performance orientated. One allocates water to minimize crop losses during a period and the other to maximize net benefits over a planning horizon. Performance assessment involves the evaluation of various performance indicators derived from data on the actual history of the scheme over a specified number of consecutive operational periods. It also allows hindsight analyses by enabling the user to assess how the scheme would have performed if it were operated differently, e.g. if rainfall probability or water allocation policy were different.

Performance indicators

The following are the definitions of some of the performance indicators that allows IRMOS to track the performance of an irrigation scheme:

Unsatisfied Demand Ratio (UDR) The UDR is defined for any instance when the water allocated is less than demand as the ratio of the shortfall to the demand. If there is more than one instance of water deficit then the UDR is computed as the ratio of the sum of all deficits to the sum of all demands.

Over-Supply Ratio (OSR) The OSR is defined for any instance when the volume of water allocated is higher than demand as the ratio of the volume allocated in excess of the demand to the total volume supplied. If there is more than one instance of water deficit then OSR is computed as the ratio of the sum of all excess allocations to the sum of all allocations.

Relative evapotranspiration The relative evapotranspiration of a crop is the ratio of actual evapotranspiration to potential evapotranspiration for a prescribed period. A relative evapotranspiration of unity indicates that the crop evaporated at its potential rate throughout the period.

Relative yield The relative yield of a crop is the ratio of actual yield to the maximum yield expected under the growing conditions. Doorenbos & Kassam (1979) proposed the following linear relationship between relative yield and relative evapotranspiration for a given growth period:

$$Yr = 1 - Ky(1 - Er) \tag{1}$$

where Yr is the relative yield, Ky is yield sensitivity index for the growth period, and Er is the relative evapotranspiration.

Specific yield The specific yield is here defined as the crop production per unit volume of water. In the IRMOS model the specific yield for a water management unit is computed as the sum of the values of all crops harvested within the unit per million cubic metres of water allocated to the unit.

Relative profitability The relative profitability is the ratio of net value of crop harvested within a season to the potential net value obtainable at maximum yield.

Effective rainfall ratio The effective rainfall ratio is the fraction of total rainfall that contributes to crop evapotranspiration.

INCORPORATING RAINFALL INTO IRMOS

Rainfall data are used in the modelling process in estimating crop irrigation demand and to compute actual crop evapotranspiration. In either case the rainfall and evaporation data must be stored in the database prior to running the water management module. The historical rainfall data are analysed to determine the periodic rainfall depths at various probability levels (Sooriyarachi & Lea, 1990) and stored in that form. The model estimates the irrigation demand using historical data when planning the water allocation for a given period. This occurs in both the pre-season planning and the in-season operational modes. The model computes the actual evapotranspiration in the process of updating the soil moisture content using actual data over the previous period.

Estimating irrigation demand

The water requirement of an individual crop is estimated by applying the procedures outlined by Doorenbos & Pruitt (1977). The irrigation demand at an off-take for a given period is the minimum amount of water that the scheme must allocate to ensure that all crops within the unit commanded by the offtake evapotranspire at their potential rate. In computing the irrigation demand for a period the expected rainfall depth is determined from historical rainfall data based on the dependable rainfall probability. The rainfall probability is chosen by the user depending on whether wet, dry or average conditions are expected during the period. The effective rainfall is then computed and applied to the crop's root zone. Any part of the crop water requirement not met by the expected effective rainfall is the irrigation demand.

Computing actual evapotranspiration

The actual evapotranspiration rate (*Eta*) measured in mm day^{-1} is estimated by modelling the water balance within the root zone of the crop. The root zone is considered as a reservoir to which water is added through irrigation or rainfall and removed by evaporation or percolation (Rao, 1987). The actual evapotranspiration rate is equal to the potential evapotranspiration rate (*ETm*) when the soil water content is above the readily available water (*RAW*) level, otherwise stress occurs and the relative evapotranspiration rate is proportional to the moisture content of the root zone.

The soil moisture balance model in IRMOS determines the soil moisture content in the root zone of a crop at the end of a period, given the soil moisture content at the start of the period, the effective rainfall and irrigation depth. The depth of water (mm) in the root zone of a crop at the end of a given period is determined generally from:

$$W_e = W_0 Dr + I + G + Re - AET - L \qquad (2)$$

where W_0 is the moisture content of the root zone (mm m^{-1}) at the start of the period, and Dr is the rooting depth (m). The symbols I, G, Re and AET are applied irrigation depth, ground water contribution, effective rainfall and actual evapotranspiration (mm), respectively, and L is the depth of water (mm) lost to runoff or percolation.

The application of the above equation in the IRMOS model is illustrated in a flow chart as presented in Fig. 3. The model allows for a daily or periodic update of the soil water content, depending on available data and level of precision required. At each update the irrigation depth and actual effective rainfall, are applied to the crop's root zone. If the total depth of water exceeds the water holding capacity of the soil then runoff or percolation losses occur and the effective rainfall is further reduced. If none of the rainfall is effective, then some of the irrigation water is lost and the irrigation efficiency is further reduced.

Application to the Rio Cobre scheme

The model was applied to the Rio Cobre scheme to assess its performance during the 1992 calendar year under different levels of predicted rainfall. At the start of the first

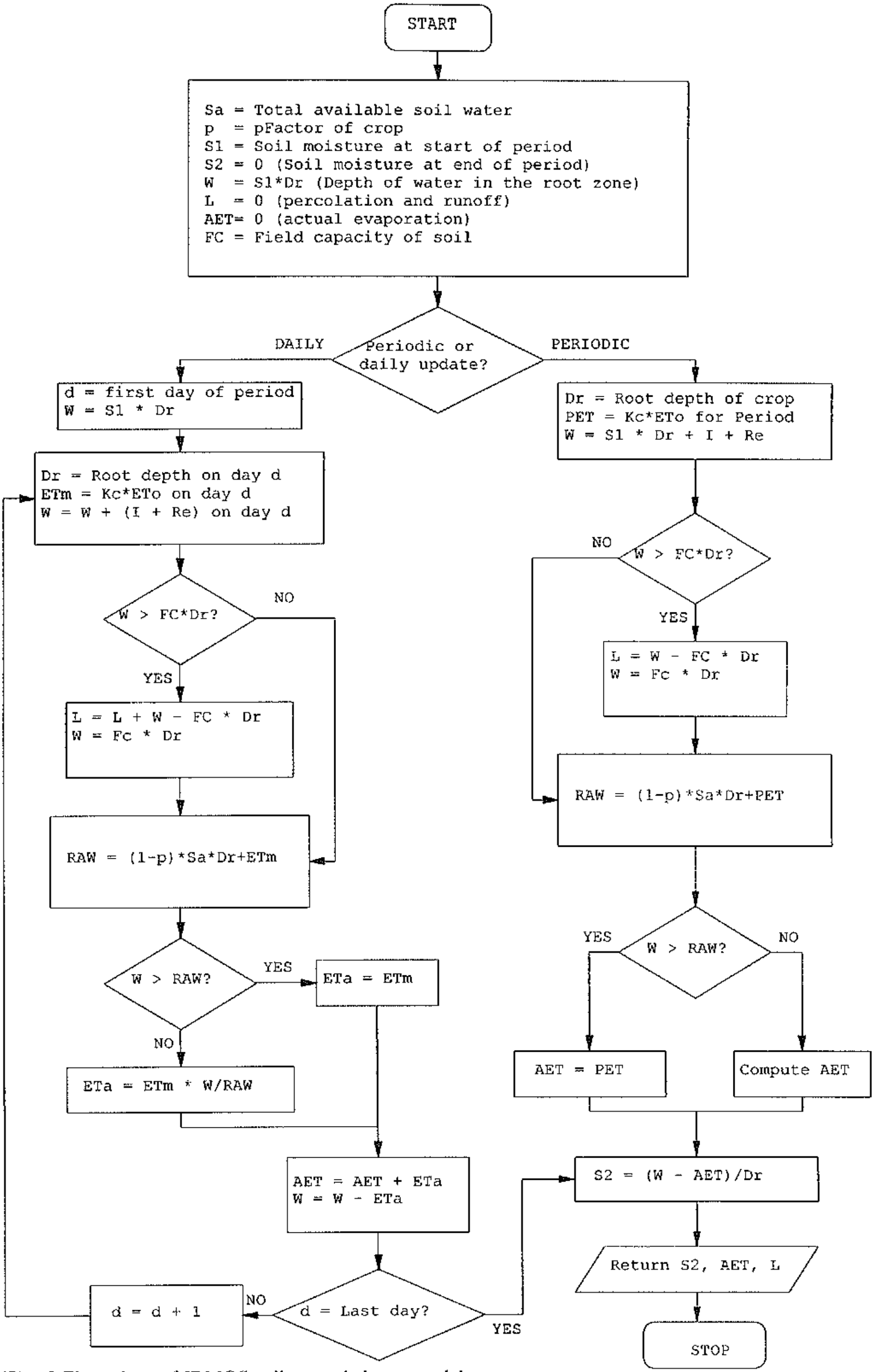

Fig. 3 Flow chart of IRMOS soil water balance model.

period, the soil moisture content, the crop development stage and the crop condition of each plot in the scheme were initialized in the model.

For each period, the irrigation demand was estimated using average evapotranspiration and expected rainfall for five periods beginning with the current period. The water allocation for the current period was then determined using the optimization component of the model to allocate the water over the five-period planning horizon to maximize crop production scheme-wide. At the end of the period, the modelled irrigation depths, actual effective rainfall and measured evaporation are used to update the soil moisture content, following the procedure charted in Fig. 3. The process is repeated for all periods in the season.

In the process of updating the soil moisture content, the model also updates the irrigation efficiency, the effective rainfall and the plot status. The model keeps track of performance indicators such as effective rainfall, actual evaporation and crop production.

IRMOS was run using different levels of predicted rainfall to estimate the water requirement. The probability of not exceeding the predicted rainfall depths varied from 20% to 80%. In addition there was one run in which rainfall was ignored.

RESULTS AND DISCUSSION

Table 1 lists the values of performance indicators for various levels of expected rainfall. During the study period the actual effective rainfall was higher than average and rainfall played a significant role in meeting the water requirement of the scheme's crops. The results show that when rainfall is not considered in scheduling water allocation then more water is allocated, resulting in more rainfall being lost to runoff and percolation. However, the effect is not dramatic, as in most periods there is a deficiency in water supply. When there is a deficiency in water supply, the allocated water is incapable of meeting the irrigation needs of some crops in the scheme, resulting in more effective use of rainfall. In addition the results are composite for 52 periods and over 200 off-takes, so an over-supply of water to one offtake may be offset by an under-supply to another.

As a higher level of rainfall was anticipated, the volume of water allocated was reduced, ranging from 54.08 million cubic metres ($\times 10^9 m^3$) for no rainfall to 50.44 $\times 10^9$ m^3 for 80% probability of non-exceedance. The effect on the relative evapotranspiration is that it remains at 93% up to the 30% rainfall level then reduces to 89% for the 80% rainfall level. This result directly affects relative yield and hence relative profitability which shows a similar trend. The specific yield, however, improves as higher levels of rainfall are anticipated. This is consistent with the result that the effective rainfall ratio increases with the level of expected rainfall.

The scheme-wide irrigation efficiency shows little change for the various levels of expected rainfall. This is due in part to the optimizing nature of the model which does not allow more water than required to be allocated. In addition, when the model updates the soil moisture content at the end of each period it assumes that irrigation water is applied before rainfall and that rainwater contributes to losses before

Table 1 Performance of Rio Cobre scheme at different rainfall probability levels.

Performance indicators	Rainfall (probability of non-exceedance):				
	No rain	20%	30%	50%	80%
PET demand at off-takes ($\times 10^9 m^3$)	92.05	92.05	92.05	92.05	92.08
Total volume allocated ($\times 10^9 m^3$)	54.08	53.66	53.36	52.42	50.44
Expected effective rainfall ($\times 10^9 m^3$)	0	4.44	7.21	14.70	25.90
Actual effective rainfall ($\times 10^9 m^3$)	17.31	17.38	17.45	17.56	17.70
Relative water supply	0.78	0.77	0.77	0.76	0.74
Over-supply ratio	0	0	0	0	0
Unsatisfied demand ratio	0.40	0.39	0.39	0.38	0.37
Relative evapotranspiration(ETa/Etm)	0.93	0.93	0.93	0.92	0.89
Total crop yield losses (US$)	621 476	654 899	682 250	809 231	1 114 239
Gross crop value at maximum yield (US$)	13 371 980	13 371 980	13 371 980	13 371 980	13 371 980
Pre-harvest cost of crops (US$)	4 349 065	4 349 065	4 349 065	4 349 065	4 349 065
Net crop value at maximum yield (US$)	9 022 916	9 022 916	9 022 916	9 022 916	9 022 916
Potential net value at present yield (US$)	8 401 440	8 368 017	8 340 666	8 213 686	7 908 678
Relative yield (gross)	0.95	0.95	0.95	0.94	0.92
Relative profitability	0.93	0.93	0.92	0.91	0.88
Specific yield (US$/$10^9 m^3$)	195 411	196 444	197 102	198 659	201 526
Conveyance efficiency (%)	82.88	82.89	82.88	82.89	82.93
Irrigation efficiency (%)	50.44	50.51	50.56	50.47	49.99
Effective rainfall:total rainfall ratio	0.70	0.70	0.71	0.71	0.72

irrigation water. It is noticeable, however, that the irrigation efficiency is highest at the 30% rainfall probability level.

CONCLUSIONS

Allowing for rainfall in irrigation scheduling at the main systems level is not easy and the benefits to be derived therefrom are not readily apparent. The IRMOS model makes it easier to evaluate the effects of allowing for expected rainfall in irrigation scheduling by allowing the user to incorporate rainfall at various probability levels under varying conditions of soil moisture content and available water supply. To derive the full benefits of the modelling process, however, some resources have to be invested to ensure that personnel and processes are in place to implement the required actions.

The level of expected rainfall in irrigation scheduling does have an impact on the performance of the Rio Cobre irrigation scheme. If the water supply is limited it is possible to ignore rainfall without adversely affecting scheme performance. Anticipating rainfall at the 30% probability level, as is often practised by scheme managers, gives good results in irrigation scheduling and is recommended for the Rio Cobre scheme.

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