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THE RELATIONSHIPS BETWEEN GRAIN YIELD OF SPRING WHEAT AND RAINFALL DISTRIBUTION IN WESTERN AUSTRALIA USING REGRESSION MODELS

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ABSTRACT

Linear regression models were used to relate long term grain yield of spring wheat cv. Gamenya and rainfall at eight sites in the wheatbelt of Western Australia. Periodic and monthly models, using stepwise linear regression described the grain yield of wheat better than simple regression equations using total crop seasonal or annual rainfall. The monthly model had the greatest R^2, particularly at low rainfall sites and was the best predictor of grain yield.

Fallow rains (October to March of preceding cropping) contributed to grain yield at Merredin, Salmon Gums and Wongan Hills. These positive effects may be due to more soil moisture storage at sowing time and better seed bed preparation. The autumn (April-May) rainfall was positively correlated with yield only at low rainfall sites. Winter (June-August) rainfall had positive effects on grain yield at sites with

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seasonal (May-October) rainfall less than 400 mm which may be attributed to better early crop growth. The main benefits of winter rains were gained from June and/or July rainfall at Merredin, Salmon Gums, Wongan Hills and Chapman. However, June rainfall at Newdegate and both July and August rainfall at Badgingarra had negative effects on grain yield which may be attributed to waterlogging at Newdegate and probably to greater incidence of foliar diseases at Badgingarra. The high and reliable winter rainfall at Esperance and Mount Barker appeared to make wheat grain yield independent of winter rain.

Grain yield was also positively correlated with spring (September-October) rainfall at low and medium rainfall sites. The contribution of spring rains to grain yield was mainly from September, i.e. when the plants were at anthesis. The November rainfall was negatively correlated with grain yield at Salmon Gums, Esperance and Mount Barker which may be due to losses associated with harvesting under wet conditions. Comparison of actual and predicted yield using monthly models at the two drier sites (Merredin and Salmon Gums) for five randomly selected years showed good agreement.

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روابط بین عملکرد دانه گندم بهاره و توزیع بارش در استرالیای غربی با استفاده از مدلهای رگرسیون

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به ترتیب دانشیار دانشکده کشاورزی دانشگاه صنعتی اصفهان، ایران و پژوهشگر بخش کشاورزی استرالیای غربی.

<u>چکیده</u>

در مدلهای رگرسیون که در ۸ ایستگاه تحقیقاتی واقع در کمربند گندم استرالیای غربی برای تعیین همبستگی بین عملکرد دانه گندم بهاره رقم "گمنیا" و بارش بدست آمد، مدلهای دوره‌ای و ماهانه نسبت به مدلهای سالانه و فصلی مناسبتر تشخیص داده شدند. مدلهای ماهانه با ضریب تشخیص (R^2) بالاتر در مناطق کم‌بارش به عنوان بهترین مدل در تخمین عملکرد گندم بهاره تعیین گردیدند.

بارشهای قبل از کشت یعنی اکتبر تا مارس در ایستگاه‌های مریدین، سالمون گامز و وانگن‌هیلز در عملکرد دانه مؤثر بود. اثرات مثبت بارشهای قبل از کاشت را می‌توان در رابطه با ذخیره رطوبت بیشتر در خاک و نیز تسهیل عملیات آماده‌سازی زمین نسبت داد. بارشهای پاییزه یعنی بارشهای آوریل و مه فقط در ایستگاه‌های کم بارش باعث افزایش عملکرد دانه گندم گردید، در صورتیکه بارشهای زمستانه ماه‌های ژوئن و ژوئیه در ایستگاه‌هایی بر عملکرد دانه موثر بودند که میزان بارش فصلی یعنی مه تا اکتبر آنها کمتر از ۴۰۰ میلیمتر بود. اثرات مثبت بارش زمستانه در چنین مناطقی را می‌توان به رشد بهتر در مراحل اولیه نمو مرتبط دانست. تاثیر مثبت بارش‌های زمستانه در ایستگاه‌های مریدین، سالمون گامز، وانگن‌هیلز و چیمن مربوط به ماههای ژوئن و یا ژوئیه بود. در هر صورت، بارش در ماه ژوئن در ایستگاه نیود گیت و در ماه ژوئیه و اوت در بجین گارا اثرات منفی بر عملکرد دانه را باعث شد. اثرات منفی بر عملکرد دانه شاید بستگی به اثرات ماندابی خاک در نیود گیت و شیوع بیماری‌ها در بجین گارا داشته باشد. بارش زیاد و قابل اعتماد زمستانه در ایستگاه‌های اسپرنس و مانت‌بارکر باعث عدم همبستگی بارش با عملکرد دانه شده است.

عملکرد دانه گندم در مناطق کم بارش کمربند گندم استرالیای غربی با بارش بهاره یعنی بارندگی ماههای سپتامبر و اکتبر که مرحله گرده‌افشانی گندم بر این زمان منطبق است همبستگی مثبتی را نشان داد. بارش ماه نوامبر در ایستگاه‌های سالمون گامز، اسپرنس و مانت بارکر با عملکرد دانه همبستگی منفی داشت. اثرات منفی بارش ماه نوامبر در این مناطق ممکن است در اثر اتلاف دانه در شرایط مرطوب زمان برداشت باشد. مقایسه عملکرد واقعی و تخمینی دانه در ایستگاه‌های کم‌بارش مریدین و سالمون گامز بیان کننده این واقعیت است که مدلهای ماهانه در این مناطق می‌توانند بخوبی در تخمین عملکرد دانه کاربرد داشته باشند.

INTRODUCTION

In Australia most wheat production is confined to areas bounded by the 300 and 650 mm rainfall isohyets. Wheat grain yield varies considerably and depends upon the amount and distribution of rainfall received in any season. Nix and Fitzpatrick (11) reported simple correlation coefficient of 0.38 between grain yield and total rainfall from sowing to heading for the cv. Gabo grown in Queensland. Relationships between rainfall and grain yield is often improved by considering specific periods within the growing season. In South Australia, Cornish (3) reported that winter rainfall (June–August) was a more important determinant of grain yield than was either autumn (April–May) or spring (September–October) rainfall. Seif and Pederson (14) in the central part of New South Wales showed a significant correlation (r=0.86) of wheat yield with spring rainfall, i.e. from three weeks before to two weeks after anthesis. In Western Australia, Gentilli (6) reported negative correlation between winter rainfall and grain yield for the higher-rainfall western shires, and a positive correlation between spring rainfall and yields for the lower-rainfall eastern shires. French and Shultz (4, 5) found that factors other than rainfall also contributed to grain yield.

Pre-growing season rainfall has also been found to contribute to grain yield. In the arid Negev region of Israel Lomas and Shashoua (10) reported that additional rainfall above the average prior to sowing or during the period of germination was beneficial for initial growth of the crop, while above average rainfall during mid-winter and at the end of the growing season affected the crop adversely. Lehane and Staple (9) in south-western Saskatchewan showed that multiple regression gave better estimates of yield than did simple linear equations using total seasonal rainfall only. They concluded that rainfall received during June and July (early boot to anthesis stage) and available moisture stored below 30 cm depth significantly contributed to grain yield.

The aims of this study were to examine relationships between rainfall and wheat yield in the wheat belt of Western Australia and to compare simple linear regression equations using annual (January–December) and seasonal (May–October) rainfall with stepwise linear regression models using periodic and monthly rainfall.

MATERIALS AND METHODS

Grain Yield Trials

The long term grain yield data of spring wheat cv. Gamenya were obtained from Western Australian Department of Agriculture (WADA)

Crop Variety Trials (CVTs) 1961-1989 (G. Brown and R. Hunter, personal communication, 1990). Gamenya was chosen since this was the most widely grown wheat cultivar in Western Australia between 1960-1980. Although Gamenya has been replaced by other high yielding cultivars, it is still included in CVTs as historical check. The grain yield data from CVTs at eight WADA research stations (Fig. 1 and Table 1) covering the major wheat growing areas were examined. Although the crop management practices (sowing date, cultivation, fertilizers, weed control, etc.) have changed over the years, the CVTs followed the approximate recommended cultural and management practices for each site and year. There was no trend at any specific site between grain yield of Gamenya and recent advances in agronomic package. The main reasons for this may be that response of Gamenya to recent advances in agronomic practices are less than that of modern high yielding semi-dwarf wheat cultivars (1, 2) and also majority of CVTs (pre-1980s) were late sown (Table 3).

The number of years of experiment for CVTs were between 19 and 28 and the number of trials used in this study ranged from 76 to 103 depending on the research station (Table 2). The long term average grain yield of Gamenya at the eight research stations ranged from 1368 kg ha^{-1} at Salmon Gums to 2590 kg ha^{-1} at Wongan Hills (Table 2). Although the date of sowing differed from the first half of May to the second half of July, it was mainly in the first half of June at Newdegate, Badgingarra and Mount Barker and in the second half of June at Merredin, Wongan Hills and Chapman. The dates of sowing at Salmon Gums were mainly in the second half of May and at Esperance they were almost uniformly distributed between the beginning of June and the second half of July (Table 3).

Monthly rainfall data (1960-1989) were obtained from the Bureau of Meteorology, Western Australia. There were a few missing rainfall records which were estimated with long term average values.

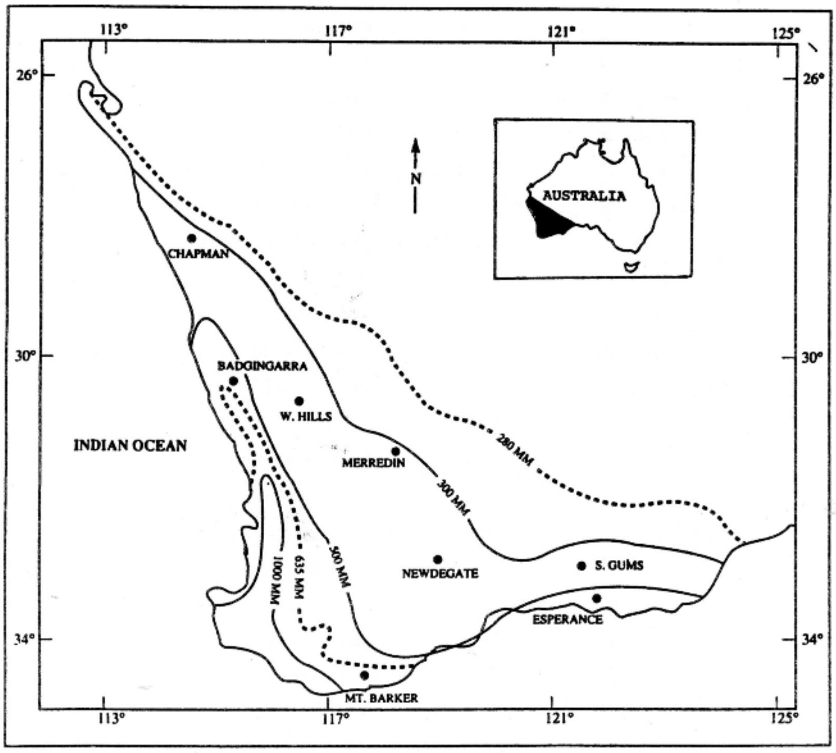

Fig. 1. Map of south western Australia, showing the annual rainfall isohyets and the eight research stations.

Table 1. The latitude, longitude and elevation of the eight research stations in western Australia and the soil types on which crop variety trials were undertaken.

Soil type†	Classification§	Research station	Latitude (S)	Longitude (E)	Elevation (m)
Sandy loam (heavy soil, red brown earth)	Dr 2.33	Merredin¶	31°29′	118°17′	315
Duplex soil (sand over clay)	Dy 5.33				
Yellow duplex (Circle valley sand)	Dy 5.43	Salmon Gums	32°59′	121°39′	250
Gravel duplex (sandy gravel)	St 5.41	Newdegate	33°06′	119°01′	250
Wongan Hills loamy sand (Wongan loam)	Uc 5.22	Wongan Hills	30°54′	116°43′	282
Duplex soil (red loam)	Dy 4.52	Chapman	28°28′	114°47′	293
Duplex soil (sand over gravel)	Dy 5.81	Badgingarra	30°24′	115°30′	258
Gravelly sand (Sandplain)	Dy 5.82	Esperance	33°20′	121°54′	25
Sand over ironstone gravel (Bangalup sand)	Dy 5.63	Mount Barker	34°38′	117°39′	280

† Local term of the soil shown in parentheses.

§ Northcote, 1979.

¶ Stations were arranged from low to high rainfall areas.

Table 2. Years of experiments, number of years and trials and the average grain yield of cv. Gamenya at eight research stations in western Australia.

Research station	Year of experiments	No. of years	No. of trials	Grain yield (kg ha^{-1})
Merredin	1961-89	28	103	1466
Salmon Gums	1961-87	25	95	1368
Newdegate	1961-89	25	90	1611
Wongan Hills	1961-89	28	98	2590
Chapman	1961-89	26	91	2229
Badgingarra	1961-89	25	91	1584
Esperance	1961-87	22	76	2373
Mount Barker	1968-86	19	86	2469

Table 3. Percentage of trials sown during the first half (1) and second half (2) of May, June and July at various research stations.

Research station	May		June		July	
	1	2	1	2	1	2
Merredin	1	21	27	37	13	1
Salmon Gums	-	54	22	5	16	3
Newdegate	3	2	46	25	24	-
Wongan Hills	2	12	29	54	3	-
Chapman	2	9	28	51	10	-
Badgingarra	3	7	58	30	2	-
Esperance	3	10	24	22	22	19
Mount Barker	6	27	43	24	-	-

Soil Types

There were considerable differences in soil type used for the CVTs between and within research stations. General description of the soil types on which the yield trials were conducted at each station are given in Table 1. At the majority of the sites, CVTs were conducted on Duplex soils, except at Merredin where sandy loams and Duplex soils were used, and at Wongan Hills where the soil was a deep Wongan loamy sand. At Merredin, no attempt was made to separate the effect of these soil types on grain yield, because the number of years of experiments on each soil type was less than 15.

Techniques

From a background of previous studies (3, 7, 9, 11, 14), four grain yield-rainfall models were defined:

1. Annual, simple linear regression between grain yield and rainfall from January to December.
2. Seasonal, simple linear regression between grain yield and rainfall from May to October.
3. Periodic, forward stepwise linear regression between grain yield and four rainfall periods as follows:

   F - fallow rain, rainfall from October to March preceding cropping;

   A - autumn rain, rainfall from April to May;

   W - winter rain, rainfall from June to August;

   S - spring rain, rainfall from September to October.
4. Monthly, forward stepwise linear regression between grain yield and monthly rainfall from October preceding cropping to November in the cropping year. In this model, R01, R02 and R03 are October, November and December rainfall preceding cropping, respectively; R1

to R11 are monthly rainfall from January to November in the year of cropping. For statistical analysis of simple and stepwise linear regression, a statistical graphic system (15) was used.

RESULTS

Rainfall Distribution

The long term (1960-1989) average of annual rainfall at the eight research stations ranged from 322.9 mm for Merredin to 737.9 mm for Mount Barker (Table 4). In general, the percentages of spring, summer, autumn and winter rainfall were 14.9, 12.3, 36.1 and 36.6 of the annual rainfall, respectively. The percentages of spring and summer rainfall were lower at Chapman and Badgingarra and higher at Salmon Gums compared to other research stations. June had the greatest percentage of rainfall at all sites except Esperance and Mount Barker which had the highest in July. The lowest percentage of rainfall was in December or January.

The coefficients of variation (CV) for annual rainfall were between 11.4 and 26.1%, and for seasonal rainfall (May-October) between 11.2 to 19.9% (Table 4). According to Leeper (8) the reliability of rainfall in south western Australia is the highest in Australia, and greater than the world normal for the annual amount received. The CV for monthly rainfall fluctuated from 19.6 to 336.7% depending on the month of the year, and the research station. Winter (June-August), had a low CV, with the lowest in August, while summer months such as December, January, February and March had the highest CV (Table 4). In general, CV decreased with increasing rainfall and at Chapman the CV was higher from November to March compared to other research stations (Table 4).

Table 4. The long term (1960-89) average of monthly, growing season (May-October) and yearly rainfall and coefficient of variation (CV%) for different research stations.

Month	Research stations: Merredin	Salmon Gums	Newdegate	Wongan Hills	Chapman	Badgingarra	Esperance	Mount Barker
Jan. mm	15.3	18.5	21.1	13.2	7.3	7.4	20.0	28.2
(CV)	135.5	111.2	98.1	157.1	285.3	156.9	93.5	73.5
Feb. mm	18.0	19.8	21.6	20.3	16.1	17.4	23.8	24.6
(CV)	143.2	116.0	119.1	127.0	159.5	132.7	93.3	104.5
Mar. mm	17.1	20.6	17.6	17.0	11.9	18.6	28.5	33.8
(CV)	156.8	100.5	152.9	158.0	225.1	138.8	93.9	79.5
Apr. mm	22.2	28.7	28.6	28.0	27.1	31.2	49.8	56.5
(CV)	86.3	75.1	67.0	68.5	70.8	71.0	76.6	34.0
May mm	44.4	42.6	45.1	52.5	73.1	82.9	79.9	83.1
(CV)	75.7	73.7	74.6	64.0	46.0	51.3	52.8	40.4
June mm	53.9	45.3	57.3	73.2	103.1	119.4	83.4	92.5
(CV)	51.4	53.2	48.4	37.9	26.9	46.1	36.7	30.0
July mm	47.4	39.5	51.8	67.3	86.7	108.1	113.2	110.6
(CV)	53.9	46.7	49.3	37.9	26.4	39.8	35.2	23.1
Aug. mm	36.2	35.4	43.3	48.3	58.9	87.9	95.5	86.2
(CV)	46.7	42.6	39.0	35.0	28.7	35.3	35.8	19.6
Sep. mm	24.7	30.0	30.8	28.3	33.6	47.2	58.6	75.1
(CV)	69.2	63.3	55.4	60.4	50.9	52.0	43.9	22.7
Oct. mm	15.4	23.2	25.7	21.0	21.2	33.1	47.6	71.0
(CV)	73.6	71.7	44.1	53.9	53.3	50.9	49.0	15.9
Nov. mm	15.9	27.0	19.2	12.6	11.4	19.2	33.9	47.4
(CV)	102.2	93.9	84.9	129.2	142.4	116.4	62.6	34.4
Dec. mm	12.4	18.5	16.1	9.5	4.8	8.7	16.7	28.7
(CV)	129.8	84.9	99.9	168.4	336.7	115.8	64.8	55.0
May-Oct. mm	222.0	215.9	254.0	290.6	376.6	478.5	478.2	518.7
(CV)	26.3	23.9	23.0	20.1	15.5	19.9	18.3	11.2
Year mm	322.9	349.1	378.2	391.2	455.2	581.0	650.9	737.9
(CV)	26.1	19.0	22.3	21.6	18.5	16.8	17.0	11.4

Grain Yield-Rainfall Models

Annual. The grain yield and annual (January-December) rainfall were significantly correlated at all sites ($p < 0.01$) except Newdegate and Esperance and these correlations were positive at all sites except Badgingarra and Mount Barker (Table 5). The coefficients of determination (R^2) show that annual rainfall accounted for 45% of grain yield variation at Merredin (Table 5) and 40% of the yield variation at Salmon Gums. At Esperance and Newdegate annual rainfall accounted for very little of the yield variation.

Table 5. Coefficients of linear regression (a and b) determination (R^2) of wheat grain yield and rainfall with annual (January-December) and seasonal (May-October) models.

Research station	Annual			Seasonal		
	a	b	R^2 (%)	a	b	R^2 (%)
Merredin	-489	5.9	45**	-281	7.8	34**
Salmon Gums	-1436	8.1	40**	-778	10.1	38**
Newdegate	1916	-1.1	4 NS	1297	0.8	1 NS
Wongan Hills	1018	3.8	18**	1493	3.5	12**
Chapman	1237	2.1	8**	1217	2.6	11**
Badgingarra	36.11	-3.5	18**	3589	-4.2	23**
Esperance	1002	0.4	0 NS	1389	1.9	0 NS
Mount Barker	5131	-3.7	18**	2630	-0.3	0 NS

** P < 0.01.

NS Non-significant.

Seasonal. The correlation coefficients between grain yield and crop growing seasonal rainfall (May–October) were similar to the annual model with a lower R^2 at Merredin, Salmon Gums and Wongan Hills; higher R^2 at Badgingarra, and no significant effect at Mount Barker. The maximum R^2 in this model was 38% for Salmon Gums (Table 5).

Periodic. Forward stepwise regression was used to select the periods of rainfall most closely associated with grain yield. In this model, only significant variables ($p < 0.05$) were retained in the regression equations. The coefficients of determination (R^2) of this model were greater than the annual or seasonal models (Tables 5 and 6). In general, the R^2 value was higher at low rainfall sites. At these sites periodic rainfall accounted for variation in grain yield up to 62% at Merredin, which is 17 and 24% greater than the maximum R^2 for annual and seasonal models, respectively (Tables 5 and 6). However, at Esperance there was no significant relationship between grain yield and periodic rainfall (Table 6).

The main positive contribution of periodic rainfall to grain yield came from fallow rainfall (October to March of preceding cropping) at Merredin, Salmon Gums and Wongan Hills (Table 7). The effect of rainfall in the same period was negative at Mount Barker which had the highest annual rainfall among the research stations. The fallow rain did not contribute to grain yield at Newdegate, Chapman, Badgingarra and Esperance. The autumn (April–May) rainfall increased the wheat grain yield at only Merredin and Salmon Gums which had the lowest rainfalls among the sites (Table 7). The winter (June–August) rain was positively associated with grain yield at Merredin, Salmon Gums, Wongan Hills and Chapman. However, the rainfall for the same period had negative effects at Newdegate and Badgingarra. The spring (September–October) rainfall contributed to grain yield at Merredin, Salmon Gums, Newdegate, Wongan Hills and Chapman (Table 7). However, the effect of spring rainfall on grain yield was negative at Mount Barker and there were no significant effects at Badgingarra and Esperance (Table 7).

Table 6. The effects of rainfall distribution on wheat grain yield, using periodic (P) and monthly (M) models.

Research station	Equations[+,X]	n	R^2(%)
Merredin	(P) Y= -535.1+2.4 F+11.1 A+5.7 W+6.0 S	81	62**
	(M) Y= -381.0+7.5 RO3+6.6 R3+14.6 R4+10.1 R5+3.6 R6+11.6 R7+6.0 R9	81	72**
Salmon Gums	(P) Y= -2178.8+8.6 F+11.7 A+9.3 W+10.2 S	75	57**
	(M) Y= -677.3+16.4 R01+17.9 R03+19.6 R3+26.8 R7+7.1 R9-8.1 R11	75	74**
Newdegate	(P) Y 1328.2-3.0 W+10.7 S	90	27**
	(M) Y= 1297.2+5.9 R03-3.9 R3-8.1 R6+13.4 R9+6.9 R10	90	47**
Wongan Hills	(P) Y= 596.4+6.4 F+5.2 W+6.9 S	98	24**
	(M) Y= 426.9+19.8 R01+7.4 R2+10.5 R3+4.8 R5+10.0 R6+11.6 R9	98	46**
Chapman	(P) Y= 1205.5+2.4 W+9.0 S	91	19**
	(M) Y= 1026.4+17.2 R02-20.1 R1+8.3 R7+12.3 R9	91	29**
Badgingarra	(P) Y= 3083.5-4.9 W	91	24**
	(M) Y= 2700.8+13.9 R01-13.6 R1-10.3 R7-8.8 R8+10.7 R10	91	41**
Esperance	(P) Y= 2242.6	76	0[NS]
	(M) Y= 3159.8-4.4 R8+8.7 R9-28.0 R11	76	39**
Mount Barker	(P) Y= 4373.4-5.1 F-4.9 S	86	18**
	(M) Y= 3398.4-10.1 R3-11.8 R11	86	30**

(Table 6 continued:)

+	Y = estimated grain yield (kg ha^{-1}).
F	Fallow (October of year preceding cropping to March rainfall (mm).
W	Winter (June to August) rainfall (mm).
S	Spring (September to October) rainfall (mm).

R01, R02 and R03 are October, November and December rainfall (mm) of year preceding cropping, respectively.

R1 to R11 Monthly rainfall (mm) from January (R1) to November (R11).

X	Stepwise independent variables selection.
**	P < 0.01.
NS	Non-significant.
A	Autumn (January to December) rainfall (mm).

Table 7. The main contribution of periodic and monthly rainfall to grain yield.

Periods or months	Research stations							
	Merredin	Salmon Gums	Newdegate	Wongan Hills	Chapman	Badgingarra	Esperance	Mount Barker
F[+]	**	**		**				**(-)
A	**	**						
W	**	**	*(-)	**	*	**(-)		
S	**	**	**	*	**			**(-)
R01		**		**		**		
R02					*			
R03	**	**	**					
R1					*(-)	*(-)		
R2				**				
R3	**	**	*(-)	**				**(-)
R4	**							
R5	**			**				
R6	**		**(-)	**				
R7	**	**			**	**(-)		
R8						**(-)	*(-)	
R9	*	*	**	**	**		**	
R10			**			**		
R11		**(-)					**(-)	**(-)

$*P < 0.05$.

$**P < 0.01$.

-Negative.

+For description of symbols see Table 6.

Monthly. As with periodic model, forward stepwise regressions were applied to select the monthly rainfall which contributed to grain yield, and only variables with significant effect ($p < 0.05$) were retained in the regression equations. The coefficients of determination (R^2) were greater than for the periodic model equations (Table 6). The maximum R^2 was 74% for Salmon Gums which is 12% higher than the maximum R^2 with the periodic. The main contribution of monthly rainfall to wheat grain yield came from December of the year preceding cropping (R03), March (R3) to July (R7) and September (R9) rainfall at Merredin; October of the year preceding cropping (R01), February (R2), March (R3), May (R5), June (R6) and September (R9) at Wongan Hills; and negative effects of March (R3) and November (R11) at Mount Barker (Table 6).

The October-December months of the year of preceding cropping (R01 and/or R02 and/or R03) affected the wheat grain yield at all sites except Esperance and Mount Barker (Table 7). January (R1) and/or February (R2) and/or March (R3) had positive effects at Merredin, Salmon Gums and Wongan Hills and negative effects at Newdegate, Chapman, Badgingarra and Mount Barker. However, rainfall for the same months had no effect on grain yield at Esperance (Table 7). The April (R4) and/or May (R5) rain contributed to grain yield only at Merredin and Wongan Hills and negative effects at Newdegate (Table 7). The July (R7) and/or August (R8) rain were negatively correlated at Badgingarra and Esperance and positively correlated at Merredin, Salmon Gums and Chapman (Table 7). The spring rainfall (R9 and/or R10) contributed to grain yields at all research stations except Mount Barker (Table 7). At Merredin and Salmon Gums monthly rainfall accounted for 72 and 74% of variations in grain yield, respectively (Table 6).

The main difficulty in validating the monthly models was the lack of independent long term grain yield data for Gamenya from a particular site in the wheatbelt. However, attempts were made to compare actual and predicted grain yield for five-year trials randomly excluded from the monthly models. Table 8 shows that the differences between actual and predicted grain yields were lower than 170 kg ha^{-1} and were not significantly different (Paired "t" test).

Table 8. The comparison of actual and predicted wheat grain yield using monthly models at Merredin and Salmon Gums research stations for five randomly selected years.

		Gran yield		
Year	Research station	Actual	Predicted	Diff.
1967	Merredin	1,361	1,324	+37
	Salmon Gums	1,866	1,923	-57
1971	Merredin	1,769	1,836	-67
	Salmon Gums	841	911	-70
1980	Merredin	659	824	-165
	Salmon Gums	485	334	+151
1984	Merredin	1,689	1,606	+83
	Salmon Gums	2,836	2,736	+100
1985	Merredin	764	913	-149
	Salmon Gums	1,400	1,484	-84
t*(0.05)				NS

* Paired t-test.

NS Non-significant.

DISCUSSION

The monthly model described the variation in grain yield of spring wheat cv. Gamenya better than did annual, seasonal or periodic models. The greater correlation between grain yield and monthly rainfall at Merredin and Salmon Gums compared to other stations indicates that edaphic and climatic factors other than monthly rainfall are less important at low rainfall sites than at high rainfall areas. In this study although distribution of rainfall was the major environmental factor affecting wheat yield especially at low rainfall sites, crop management practices such as correct sowing time, right choice of cultivars, optimum seed rate, fertilizer application and weeds, disease and pest control are important in achieving the maximum yield (1, 2). In the field trials reported here, no data were available on specific crop characteristics such as plant density, number of tillers and ears or other factors such as occurrence of waterlogging, foliar and root diseases.

Fallow rains contributed to grain yield at sites with seasonal (May–October) rainfall less than 300 mm. In a study of the effect of fallowing on wheat yield at Merredin, Tennant (16) cited results showing greatest response to fallow moisture storage in areas with less than 250 mm seasonal rainfall, and decreasing response as seasonal rainfall increased to 450 mm. However, at Newdegate negative and positive effects for December (R03) and March (R3) compensated each other and as a result, fallow rain did not show any effect on grain yield. The negative effect of fallow rain at Mount Barker may be related to waterlogging if soil profiles are already wet, or to more difficult weed control where fallow rainfall is associated with germination of more weed seeds. The positive correlations between autumn (April–May) rains and grain yield at Merredin and Salmon Gums may be related to improved seed bed preparation, better weed control and earlier sowing in seasons of high autumn rainfall. Many trials in the northern and central parts of the wheatbelt have confirmed the possibilities for increased yield through early sowing provided that variety is matched to sowing date (13).

Winter (June-August) rainfall had positive effects on grain yield of Gamenya at sites with seasonal (May-October) rainfall less than 400 mm. This corresponds with the findings of Cornish (3), who showed that winter rainfall was a more important determinant of grain yield than was either autumn or spring rainfall. The positive effects of winter rainfall can be related to better early crop growth. The effect of winter rainfall on grain yield was highest at Salmon Gums, which also had the lowest growing season rainfall. It seems that earlier sown crops at Salmon Gums (Table 3) could gain more advantage from above average winter rain than crops at the other sites. The main benefits of winter rains were gained from June and/or July rainfall at Merredin, Salmon Gums, Wongan Hills and Chapman. However, June rainfall at Newdegate and both July and August rainfalls at Badgingarra had negative effects on grain yield which may be attributed to waterlogging at Newdegate but probably to greater incidence of foliar diseases at Badgingarra (R. Wilson, personal communication, 1990). The high and reliable winter rainfall at Esperance and Mount Barker (Table 4) appeared to make wheat grain yield independent of winter rain (Table 6).

Spring rainfall had positive effects on grain yield at all research stations except Badgingarra, Esperance and Mount Barker. The contribution of spring rainfall to grain yield was probably due to the critical importance of water supply at anthesis which mostly occurred during September. Negative or zero effects of spring rainfall at high rainfall sites may be associated with a higher incidence of wheat foliar diseases such as the septorias. The higher November rainfall at Salmon Gums, Esperance and Mount Barker compared to other research stations (Table 4) had negative effects on grain yield, which may be related to losses associated with harvesting under wet conditions.

This study shows that a monthly rainfall model gives a better prediction of the grain yield of spring wheat in Western Australia, especially in the low rainfall regions of the wheatbelt than annual, seasonal or periodic models. From the practical point of view, this model when combined with soil water storage information and crop characteristics at particular month during the growing season, could be used by advisers and farmers for forward prediction of the potential yield of a wheat crop.

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