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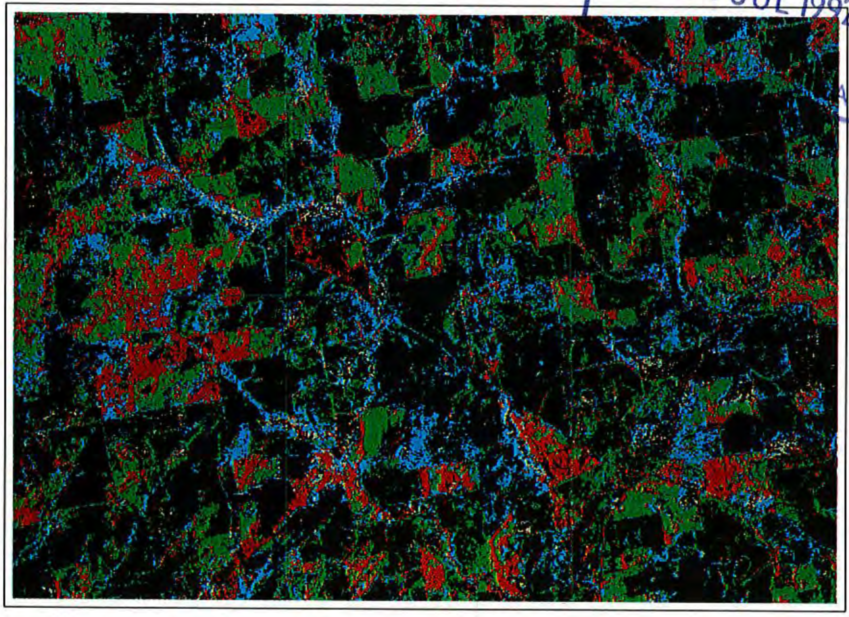

D.J. McFarlane, G.A. Wheaton, T.R. Negus, J.F. Wallace

Effects of waterlogging on crop and pasture production in the Upper Great Southern, Western Australia

By: D.J. McFarlane, G.A. Wheaton, T.R. Negus and J.F. Wallace
Editors: D.A.W. Johnston and M.J. McFarlane

Summary

Waterlogging is one reason why crops and pastures achieve only a fraction of their potential yields in south-western Australia. However, before this study, there had been no systematic attempt to estimate its extent or economic importance.

Separate estimates of the effect of waterlogging on cereal yields were made using rainfall and crop yield statistics, and remote sensing. Both methods showed that waterlogging costs tens of millions of dollars each year in lost crop production in the Upper Great Southern Statistical Division. The costs will be over $100 m in wet years. Losses in pasture production are likely to be of a similar magnitude, but are harder to quantify.

From monitored wells it was estimated that about 60% of the eastern Murray River catchment had perched waters within 30 cm of the soil surface at least once during 1987 and 1988. Over 90% of the floodplain areas around the Hotham River were waterlogged in 1987 and 1988. Lack of relief in this landform makes drainage difficult.

We believe that the effect of waterlogging on crop and pasture production has been underestimated as waterlogging is not obvious until the soil profile is saturated to the surface. Yield reductions at harvest are sometimes not associated by farmers with waterlogging earlier in the season and, in the part of the electromagnetic spectrum which we see with our eyes, the reflected spectra from waterlogged crops is very similar to that from non-waterlogged crops. However, there are major differences in the reflected spectra from waterlogged crops in the infrared part of the spectrum. It was this difference that we used to identify and map areas of waterlogged crops.

There is an urgent need for farmers to recognize the losses that waterlogging causes, and for them to adopt methods of obtaining production from areas susceptible to waterlogging. In particular, agronomic methods of alleviating the effects of waterlogging on production need more research.

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The Wheat Industry Research Committee of Western Australia funded this study because the lack of information on the extent and economic importance of waterlogging made it difficult to set priorities when allocating funds.

Introduction

Waterlogging is a soil condition in which excess water in the root zone inhibits gas exchange with the atmosphere. In general, gases diffuse about 10,000 times more slowly in water than in air (Grable 1966). Even small discontinuities in the gaseous phase of the soil pores impair gas diffusion into and out of the waterlogged part of the soil. In waterlogged soils, oxygen is used up and not replaced, carbon dioxide and ethylene accumulate and electrochemical changes occur (Ponnamperuma 1984).

While waterlogging is recognized as an important problem in agricultural areas of Western Australia which receive > 450 mm rainfall per annum (McFarlane *et al.* 1990), there had been no systematic attempts to quantify its extent before this work.

The aim of the project was to quantify the geographical extent of waterlogging and its economic significance to crop and pasture production in the Upper Great Southern Statistical Division of Western Australia.

The project was furthered by setting the following objectives:

- to find out which parts of the landscape in the Upper Great Southern Statistical Division are most susceptible to waterlogging;
- to determine how waterlogging affects crop and pasture production in the field, as opposed to previous studies in the glasshouse and under artificial conditions in the field;
- to estimate the effect of waterlogging on crop production in the Upper Great Southern Statistical Division using statistics on rainfall (from the Australian Bureau of Meteorology) and on crop production (from the Australian Bureau of Statistics); and
- to develop remote sensing methods of mapping waterlogged crops and to apply these methods to estimate the extent and cost of waterlogging in the Upper Great Southern Statistical Division.

Study area

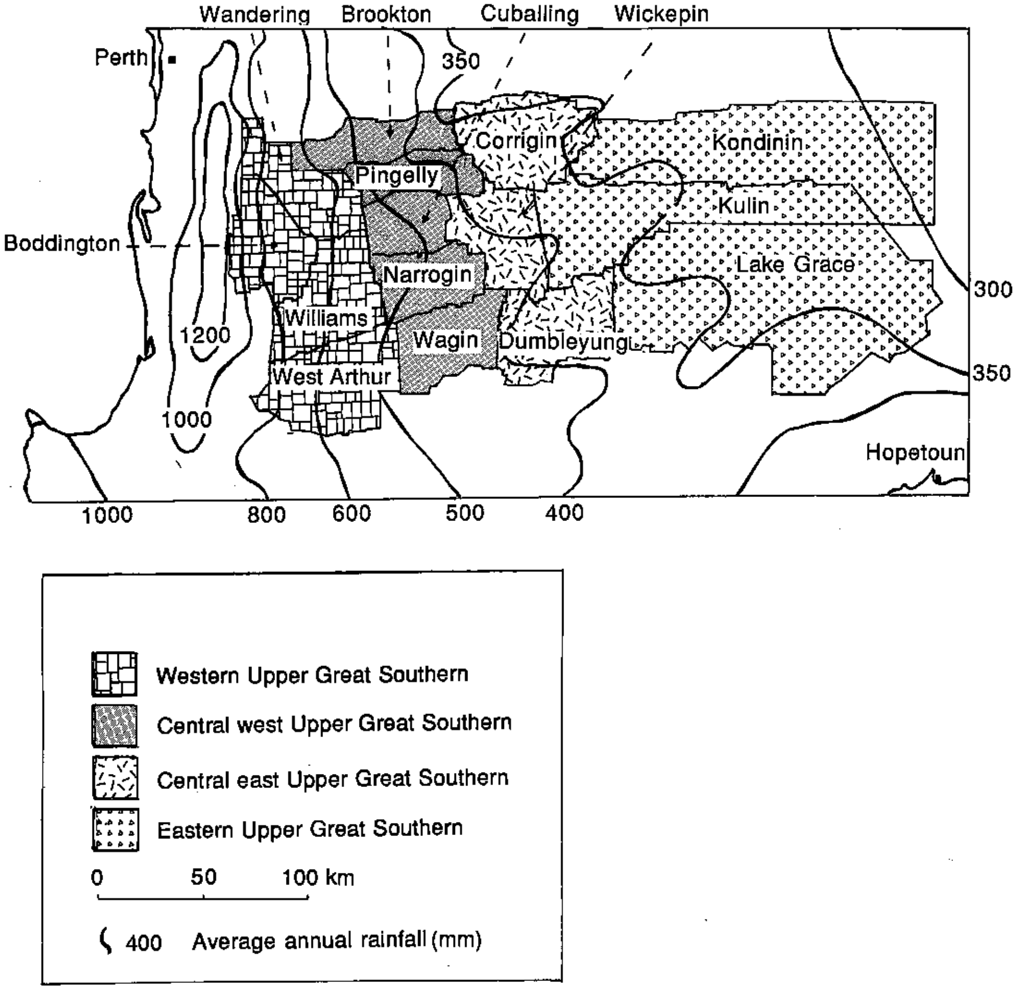
The Upper Great Southern Statistical Division comprises 15 shires which we divided into four groups on the basis of rainfall, landform and land use (Figure 1).

1. The western shires of Wandering, Boddington, Williams and West Arthur have an average annual rainfall of between 550 and 1000 mm. The main land uses are grazing of improved pastures and forestry; there are few paddocks sown to cereals grown for grain. Waterlogging is a problem mainly in pastures and cereal crops grown for hay. As farmers only crop small areas they can select the best drained parts of their farms.
2. The central west shires of Brookton, Pingelly, Cuballing, Narrogin and Wagin have an average annual rainfall of between 425 and 550 mm. Waterlogging is a common problem in cereal crops, particularly wheat (*Triticum aestivum*), which comprises about 50% of the total cropped area. The area of crops grown for grain decreased by about 15% between 1982/3 and 1986/7 (Appendix 1) . The area sown to oats (*Avena sativa*) remained constant over this period while the area sown to wheat and barley (*Hordeum vulgare*) decreased and to lupins (*Lupinus angustifolius*) increased.
3. The central east shires of Corrigin, Wickepin and Dumbleyung have an average annual rainfall between 350 and 425 mm. Between 1982/3 and 1986/7 the area sown to grain crops remained fairly constant (about 270,000 ha) with wheat comprising about 80% of the total (Appendix 1). By 1986/7 the area sown to lupins was larger than the area growing barley. The lower rainfall in these shires makes them less susceptible to waterlogging although it is important in wet years.
4. The eastern shires of Kondinin, Kulin and Lake Grace have an average annual rainfall between 300 and 350 mm. Cropping is extensive in these shires, but widespread losses because of waterlogging are fairly uncommon.

Given these characteristics of the Upper Great Southern Statistical Division, our research concentrated on waterlogging in the shires of Narrogin, Cuballing, Pingelly and Wickepin. In particular, the eastern part of the Murray River catchment was studied as it was the only area for which a landform map existed (McArthur *et al.* 1977).

Remote sensing using satellite was done in an area between Narrogin, Pingelly and Wickepin which was covered by a quarter of a LANDSAT scene. The results from this central area can be extrapolated with some confidence to the other shires in the central Upper Great Southern Statistical Division (i.e. Brookton, Wagin, Corrigin and Dumbleyung), but not to the climatically-different western or eastern shires. This is not a serious limitation of the study as the western shires experience waterlogging, but few cereal crops are grown while the reverse is found in the eastern shires.

Figure 1. The Upper Great Southern Statistical Division and rainfall isohyets



The position of waterlogging in the landscape

The susceptibility of landforms to waterlogging was studied in five areas east of the Dryandra Forest in the Murray River catchment: Dryandra, Tutanning, Yornaning, Rosedale and Trefort (Figure 2). The study area lies within the central shires (Figure 1) and detailed landform maps of these five areas are available (McArthur *et al.* 1977).

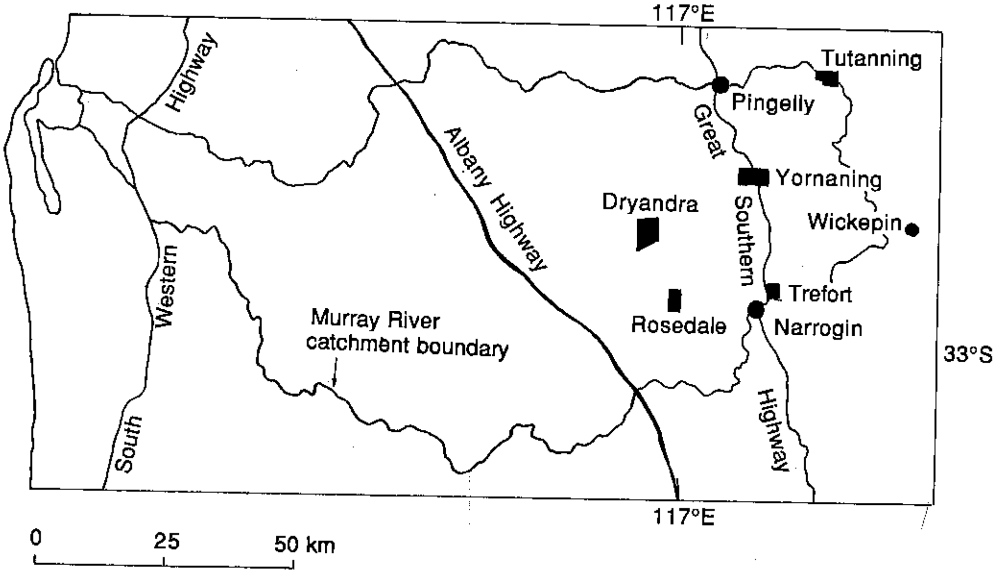
There are four main landforms:

1. Norrine - small lateritic residuals in upland areas bounded by small escarpments. The soils are gravelly sands (KS-Uc 4.12, Northcote 1979), sands (Uc 5.22) and duplex yellow soils (Dy 4.21). The Norrine unit occupies 10.2% of the study area.
2. Noombling - an erosional landform consisting of long, gentle slopes with rock outcrops being common on the upper slopes. The soils are yellow and red duplex soils (Dy 3.61, Dr 2.21). This is the major landform in the study area, occupying (along with areas of rock) 76.1% of the area.
3. Biberkine - an alluvial landform around tributaries of the Hotham and Williams Rivers. The soils are mainly duplex (Dy 3.62, Dy 3.82, Dy 3.42). This landform occupies 6.8% of the area.
4. Popanyinning - this is alluvium on the flood plain around the Hotham River. The soil types in the landform are mainly duplex (Dy 3.43, Dy 3.82) with channels of sand or clay running through the floodplain. This landform occupies 6.9% of the study area.

Methods

Waterlogging of the plant's root zone was determined by measuring the water level in shallow wells. Water that is perched on subsoil clays progressively saturates the topsoil from below and inhibits the exchange of oxygen, carbon dioxide and ethylene with the atmosphere. To install the wells, holes were drilled just into the clay subsoil, or to 70 cm if no clay had been encountered by that depth. The wells consisted of slotted

Figure 2. The eastern Murray River Catchment showing areas where the susceptibility to waterlogging was monitored



PVC pipe surrounded by coarse sand so that water perched on the clay subsoil could enter through the slots.

The number of wells placed in each landform in the Dryandra, Tutanning, Yornaning and Rosedale areas was in proportion to the landform's area. At Trefort, 49 wells were installed on a 5 x 7 m grid into the Noombling landform. A total of 209 wells was installed; 119 in the Noombling landform, 44 in the Popanyinning landform, 26 in the Biberkine landform and 20 in the Norrine landform (Table 2).

In 1987, water levels in the wells were measured manually within 24 hours of each storm and at two day intervals until levels became stable. This method enabled both the intensity and duration of waterlogging to be estimated. The 209 wells were only visited on three occasions in 1988 because of time limitations.

The intensity of waterlogging was described using the SEW_{30} index (Sieben 1964). The index is calculated by summing all daily values (in cm) of groundwater levels within 30 cm of the soil surface (Figure 3). Therefore two days with the water level at 20 cm below the surface (i.e. 10 cm above the 30 cm threshold) represents a waterlogging intensity of 20 cm.days. This is the same as one day with the water level at 10 cm below the soil surface (i.e. 20 cm above the 30 cm threshold).

Sieben (1964) used 30 cm as a critical depth for measuring waterlogging intensity as this depth was most correlated with crop yields in drainage experiments in the Netherlands. Cox (1988) showed that this depth was correlated with crop yields at Narrogin and Mt Barker.

Results

Waterlogging depended on the distribution of rain that fell in 1987 and 1988. Winter rainfall in the three towns which straddle the study area (Narrogin, Pingelly and Wickepin) had an exceedence probability of 0.7 (i.e. it would be expected to be equalled or exceeded in seven years out of ten on average) in 1987 (Table 1). Heavy rain in April was followed by light rain in May and June resulting in little waterlogging. However, heavy rain at the end of July caused moderate waterlogging. While the subsequent rainfall was very light, some soil profiles that had been saturated in July were resaturated by falls as light as 5 mm in the following weeks (Figure 3). Had the rainfall in August 1987 been average, waterlogging would have been both widespread and severe.

Rainfall in 1988 was above average in Narrogin and Pingelly, but below average at Wickepin (Table 1). At Narrogin, the winter rainfall had an exceedence probability of 0.3. While the rainfall in June and September was particularly high, the annual rainfall was only 29 mm above average. Rainfall decreased rapidly to the east so that at Wickepin the annual rainfall was 54 mm below average in 1988.

In about 60% of the wells, water levels were within 30 cm of the soil surface at least once during 1987 and 1988 (Table 2). The Popanyinning landform was the most susceptible to waterlogging with up to 95% of the wells recording water levels within 30 cm of the soil surface. The next most susceptible landform was Noombling (> 60%), followed by Biberkine and Norrine (each with 15 to 20%).

The highest average waterlogging intensities were in the Popanyinning landform (265 cm.days). Where waterlogging extended for 25 days after

Figure 3. Perched groundwater levels in relation to rainfall at Narrogin in 1987 and 1988

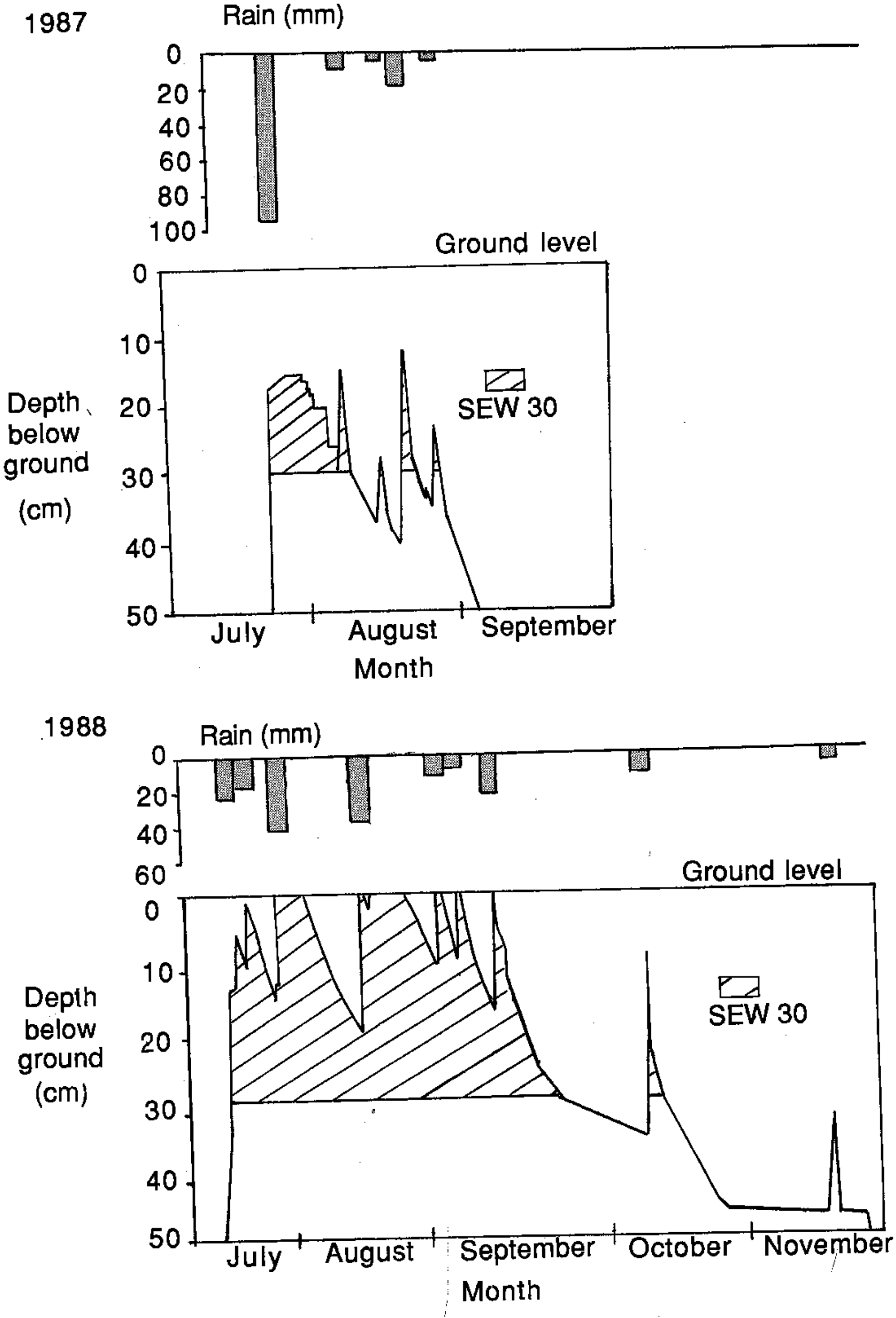


Table 1. Monthly rainfall (mm) for the towns of Narrogin, Pingelly and Wickepin during 1987 and 1988

Town	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total	Ave.
1987														
Narrogin	1	2	5	64	26	50	155	31	44	12	27	32	449	506
Pingelly	0	0	4	46	47	53	115	31	29	12	25	19	381	455
Wickepin	0	0	3	36	43	43	93	38	39	11	36	13	355	420
1988														
Narrogin	0	0	19	35	75	115	91	65	79	27	15	14	535	506
Pingelly	0	0	26	57	58	101	79	72	51	18	6	16	484	455
Wickepin	0	0	24	25	54	80	57	46	43	12	15	10	366	420

Table 2. Wells recording waterlogging, and average waterlogging intensities, in four landforms in 1987 and 1988

Landform	No. wells monitored	Percentage of wells with water within 30 cm of the soil surface		Average waterlogging intensity (SEW_{30} index in cm.days)
		1897	1988†	1987
Norrine	20	15	20	59
Noombling	119	63	61	104
Biberkine	26	20	15	23
Popanyinning	44	91	95	265
Average††		59	60	124

† Wells monitored on three occasions in 1988. This is a minimum percentage.

†† Weighted for the number of wells

the July rain, 265 cm.days represents a water level about 20 cm below the soil surface during the period. Six wells had intensities in excess of 600 cm.days (equivalent to > 20 days saturated to the surface).

Waterlogging was very variable over short distances as shown by the intensity of waterlogging within the one paddock at Trefort (Figure 4). The least amount of waterlogging occurred at the top of the grid, immediately downslope of a seepage interceptor drain. While there was an increase in waterlogging intensity away from the drain, there was considerable variability in intensity over 5 to 10 m. This means that we can only associate waterlogging intensity recorded in a well with the performance of crops and pastures growing within a few metres of that well.

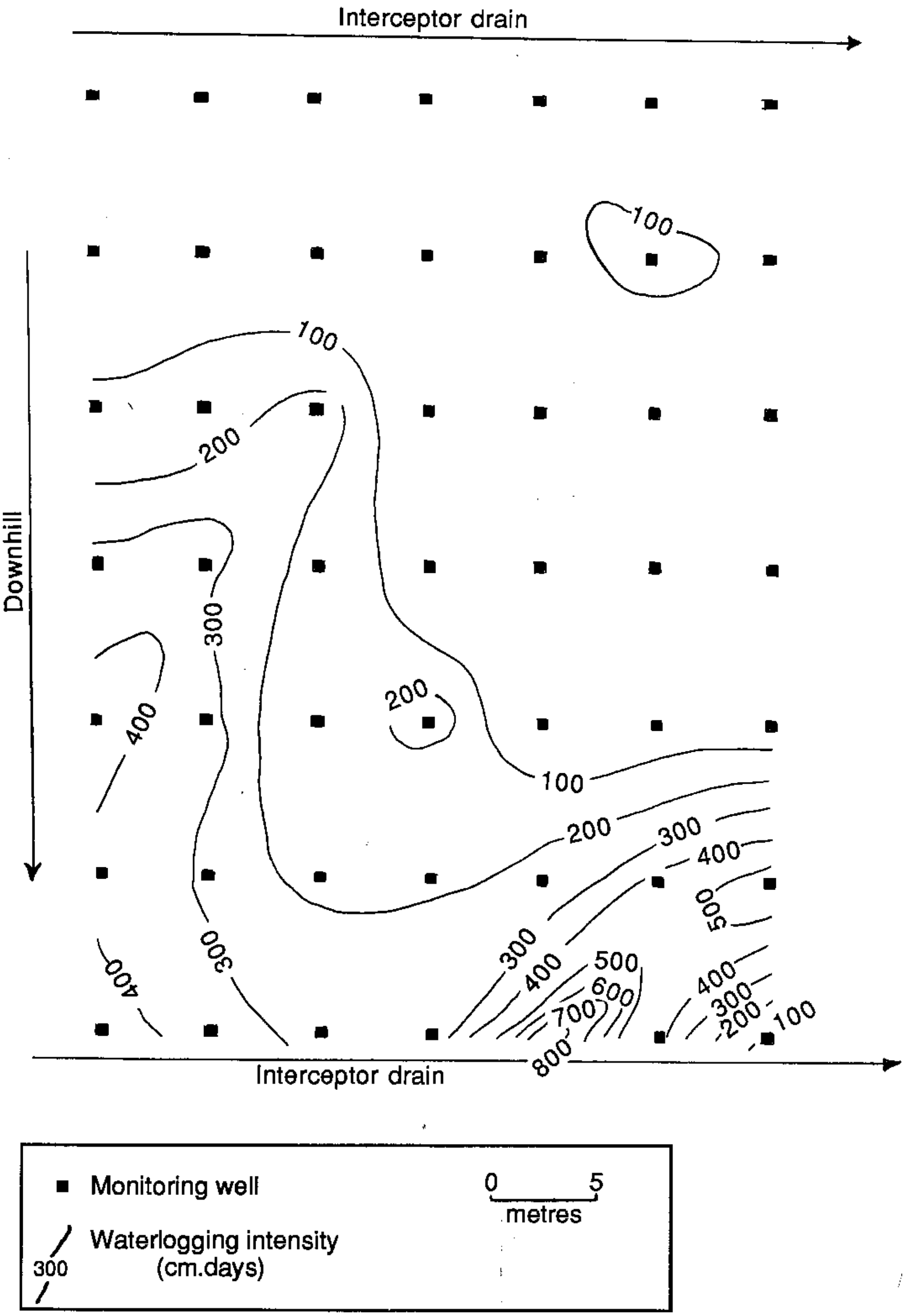
Discussion

Waterlogging was present in all of the landforms, but was most common and intense in the Popanyinning and Noombling landforms. Together, these landforms comprise 83% of the eastern Murray River catchment. Up to 20% of the gravelly Norrine landscape was susceptible to waterlogging. Part of this landform has gentle slopes and shallow duplex soils.

If the data from the five detailed study areas are representative of the eastern Murray River catchment, about 57% of this area (or 93,000 ha) had a perched watertable within 30 cm of the surface during both 1987 and 1988. About 77,000 ha was in the Noombling landform which can usually be drained with seepage interceptor drains, while about 10,500 ha was in the Popanyinning and 2,000 ha was in the Biberkine, neither of which can be drained easily.

The high variability of waterlogging in duplex soils has also been reported by Cox (1988) who attributed it mainly to differences in the hydraulic conductivity of the subsoils. While there is high spatial variability there is considerable consistency from year to year such that areas that were waterlogged in 1987 were also waterlogged in 1988.

Figure 4. Variability in waterlogging intensity over a 30 * 42 m grid, Noombling landform, 1987



Effects of waterlogging on crops and pastures

Introduction

The effect of waterlogging on wheat in Australia has been studied in the glasshouse (Watson *et al.* 1976) and under artificial conditions in the field (Barrett-Lennard *et al.* 1986). However, these measurements cannot be used to estimate the effect of fluctuating water levels on crops grown under dryland conditions. In several other studies, measurements of naturally waterlogged crops did not record waterlogging intensity (Poole 1971, Negus 1983). Only Cox (1988) has measured waterlogging intensity and wheat yields under field conditions. During 1985, at Narrogin, Cox (1988) found that wheat yields declined by about 56 kg/ha for every 100 cm.days of waterlogging when grown on the Noombling landform.

At Mt Barker in 1984, oat yields were unaffected by waterlogging until SEW_{30} exceeded about 500 cm.days (Cox 1988). Thereafter yields declined by about 176 kg/ha for every 100 cm.days of waterlogging.

The effect of waterlogging on 75 cultivars of subterranean clover (*Trifolium subterraneum*) were examined in pots by Francis and Devitt (1969). The relative tolerance to waterlogging of the subspecies was *yanninicum* > *subterraneum* > *brachycalycinum*. Francis and Poole (1973) found that annual *Medicago* species, particularly early maturing species, were more susceptible to waterlogging than subterranean clover. No field measurements of the effect of waterlogging on pasture growth in Australia have been published.

Method

The growth of wheat, oats and pastures was monitored adjacent to most of the 209 wells which were monitored in 1987. Five replicates of 0.25 m^2 quadrats were taken from within 6 m of the wells. Dry matter production of crops was measured at tillering, stem elongation, anthesis and harvest. Grain yields were determined from the harvest samples.

Pasture growth was recorded under pasture cages (0.36 m^2). Both dry matter production and the composition of the pastures were recorded at 21 day intervals throughout the growing season. The cages were moved after each measurement.

Growth responses of both crops and pastures were related to paddock management. By locating up to 12 wells in a single paddock the influence of different management practices on growth could be separated from the effect of waterlogging.

Results

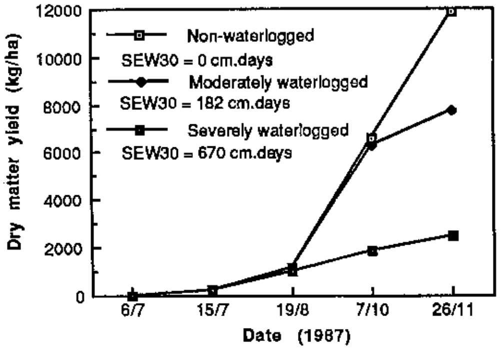
Wheat

Rainfall was well below average in 1987 and waterlogging was only one factor affecting crop growth.

The effect of waterlogging on the dry matter production of wheat throughout the year can be shown by comparing three sites in the same paddock (Popanyinning landform north of Yornaning) with different intensities of waterlogging (Figure 5). The site with 670 cm.days of waterlogging had reduced dry matter production and slightly delayed development compared with the other two sites. The difference in production between the sites became progressively greater throughout the year. In this example, the site with 670 cm.days of waterlogging produced 23% of the final dry matter yield (and 12% of the grain yield) of the unaffected site while the comparative figures for the site with 182 cm.days of waterlogging was 66% (dry matter yield) and 47% (grain yield). Grain yields were more affected than were dry matter yields.

There was a tendency for dry matter and grain yields of wheat to decrease with increasing waterlogging intensity for 12

Figure 5. The effect of waterlogging on the dry matter production of wheat throughout the growing season



sites within the same paddock (Figures 6 and 7). However, there were two anomalous sites (7 and 10) which have been ignored in subsequent analyses; the reasons are given in the Discussion. The data indicated that, for every 100 cm.days of waterlogging, dry matter yields decreased by about 1170 kg/ha and grain yields decreased by about 520 kg/ha.

Figure 6. The effect of waterlogging on the total dry matter production of wheat

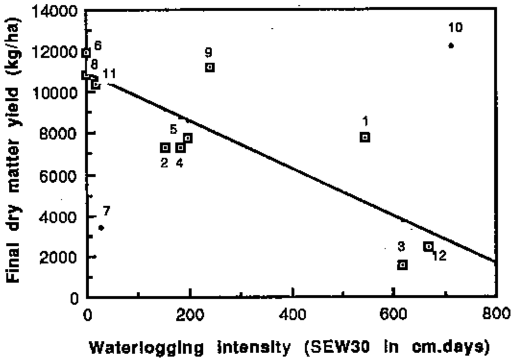
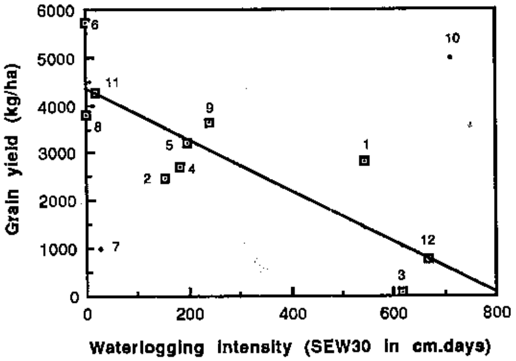


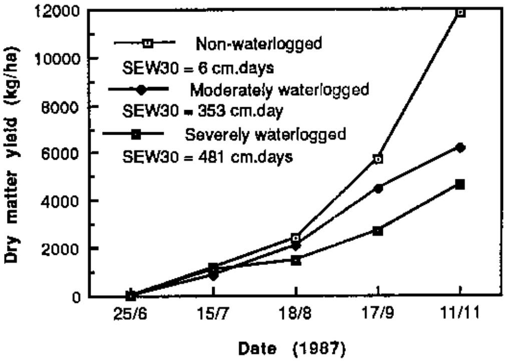
Figure 7. The effect of waterlogging on the grain yield of wheat



Oats

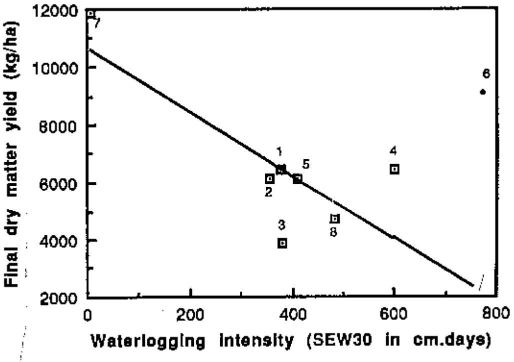
The effect of waterlogging on the growth of oats (Figure 8) was similar to that shown for wheat. The site with 481 cm.days of waterlogging produced 39% of the final dry matter yield (and 19% of the grain yield) of the unaffected site while the comparative figures for the site with 353 cm.days of waterlogging were 53% (dry matter yield) and 44% (grain yield). As for wheat, grain yields were more affected than dry matter yields.

Figure 8. The effect of waterlogging on the dry matter production of oats throughout the growing season



The effect of waterlogging on dry matter production and grain yield for oats was not clear in 1987 (Figures 9 and 10). If site 6 is ignored (see Discussion), the data show that for every 100 cm.days of waterlogging, dry matter yields decrease by about 1070 kg/ha and grain yields decreased by about 550 kg/ha. These decreases are similar to those found in the wheat. However, the relationship is dependent on the value from site 7.

Figure 9. The effect of waterlogging on the total dry matter production of oats



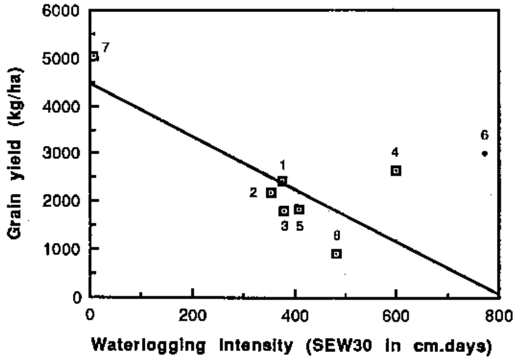


Figure 10. The effect of waterlogging on the grain yield of oats

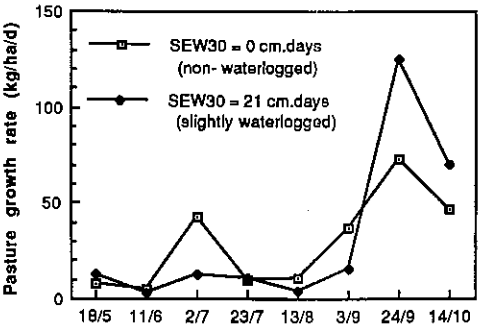
Pastures

The effect of waterlogging on pasture production depended on the site, time of the year and the intensity of the waterlogging. At the most waterlogged site (Yornaning) annual pasture production was lowest, and conversely, at the least waterlogged site (Dryandra), production was highest (Table 3). However, waterlogging intensity was only one factor affecting production. For example, at Tutanning, where waterlogging was only slightly worse than at Dryandra, production was 40% lower than at Dryandra.

The waterlogging in 1987 occurred in late July and early August. Average pasture production in July at Yornaning was 11.1 kg/ha/day which was similar to the average of 10.1 kg/ha/day for the other three sites. However, after waterlogging started, pasture production at Yornaning was only 25 - 30% of that at the other three sites (Table 3).

The comparison of sites in Table 3 ignored the effects of different soil types and management systems on pasture production. Production from waterlogged and non-waterlogged parts of the same paddock is now compared. At Dryandra, slight waterlogging (21 cm.days) reduced pasture production relative to non-waterlogged areas until September (Figure 11). In the spring flush the wet areas produced greater growth which more than compensated for the reduced winter growth.

Figure 11. Effect of waterlogging on pasture production at Dryandra in 1987

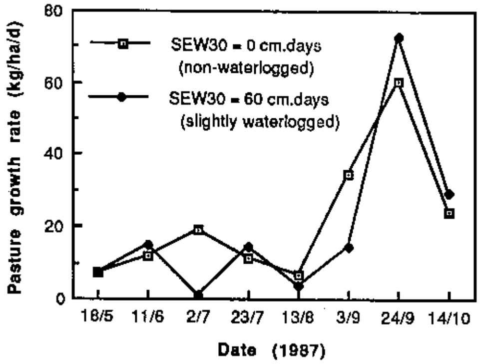


At Rosedale, slight waterlogging (average of 69 cm.days) also reduced pasture production in winter and increased growth in the spring relative to non-waterlogged areas (Figure 12). However the increased spring growth was insufficient to compensate for the reduced winter growth. Total production from the waterlogged areas was 10% lower than from the non-waterlogged sites.

Table 3. Average pasture production from four sites in the Upper Great Southern Statistical Division during 1987

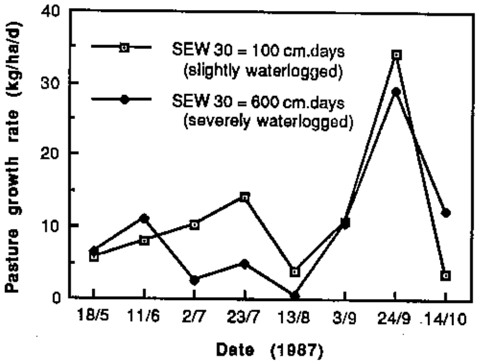
Site	Production (kg/ha/d)									
	Germ. to 17 May	20 May to 10 June	10 June to 1 July	1 July to 22 July	22 July to 12 Aug.	12 Aug. to 2 Sept.	2 Sept. to 23 Sept.	23 Sept. to 13 Oct.	Total 168 d	Average SEW30 (cm.days)
Dryandra	8.8	4.8	37.3	9.7	9.5	33.5	81.5	50.7	4,946	4
Tutanning	4.4	4.8	13.9	7.0	11.0	57.0	33.1	9.3	2,941	5
Rosedale	6.2	12.9	16.4	13.6	7.3	32.5	54.3	20.6	3,430	14
Yornaning	5.5	9.1	7.6	11.1	2.7	10.7	32.6	5.1	1,765	338

Figure 12. Effect of waterlogging on pasture production at Rosedale in 1987.



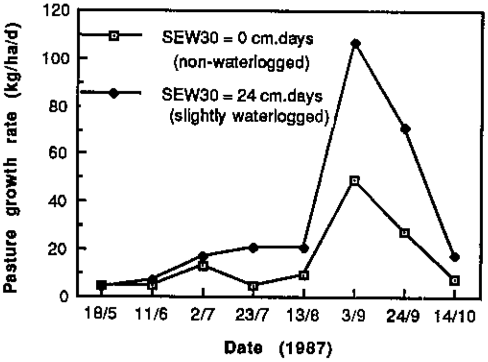
At Yornaning, severe waterlogging (average of 699 cm.days) reduced pasture production relative to moderate waterlogging (average of 158 cm.days) except in October (Figure 13). Over the growing season the waterlogged areas had 11% less production.

Figure 13. Effect of waterlogging on pasture production at Yornaning in 1987



The driest site where pasture production was assessed was at Tutanning. The one area that recorded waterlogging (34 cm.days) had better pasture production throughout the year (Figure 14).

Figure 14. Effect of waterlogging on pasture production at Tutanning in 1987



In general, waterlogged areas had lower reserves of clover seed indicating that these areas had poorer quality pasture as well as reduced early pasture growth compared with non-waterlogged areas. In the three higher rainfall sites (Dryandra, Rosedale and Yornaning), the clover seed reserves in August and December were generally lower in waterlogged areas compared with the non- (or less-) waterlogged areas (Table 4).

Discussion

In 1987, waterlogging occurred in late July after the crops had tillered. After tillering, crops are thought to be less susceptible to waterlogging because of the development of short crown roots which form aerenchyma after waterlogging begins (E.G. Barrett-Lennard, personal communication). Aerenchyma are continuous gas-filled channels inside roots which enable oxygen to diffuse to the root tip (Armstrong 1979).

Table 4. Clover seed reserves (kg/ha) in waterlogged and non- (or less-) waterlogged sites

Site	Clover seed reserves			
	August		December	
	Waterlogged	Non-waterlogged	Waterlogged	Non-waterlogged
Dryandra	38	115	197	368
Rosedale	20	46	167	160
Yornaning	3	59	15	72
Tutanning	87	57	275	142

In addition, soils are cold in July which is thought to have two effects. First, after soil becomes waterlogged there may be a delay of several days or weeks before the soil becomes low in oxygen because the low soil temperatures slow the activity of soil microorganisms. Second, as the plants grow slowly there is less demand for oxygen in the waterlogged part of the soil profile. Watson *et al.* (1976), showed that waterlogging at an early growth stage resulted in reduced tillering and reduced yields. Thus, waterlogging may have had a more severe effect had it happened before tillering or when the crop was growing rapidly.

For each 100 cm.days of waterlogging the grain yield of wheat and oats was reduced by about 520 and 550 kg/ha respectively. This rate of decrease is almost ten times greater than that recorded by Cox (1988), in 1985 for wheat at Narrogin and about three times greater than his figures for oats at Mt Barker. Severe waterlogging reduces growth to a common low value. Under these circumstances, the rate of decrease depends on the yield of the non-waterlogged site. This yield is dependent on a number of factors (e.g. seasonal conditions, sowing date, nitrogen, variety and management). At Yornaning in 1987, the yield of the non-waterlogged sites was close to their potential which made the effect of waterlogging more severe.

The yield of wheat and oats was high at two sites (sites 10 and 6 respectively) despite intense waterlogging. Both of these sites were in sandy channels which are common in the Popanyinning landform. In sandy soils there is a lower capillary fringe above the water table than in loamy soils, which results in better aeration of the root zone. McDonald and Gardner (1987) found that soils with different structures may have different air-filled porosities, despite having the same fluctuations in the water table. The same is likely for differences in soil texture. The sandy soils at Popanyinning had little organic matter and so anoxic conditions would be established slowly. The yield of wheat was very low at one site (site 7) but this was because of an unknown factor, not waterlogging.

Moderate waterlogging reduced winter pasture growth but increased spring growth. However, pasture production in May and June is three to four times more valuable than growth in September and October (McFarlane and Setter 1990). Annual pasture growth by itself is not a good indicator of the losses caused by waterlogging. Severe waterlogging reduced both early and annual pasture growth at Yornaning. However, at Tutanning, where water limited pasture growth, the wettest part of a paddock produced the most pasture throughout the year.

As well as decreasing early growth, waterlogging reduced the clover content of the pasture (Table 4). The clover seed reserves in August indicate the reserve of hard seed after germination. Levels above 40 kg/ha in a cropped paddock are adequate for clover production in the subsequent year (D.A. Nicholas, personal communication). From our research, all the non-waterlogged areas met this criteria but at the driest site, Tutanning, this level was attained only from the wettest part of the paddock.

The December clover seed reserves indicate the summer reserves available for the next season. At least 300 kg/ha of seed is required in December if the paddock is to be cropped in the next year and adequate clover is to regenerate after the crop (D.A. Nicholas, personal communication). Only the non-waterlogged sites at Dryandra met this criterion.

Extent of waterlogging as estimated from statistics

The effect of waterlogging on wheat production in 1974 in the Narrogin and Kondinin Shires was estimated by Negus (1983) using rainfall statistics and production data. By attributing reduced production in 1974 to waterlogging, Negus (1983) estimated that the losses were about $650,000 for the Narrogin Shire and $4,000,000 for the Kondinin Shire. This method is unreliable for two reasons. First, the method assumes that waterlogging did not affect production in the 18 years with which 1974 was compared, which is unlikely. Therefore, the effect of waterlogging will have been underestimated. Second, the method assumed that all of the losses in 1974 were because of waterlogging.

In this study a statistical method was used to estimate waterlogging, independent of the remote sensing method reported later.

Methods

To estimate the effect of wet years on crop production, crop yields from upland and lowland areas in the eastern Murray River catchment (Figure 15) were related to rainfall. We showed that the Popanyinning landform was very susceptible to waterlogging. Therefore, it was necessary to separate the upland landforms (Norrine and Noombling) from the lowland landforms (Biberkine and Popanyinning) in the analysis.

The areas sown to wheat, oats and lupins and the production from three upland and three lowland parts of the Upper Great Southern Statistical Division were obtained from the Australian Bureau of Statistics for the years 1983/4 to 1987/88. Most farms were within upland landforms (Table 5) resulting in these statistics being more accurate. The production data are attributed as coming from the location of the homestead making it possible for a homestead to be in one landform and most of the farm in another.

Table 5. Details of landform areas from which crop production data were obtained

No.	Landform	No. farms in sample	Nearest rainfall gauge
1	Lowland	12	Williams
2	Upland	60	Minijin
3	Upland	48	Pingelly
4	Lowland	4	Pingelly
5	Upland	34	Cuballing
6	Lowland	4	Cuballing

Results

When data from all landforms were combined, wheat yields decreased with increases in August rainfall (Figure 16). The linear relationship explained about 60% of the variability in wheat yield. A polynomial function did not improve the fit to the data. This rainfall interval (31 to 92 mm) has an exceedence probability of between 0.9 and 0.2 (i.e. 31 mm would be exceeded in 90 years out of 100 on average and 92 mm would be exceeded in 20 years out of 100 on average). In the calculations outlined below, the relationship has been used to estimate wheat losses for August rainfalls between 0.6 and 0.1 exceedence probabilities (i.e. it has been extrapolated to estimate losses in the wettest years).

The more rainfall in April and May, the higher the yield of wheat, oats and lupins while rain in June and August adversely affected crop yields (Figure 17). Crop yields were not significantly correlated ($P > 0.05$) with July rainfall.

Figure 15. Upland and lowland areas from which crop production data were compared with local raingauges

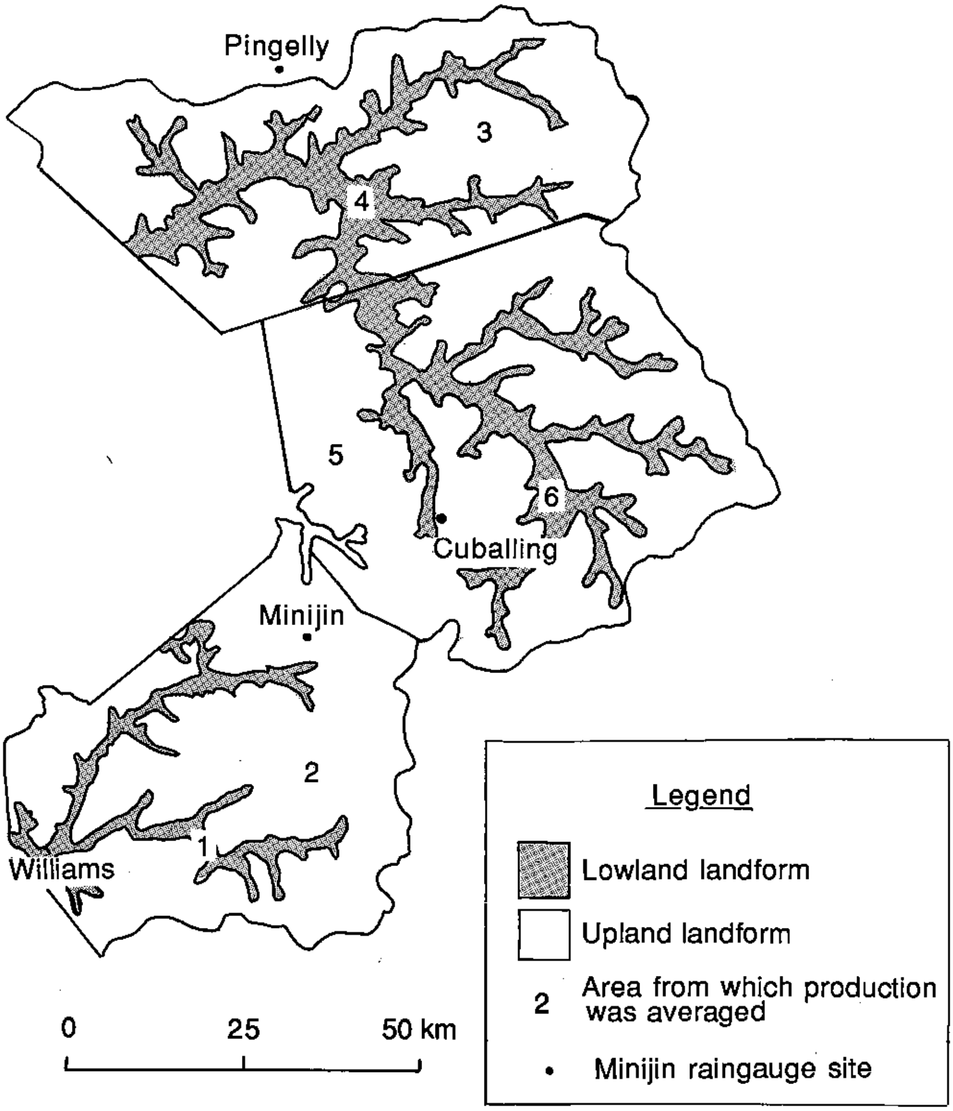


Figure 16. Wheat yields in all landforms as a function of August rainfall

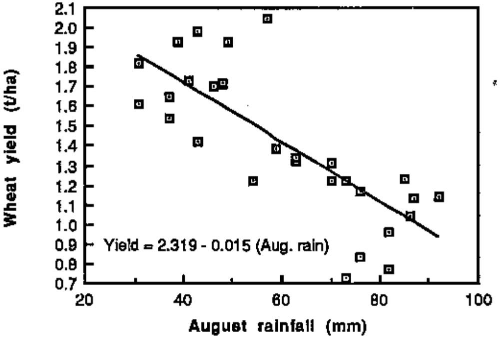
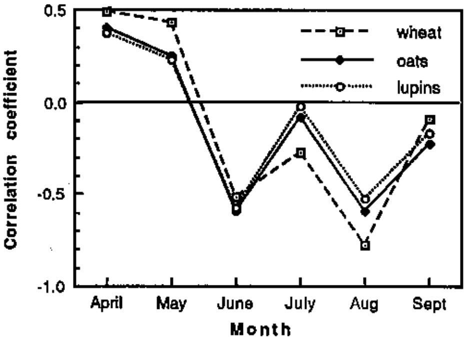


Figure 17. Correlations between wheat yields in all landforms with monthly rainfall



Regression equations were fitted between the grain yields of the three crops and rainfall for individual months and for groups of months for the different landforms (Table 6). Some equations were very good predictors of yields. For example, wheat yields in uplands areas were predicted with 86% accuracy from rainfall in April and August (Figure 18). Wheat yields were highest when April rainfalls were high and August rainfalls were low (and vice versa).

Figure 18. Wheat yields in upland areas as a function of April and August rainfall

Uplands wheat yield = 2.16-0.015 (Aug. rain) + 0.005 (April rain)

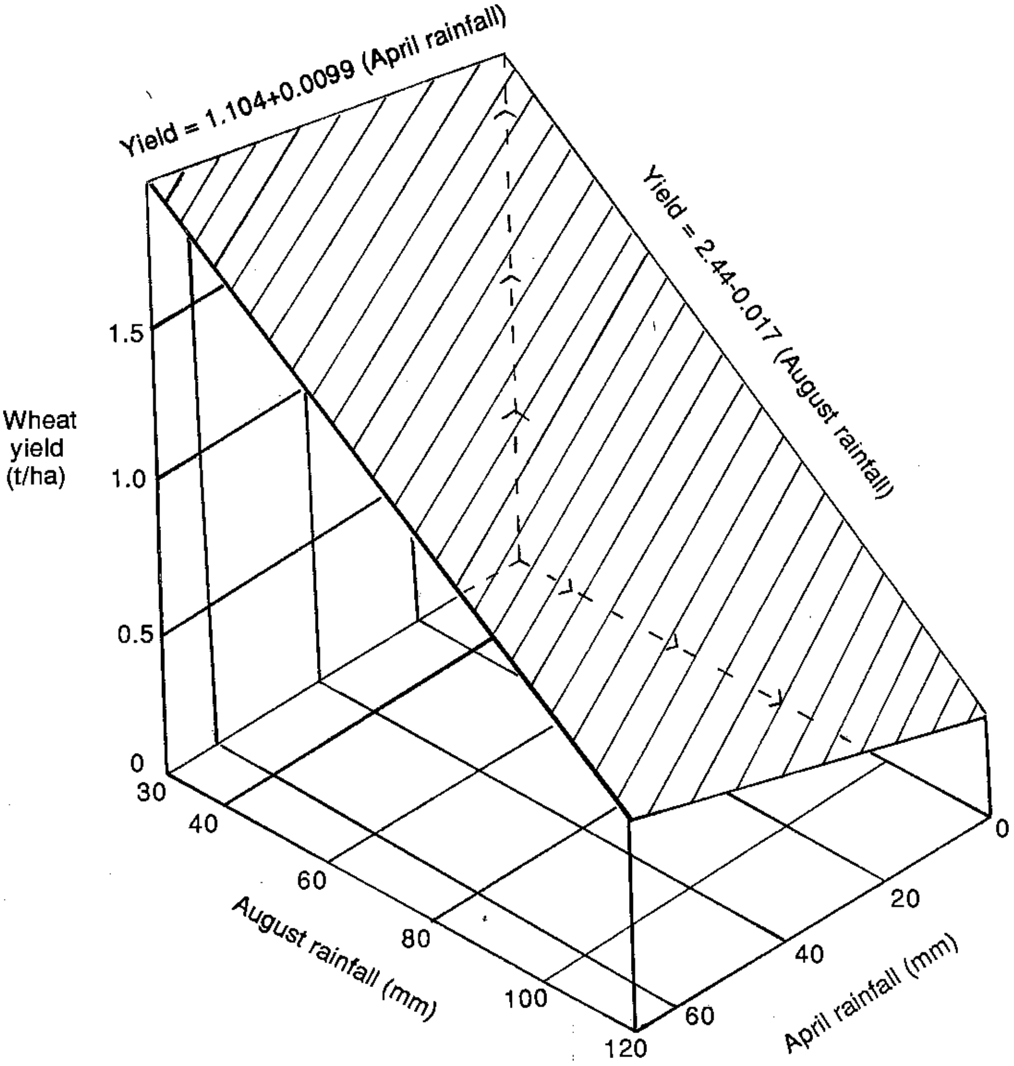


Table 6. Equations for predicting grain yield from rainfall.

Crop	Landform	Equation	r^2
Wheat	Uplands	$Y = 2.44 - 0.017$ Aug	0.80
	Uplands	$Y = 2.16 - 0.015$ Aug + 0.005 Apr	0.86
	Lowlands	$Y = 2.20 - 0.014$ Aug	0.44
	All	$Y = 2.32 - 0.015$ Aug	0.60
Oats	Uplands	$Y = 2.36 - 0.015$ Aug	0.51
	Lowlands	$Y = 1.96 - 0.002$ JJA	0.33
	All	$Y = 2.11 - 0.011$ Aug	0.35
Lupins	Uplands	$Y = 1.49 - 0.008$ Aug	0.57
	Lowlands	N.S.	
	All	$Y = 1.17 - 0.003$ June	0.34
	All	$Y = 1.31 - 0.006$ Aug	0.28

Y = Yield (t/ha)
Aug. = August rainfall (mm)
Apr. = April rainfall (mm)
June = June rainfall (mm)
JJA = June + July + August rainfall (mm)
N.S. = not significant ($P > 0.05$)

When the upland and lowland landforms are combined, August rainfall was the best predictor of wheat and oat yields and the second best predictor (after June rainfall) of lupin yields. The relationships indicated that for every 1 mm of rainfall in August, grain yields of wheat, oat and lupin seed decreased by 15, 11 and 6 kg/ha respectively.

The predictive equations in Table 6 and rainfall probabilities (Appendix 2) were used to calculate the minimum yield losses that were likely to be caused by excess rainfall in August (Table 7). It was assumed that yields were reduced in the central west shires when August rainfall had an exceedence probability of 0.6 or less (i.e. > 52 mm, Appendix 1). For the drier central east shires, it was assumed that August rainfall needed to have an exceedence probability of 0.5 or less for yields to be reduced (i.e. > 45 mm, Appendix 1).

These assumptions are conservative for the following reasons:

- Figure 16 showed that yields decrease at about 45 mm, lower than the 52 mm threshold used for the central west shires;
- the data are from all landforms and there are likely to be large losses from susceptible landforms before the average yields begin to decline.

The losses were greatest in the western shires because of their higher August rainfall (Table 7). In the wettest years (0.1 exceedence probability), wheat yields were estimated to be reduced by over 1 t/ha in the western shires.

The losses in yield can be converted to financial losses using the average area cropped to each of these crops (Appendix 1) and a value of wheat, oats and lupins of $150, $125 and $185 per tonne respectively (Table 8). The values are the farm gate price of the crops as the

Table 7. Estimated yield losses (t/ha) because of excess rainfall in the central Upper Great Southern Statistical Division

Crop/	Exceedence probability					
	0.6	0.5	0.4	0.3	0.2	0.1
Shire	(6 years in 10)	(1 year in 2)	(4 years in 10)	(3 years in 10)	(1 year in 5)	(1 year in 10)
Wheat						
Wagin	0.12	0.20	0.38	0.55	0.78	1.16
Narrogin	0.14	0.26	0.40	0.57	0.80	1.18
Cuballing	0.11	0.23	0.37	0.55	0.78	1.18
Pingelly	0.11	0.22	0.35	0.51	0.75	1.13
Brookton	0.11	0.22	0.35	0.52	0.75	1.13
Corrigin	0.00	0.10	0.20	0.33	0.53	0.85
Wickepin	0.00	0.11	0.22	0.35	0.55	0.89
Dumbleyung	0.00	0.09	0.18	0.32	0.49	0.78
Oats						
Wagin	0.09	0.14	0.27	0.40	0.56	0.84
Narrogin	0.10	0.19	0.28	0.41	0.57	0.85
Cuballing	0.08	0.17	0.27	0.40	0.56	0.85
Pingelly	0.08	0.16	0.25	0.37	0.54	0.82
Brookton	0.08	0.16	0.25	0.38	0.54	0.82
Corrigin	0.00	0.07	0.14	0.24	0.38	0.61
Wickepin	0.00	0.08	0.16	0.25	0.40	0.64
Dumbleyung	0.00	0.06	0.13	0.23	0.35	0.56
Lupins						
Wagin	0.05	0.08	0.15	0.22	0.31	0.46
Narrogin	0.05	0.10	0.15	0.22	0.31	0.46
Cuballing	0.04	0.09	0.14	0.21	0.30	0.46
Pingelly	0.04	0.09	0.14	0.21	0.30	0.45
Brookton	0.05	0.09	0.14	0.21	0.30	0.45
Corrigin	0.00	0.04	0.08	0.13	0.21	0.34
Wickepin	0.00	0.04	0.09	0.14	0.22	0.35
Dumbleyung	0.00	0.04	0.07	0.13	0.19	0.31

costs of production are the same with and without losses attributable to waterlogging.

The main losses in crop yield because of waterlogging were from wheat. This results from the larger area under wheat and to the greater sensitivity of wheat to high August rainfall as shown by the regression equations. Even though the central east shires (Corrigin, Wickepin and Dumbleyung) have lower rainfalls and it was assumed that waterlogging was not a problem in these shires in years with less than average August rainfall, the greatest financial losses occur in these shires. In a very wet year (1 year in 10), at least $12 m of wheat production will be lost from the Corrigin Shire alone.

Over a 10 year period (i.e. including years with high and low rainfalls) the average annual losses for the eight shires

Table 8. Estimated financial losses (in thousands of dollars) because of excess rainfall in the central Upper Great Southern Statistical Division

Crop/ Shire	Exceedence probability					
	0.6 (6 years in 10)	0.5 (1 year in 2)	0.4 (4 years in 10)	0.3 (3 years in 10)	0.2 (1 year in 5)	0.1 (1 year in 10)
Wheat						
Wagin	476	768	1,471	2,114	2,992	4,455
Narrogin	286	532	808	1,147	1,608	2,377
Cuballing	203	434	695	1,042	1,475	2,227
Pingelly	411	813	1,329	1,903	2,821	4,256
Brookton	365	722	1,180	1,741	2,505	3,779
Corrigin	0	1,450	2,741	4,676	7,472	11,988
Wickepin	0	854	1,688	2,760	4,308	6,929
Dumbleyung	0	927	1,895	3,347	5,122	8,187
Total	1,741	6,501	11,807	18,730	28,303	44,197
Oats						
Wagin	120	195	375	540	764	1,139
Narrogin	162	310	476	678	955	1,415
Cuballing	59	127	202	303	429	647
Pingelly	56	111	182	260	385	581
Brookton	85	168	274	404	582	877
Corrigin	0	38	72	122	196	314
Wickepin	0	81	160	261	408	656
Dumbleyung	0	47	97	171	262	419
Total	482	1,076	1,837	2,740	3,980	6,048
Lupins						
Wagin	21	35	67	97	136	202
Narrogin	11	20	31	45	63	94
Cuballing	10	22	36	55	78	119
Pingelly	14	27	44	63	93	140
Brookton	41	78	126	185	265	398
Corrigin	0	71	129	216	341	544
Wickepin	0	43	84	137	214	343
Dumbleyung	0	22	42	73	111	177
Total	96	318	560	870	1,301	2,017

were estimated to be about $11 m from wheat, $1.6 m from oats and $0.5 m from lupins (Table 9). This represented about 20% from the annual wheat production from the western shires and about 13% from the eastern shires (Table 9). Oats yields were about 14% lower from the western shires and 9% lower from the eastern shires. About 8% of the lupin crop was lost because of excess rainfall.

Table 9. Estimated financial losses (in thousands of dollars) because of excess rainfall over a ten year period in the central Upper Great Southern Statistical Division

	10 Year average loss	Value of average production	Percentage loss
Wheat			
Wagin	1,230	6,311	19
Narrogin	677	3,317	20
Cuballing	609	3,118	20
Pingelly	1,156	6,188	19
Brookton	1,031	5,494	19
Corrigin	2,842	21,785	13
Wickepin	1,659	12,067	14
Dumbleyung	1,955	16,345	12
Total	11,159	77,864	14
Oats			
Wagin	314	2,248	14
Narrogin	401	2,908	14
Cuballing	177	1,258	14
Pingelly	158	1,176	13
Brookton	240	1,774	14
Corrigin	75	794	9
Wickepin	158	1,589	10
Dumbleyung	100	1,163	9
Total	1,623	13,138	12
Lupins			
Wagin	56	555	10
Narrogin	26	254	10
Cuballing	32	324	10
Pingelly	38	393	10
Brookton	110	1,110	10
Corrigin	131	2,012	7
Wickepin	83	1,226	7
Dumbleyung	43	717	6
Total	519	6,591	8

Discussion

The correlations between monthly rainfall and crop yields indicate the dominant role that the amount and distribution of rainfall plays in the Upper Great Southern Statistical Division (Figure 17). Rainfall in April and May lengthens the growing season while rainfall in June and August is likely to damage the crop because of waterlogging, nitrogen loss and disease. July rainfall had a low correlation with final yield, possibly because of low soil temperatures slowing both crop growth and the development of anoxic conditions in the soil.

Heavy rainfall in April increased wheat yields, even when August was wet (Figure 18). An early break to the season will result in crops being at an advanced stage of development when waterlogging begins in winter, making them less susceptible to damage if nodal roots have formed (which can form aerenchyma).

The biggest losses in yield (t/ha) are likely in the western shires of Narrogin, Cuballing, Pingelly, Wagin and Brookton. Farmers in these shires have the most to gain from drainage and early sowing. However, the much greater areas under crop in the eastern shires of Wickepin, Corrigin and Dumbleyung means that the greatest financial losses are likely from these shires. This agrees with the estimates by Negus (1983) that about $4 m of wheat production was lost in the Kondinin Shire in 1974.

In a glasshouse experiment, Watson *et al.* (1976) found that lowland soils had higher yields under non-waterlogged conditions than upland soils, but similar yields under waterlogged conditions. The loss of yield because of waterlogging could be greater in lowland areas. Our results did not find any significant difference between upland and lowland landforms and the data were combined.

From the statistical analyses alone, excess rainfall has been shown to be a major limitation for crop production in the Upper Great Southern Statistical Division. The analyses are likely to underestimate the yield and financial losses.

Using remote sensing to map waterlogged crops

Any method of mapping the extent of waterlogging should be:

- accurate - few errors of omission (failure to map waterlogged areas) and commission (mapping non-waterlogged areas as being waterlogged);
- have adequate spatial resolution - ability to map areas of waterlogging as small as 50 m across;
- cost-effective - ability to map large areas at a price that farmers can afford;
- reproducible; and
- timely - available when waterlogging is being expressed at its full extent enabling the map to be checked in the field before the conditions disappear.

Three remote sensing methods of mapping waterlogged crops were assessed; colour aerial photographs, an airborne multispectral scanner (AMSS) and LANDSAT Thematic Mapper (TM).

The canopy of crops affected by waterlogging are often yellow, red or brown and colour aerial photographs were assessed as a method of mapping the problem. It is possible to measure the wavelength of light reflected from crops using instruments mounted in an aeroplane (AMSS) or on a satellite (LANDSAT TM). Airborne scanners have greater spectral and spatial resolution than satellite scanners , but are not routinely available. To determine which wavelengths most discriminated waterlogged crops from non-waterlogged crops, a portable field spectroradiometer (PFS) was used. The ability of different scanners to map waterlogged crops can be predicted once the areas of discrimination are known.

Colour aerial photography

Method

Colour aerial photographs with a scale of 1:10,000 were taken of four paddocks at Yornaning in September, 1987.

Results

Severely waterlogged wheat and oat crops were detectable by their brown colour. Moderately waterlogged areas of wheat (yellow old leaves) and of oats (red old leaves) were not apparent on the photographs. Known areas of waterlogging in pasture paddocks could not be distinguished on the colour aerial photographs.

Discussion

Colour aerial photographs can only be used to map severe waterlogging. The inability to detect moderately waterlogged crops is probably because the symptoms occur on the old leaves which are low in the canopy. Field checks are necessary to confirm that waterlogging is the cause of the colour on the photograph. The visual symptoms of waterlogging can be confused with several other crop conditions (e.g. nitrogen deficiency and barley yellow mosaic virus).

Portable field spectroradiometry

Method

A portable field spectroradiometer (PFS) was used in October 1987 on waterlogged and non-waterlogged areas of wheat, oats and pasture. The PFS measured the spectra in 256 continuous bands over the visible and reflected infrared wavelengths (0.4 to 2.5 µm).

Results

For wheat crops there was a poor separation in the visible part of the spectrum (0.40 to 0.75 µm) but a good separation between 0.80 and 1.08 µm in the near infrared (Figure 19). The latter interval is covered by bands 4 and 5 in AMSS and by band 4 in LANDSAT TM. There were separations between 1.20 and 1.38, between 1.46 and 1.82 and between 1.94 and 2.50 µm. The second of these intervals is covered by LANDSAT TM band 5 while the last interval is covered by AMSS bands 6, 7, 8 and 9 and LANDSAT TM band 7.

The PFS spectra for waterlogged and non-waterlogged oat canopies showed that there was slightly better separation in the visible part of the spectrum (0.40 to 0.65 µm) than for wheat (Figure 20).

Figure 19. Spectra from waterlogged and non-waterlogged wheat crops as determined by a portable field spectroradiometer

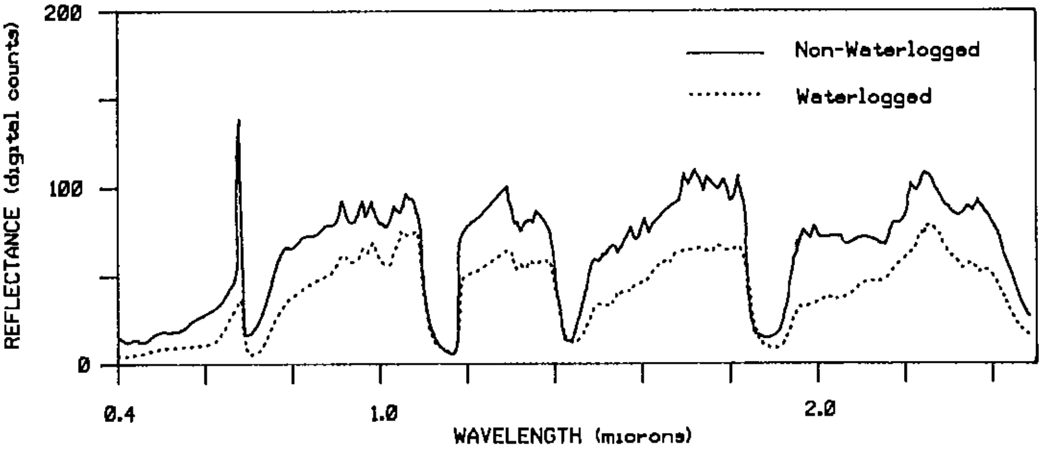


Figure 20. Spectra from waterlogged and non-waterlogged oat crops as determined by a portable field spectroradiometer

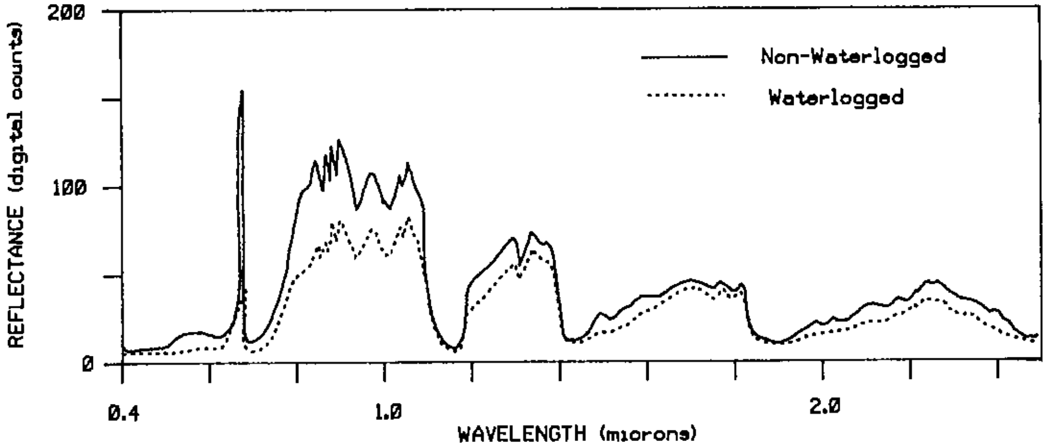
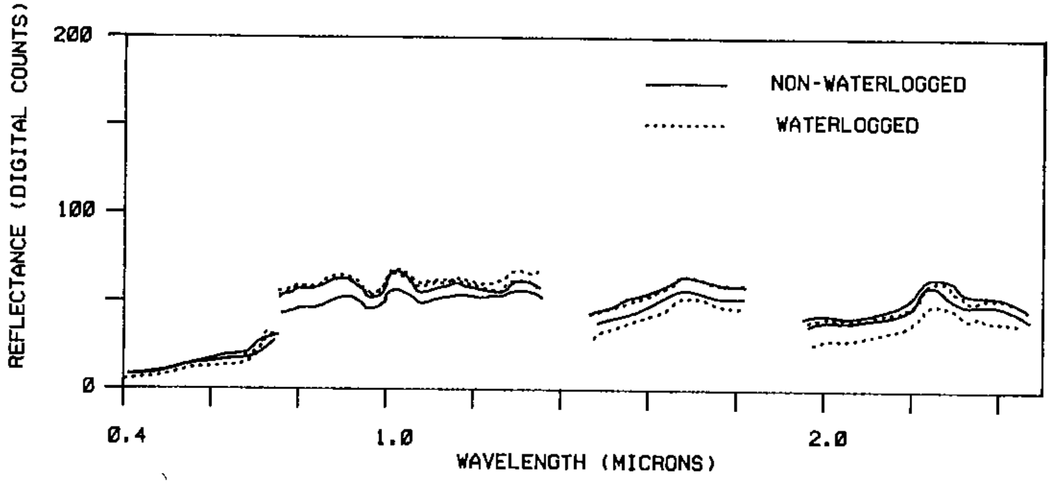


Figure 21. Spectra from waterlogged and non-waterlogged pastures as determined by a portable field spectroradiometer



The best separation was between 0.70 and 1.08, between 1.20 and 1.38, between 1.46 and 1.82 and between 1.90 and 2.50 µm.

There was an overlap between the spectra of two waterlogged and two non-waterlogged pasture canopies in October (Figure 21). In general, pasture spectra were more variable than crop spectra.

Discussion

Both AMSS and LANDSAT TM appear capable of differentiating waterlogged from non-waterlogged wheat crops (Figure 19). The poor separation in the visible wavelengths explained the difficulty of detecting waterlogged crops on colour aerial photographs. The separation for oats was at the same wavelengths as for wheat, but the degree of separation was wider for oats. It is likely that the same bands could be used to map both cereals (although the spectral classifiers may be different).

The variability in pasture spectra may result from different pasture compositions. It will probably be more difficult to map waterlogged pastures than waterlogged cereal crops.

Airborne multispectral scanning

Methods

Waterlogging in four paddocks at Yornaning was mapped using the GEOSCAN airborne multispectral scanner (AMSS) in 1987. The scanner recorded spectral reflectance values in 13 bands. Bands 1 to 5 (0.45 to 0.97 µm) covered the visible and near infrared (NIR) region , bands 6 to 9 (1.98 to 2.40 µm) covered the shortwave infrared (SWIR) region while bands 10 to 13 (8.5 to 12.0 µm) covered the thermal infrared (TIR) region.

Spectral data in the 13 bands were collected from each 5 m x 5 m picture element (or pixel) of the four paddocks on 22 October, 1987, the earliest that the instrument was available. Waterlogging symptoms were still evident at this time. Known areas of waterlogged and non-waterlogged crops were selected in the paddocks to act as training areas (see Glossary of terms). Waterlogged areas were identified by frequent field visits, from shallow wells, by crop symptoms and by monitoring crop growth using quadrat cuts.

A statistical procedure (canonical variate analysis) was used to discriminate between 18 training areas in the wheat paddocks and between 14 areas in the oat paddocks. The A-IMAGE method of image analysis was used (Campbell and Wallace 1987). A crop condition was allocated to most of the pixels in the four paddocks. Those areas not typical of any of the crop conditions in the training areas were classified as "atypical".

Results

In both the wheat and oat crops, there was a high degree of separation in the spectral data between the waterlogged and non-waterlogged conditions (Figures 22 and 23). The figures are scaled such that a separation of two units is considered to be a good discrimination.

A simplified set of 5 or 6 of the 13 spectral bands retained most of the discrimination. For wheat, the subset of bands was 2, 4, 6 , 10 and 11, while for oats the subset of bands was 3, 4, 9, 10, 12 and 13. Both subsets included bands from the NIR, SWIR and TIR parts of the spectrum.

About 33% of the wheat areas were labelled as being waterlogged (yellow areas in Figure 24). The areas mapped as being waterlogged agreed closely with the information that was collected from the paddock.

An estimate of the wheat yield that was lost because of waterlogging was made using production data from the paddocks. Perched water levels were measured in several parts of each paddock. Using an average waterlogging intensity for the waterlogged areas of 250 cm.days (SEW_{30} index) then the grain yield would have been decreased by about 1.3 t/ha over 15 ha (Figure 7). This represents a loss of about $3000.

The allocation map for the two oat paddocks (Figure 25) shows that about 28% of area was labelled as being waterlogged (yellow areas) in 1987. There was good agreement between the map and field knowledge. Using the production data from the paddocks and an average waterlogging intensity for the waterlogged areas of 300 cm.days, yields are estimated to have been reduced by about 1.5 t/ha (Figure 10) over 12 ha. This represents a loss of about $2400.

Discussion

Waterlogging in wheat and oat crops can be mapped accurately using AMSS. However, AMSS cannot be used routinely as it requires a flight with a specialized aeroplane which is in heavy

Figure 22. AMSS spectral separation of crop conditions. First two canonical variate means for 14 wheat training sites

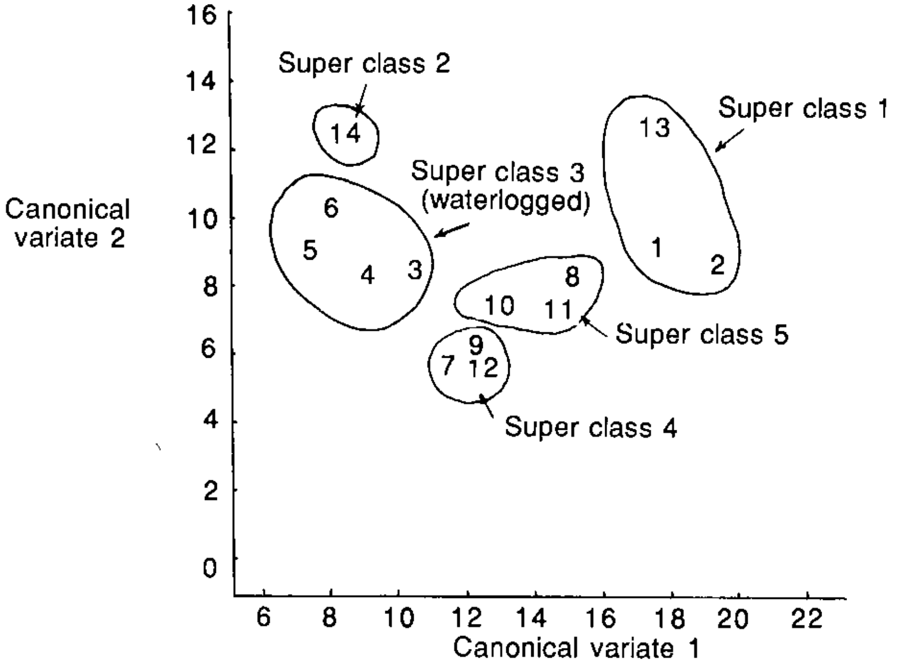
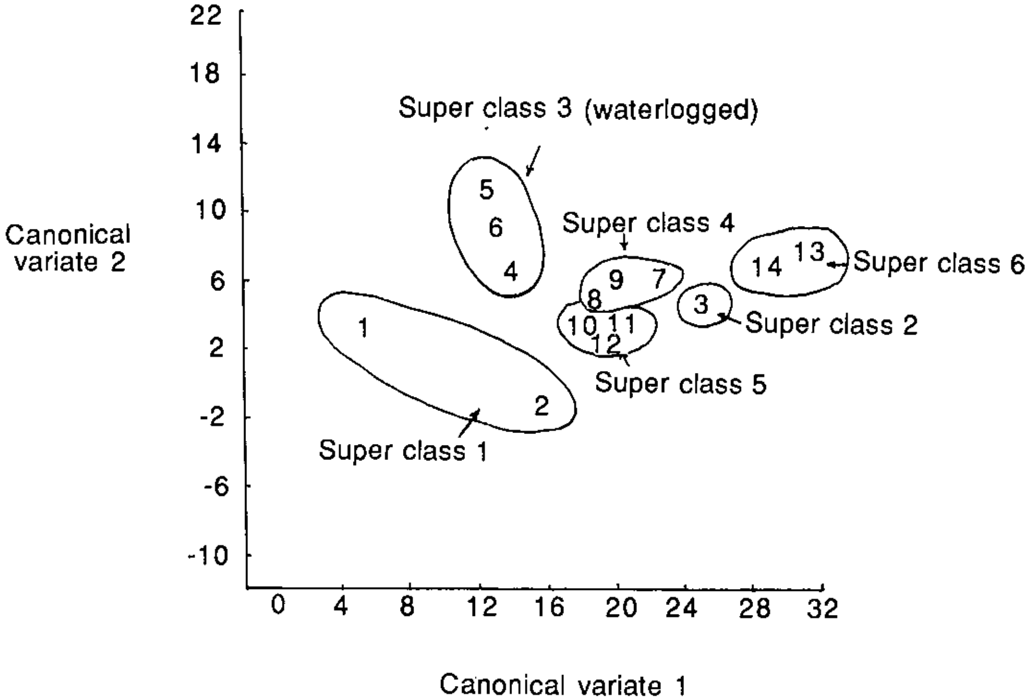


Figure 23. AMSS spectral separation of crop conditions. First two canonical variate means for 14 oat training sites



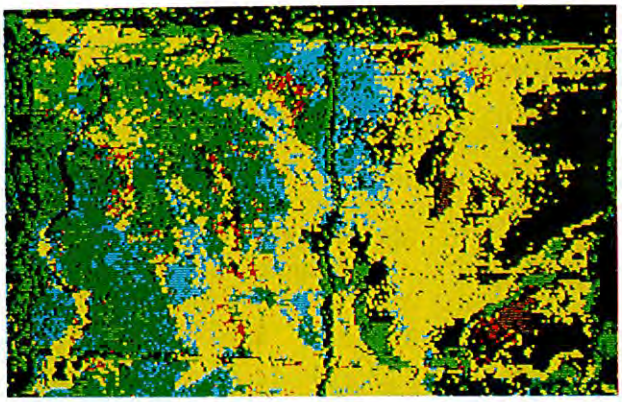


Figure 24: Classification map of two wheat paddocks with a 2 per cent typicality threshold. Yellow = waterlogged crop, red = possible waterlogging. Other colours = non-waterlogged but different crop conditions. Black = atypical.

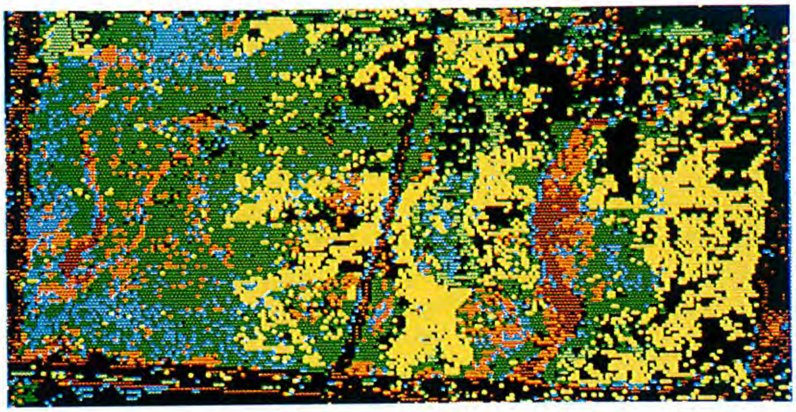


Figure 25: Classification map of two oat paddocks with a 2 per cent typicality threshold. Yellow = waterlogged crop. Other colours = non-waterlogged but different crop conditions. Black = atypical.

demand by mining companies. The method is also more expensive on a per hectare basis than LANDSAT TM.

N.A. Campbell (personal communication) found that AMSS bands 4, 6, 9, 10 and 11 differentiated waterlogged crops from non-waterlogged crops in the Corrigin area in September 1986. Four of the bands are the same as those for wheat and three are the same as those for oats at Yornaning. It is likely that the bands which distinguish waterlogging are fairly constant between areas, seasons and crops.

The losses in yields caused by waterlogging were in a year with below average rainfall. The crop had also reached an advanced stage of growth before the waterlogging began, which would have reduced the losses. Losses in wetter years, or years with earlier waterlogging, are likely to be much greater than was recorded in 1987.

LANDSAT TM

Methods

LANDSAT TM recorded digital reflectance values from seven bands within the electromagnetic spectrum. Bands 1, 2 and 3 covered the visible part of the spectrum, band 4 is in the NIR, bands 5 and 7 are in the SWIR and band 6 is in the TIR. All except band 6 have a spatial resolution (pixel size) of 30 m x 30 m. Band 6 has a spatial resolution of 120 m x 120 m.

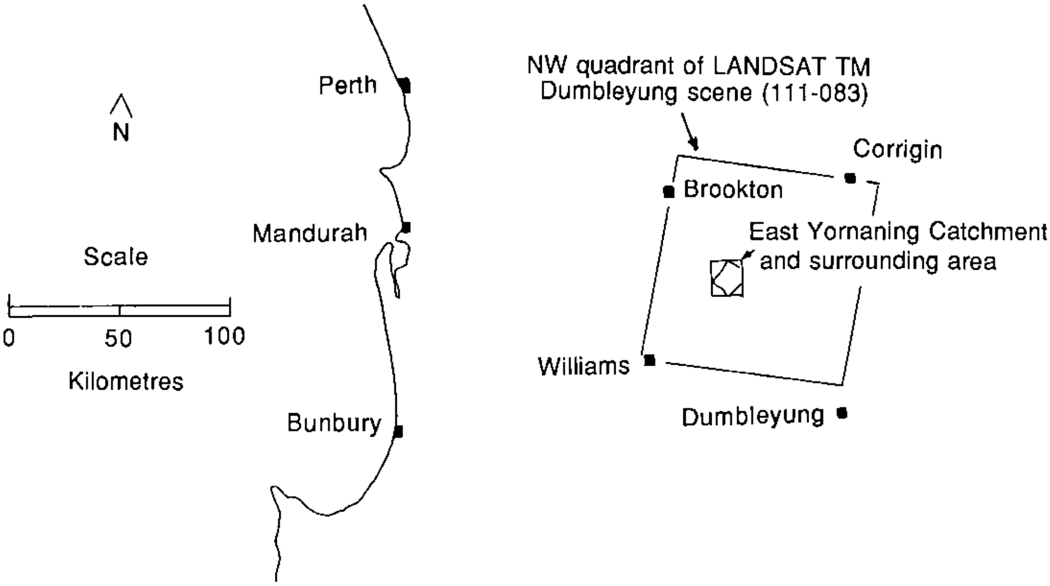
A quarter LANDSAT TM scene was obtained for the overpass on 23 August 1988 (Figure 26). The scene covers an area of 90 km x 90 km between Brookton, Corrigin and Williams. A 27,000 ha part of this area (15 km x 17.5 km), which included about 90% of the East Yornaning catchment, was chosen for detailed study. The study area is located in the centre of the quarter LANDSAT scene and represents 3.25% of the scene.

While rainfall was only slightly above average in the west and slightly below average in the east, there was widespread waterlogging in the study area in 1988. Colour aerial photographs of the area were obtained on 18 September 1988 to help with the selection of training sites.

Waterlogged and non-waterlogged areas of wheat, oats and barley were monitored throughout the 1988 growing season. The presence of waterlogging was determined by field observations, by temporary auger holes and by permanent wells, some of which were fitted with continuous water level recorders. Areas of obvious salinity were not included as training areas. However, given the sensitivity of waterlogged crops to salinity (Barrett-Lennard 1986) it is likely that some of the training areas were affected by both waterlogging and salinity. The training areas were surveyed using a compass and measuring wheel. Because of the spatial resolution of the LANDSAT TM scanner, only areas greater than 3600 m^2 (four pixels) were used for training.

As wheat was the major crop grown in the study area, it was used for training purposes. In all, 32 sites in 16 paddocks on six properties were used for training

Figure 26. Location of the study area (East Yornaning Catchment and surrounding area) in relation to the NW quadrat of the LANDSAT TM Dumbleyung scene (111-018)



and a further 12 sites were used for checking the accuracy of the method. The size of the training areas ranged from 4 to 20 pixels.

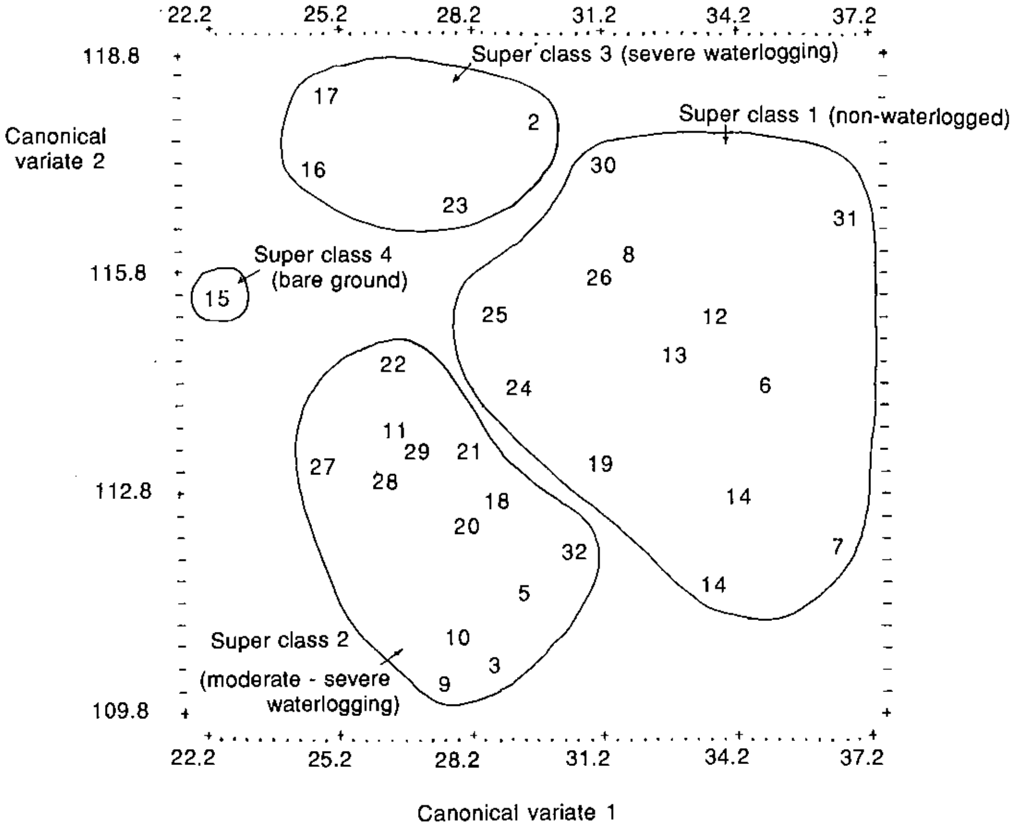
A Global Positioning System (GPS) was used to locate the training sites accurately on the image. A GPS is a satellite-based navigational system which uses several satellites to obtain the geographic position of any point on the earth's surface. The method enabled the location of the training pixels on the image on the computer to within one pixel (i.e. 30 m).

Of the 32 training sites, 19 were in waterlogged wheat crops and 13 were in non-waterlogged wheat crops. The data were analysed using the A-Image method (Campbell and Wallace 1987).

Results

From the first two canonical vectors, four superclasses (or groups of training areas) were selected (Figure 27). Superclass 1 included all of the non-waterlogged sites, Superclass 2 all of the moderate to severely waterlogged sites (crops still standing), Superclass 3 all of the very severely waterlogged and weedy sites (including some bare ground) and Superclass 4, waterlogged bare ground. The first canonical variate separated the non-waterlogged and moderate to severely waterlogged sites. This variate was composed largely of the weighted sum of bands 4 and 5. Bands 4 (NIR), 5 (SWIR) and 6 (TIR) were the most useful bands for separating waterlogged from non-waterlogged areas.

Figure 27. First two canonical variate means for 32 wheat training sites



The pixels in the 27,000 ha study area were allocated to the different superclasses to map the cropped areas which were affected by waterlogging and those which were not (Figure 28). As there were no training areas located in pasture or bush, these areas are shown mainly in black (atypical areas). There are some coloured pixels inside atypical (non-cropped) areas which is an indication of the accuracy of the map in locating cropped areas. The moderate to severely waterlogged areas (brown) are closely associated with cropped paddocks (Figure 28). The very severely waterlogged areas (blue) are also mainly confined to cropped paddocks. However, some of these areas, and areas of bare ground (grey), also appear in some pasture paddocks, along creek lines and in salt-affected areas.

Oat and barley paddocks were almost completely labelled by the wheat classifier. In those paddocks where the ground conditions were known, there was close agreement between the areas mapped as being waterlogged and their field condition.

The accuracy of the allocation map was checked by examining 12 training sites which were not included in the development of the superclasses (Table 10).

Of the 74 pixels from waterlogged field sites, 65 were correctly mapped (88% accuracy) meaning the error of omission was 12%. Of the 64 non-waterlogged pixels, only four were incorrectly mapped as being waterlogged, meaning the error of commission was 6%. From the allocation map of the 27,000 ha area it was calculated that about 30% was sown to cereals in 1988. Of this area, about 62% was classified as non-waterlogged, 32% as moderate to severely waterlogged, and 6% as very severely waterlogged or bare.

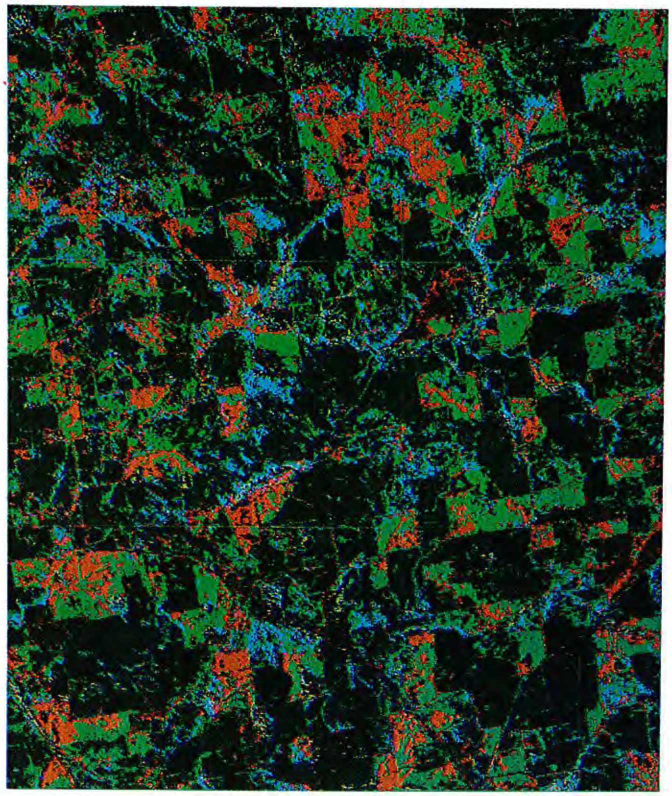


Figure 28: Classification map of the East Yornaning Catchment and surrounding area with a 2 per cent typicality threshold.
Green = non-waterlogged crop, brown = waterlogged standing crop, some yield possible, blue = waterlogged (and saline areas) - severe depression of growth, weedy understorey, minimum yield, grey = waterlogged - crop failure, black = atypical (mainly pasture paddocks and remnant vegetation). A full page enlargement of this image is included on inside back cover.

The final dry matter and grain yields of wheat, oats and barley crops in the moderate to severely waterlogged and non-waterlogged areas were determined from quadrat cuts (Table 11).

Waterlogging reduced the final dry matter yield of wheat, oats and barley by 68, 75 and 73% respectively while the reduction in grain yield was 83, 80 and 85% respectively. Waterlogging reduced grain yields more than it reduced final dry matter yields.

An estimate of the financial loss waterlogging caused to farmers in the 27,000 ha study area can be made from the remote sensing and grain yield data. If grain yields in moderate to severely waterlogged areas were decreased by 2.6 t/ha over an area of 2600 ha then losses were over $1.0 m (assuming a price of $150/t). If half of the bare and weedy areas in crops was caused by waterlogging, and yields were reduced by 3.0 t/ha over an area of 250 ha, then these losses were about $0.1 m. Total crop losses because of waterlogging were about $1.1 m, or $135 per cropped ha.

There may be additional costs of harvesting and carting a higher yielding crop but all of the costs of establishing it are the same. The yield losses used in the above calculations (2.6 and 3.0 t/ha) appear excessive given the current average yields in the area. They are

Table 10. Agreement between the field and map classifications (number of pixels)

Field class	Map class Waterlogged	Non-waterlogged	Atypical	Total
Waterlogged	65	5	4	74
Non-waterlogged	4	54	6	64
Total	69	59	10	138

Table 11. The final dry matter and grain yield (t/ha) of moderate to severely waterlogged and non-waterlogged wheat, oat and barley crops in 1988 (standard errors in brackets)

Crop	Waterlogged Dry matter	Grain yield	No. of samples	Non-waterlogged Dry matter	Grain yield	No. of samples
Wheat	3.22 (0.43)	0.53 (0.51)	26	9.94 (0.63)	3.16 (0.31)	15
Oats	2.74 (0.23)	0.74 (0.08)	18	10.92 (1.12)	3.63 (0.58)	6
Barley	2.12 (0.30)	0.42 (0.05)	8	7.71 (1.06)	2.71 (0.07)	2

Table 12. Estimated cereal crop losses in the west Central Upper Great Southern Statistical Division because of waterlogging in 1988

Shire	Cropped area (ha)	Estimated loss ($m)
Wagin	44,700	6.0
Narrogin	33,200	4.5
Cuballing	23,100	3.1
Pingelly	35,600	4.8
Brookton	36,400	4.9
Total	173,000	23.3

based on point measurements from waterlogged and non-waterlogged crops and therefore show what the potential yields may be without waterlogging. To achieve such high yields over large areas may be unrealistic without additional inputs (e.g. nitrogen and pest control).

The study area is located in the Cuballing Shire and the losses are probably indicative of the losses in surrounding shires in the west central Upper Great Southern Statistical Division (which had above average rainfall in 1988). If losses in cereal crops averaged $135 per cropped ha then over $23 m was lost from cereal crops in the five shires which make up the west central Upper Great Southern Statistical Division (Table 12).

Discussion

The colour aerial photographs and PFS showed that waterlogging in wheat and oat crops cannot be easily detected in the visible parts of the electromagnetic spectrum. The AMSS and LANDSAT TM results showed that crops stressed by earlier waterlogging can be accurately mapped by sensors which have bands in the near, short wave and thermal infrared parts of the spectrum. The most accurate maps can be made using AMSS, but for routine mapping of large areas, LANDSAT TM appears to be better suited.

The map of waterlogged areas produced by LANDSAT TM came from spectral data only. Incorporating other information (e.g. the location of cropped paddocks) could improve the accuracy of the map by excluding those waterlogged areas that were mapped in pasture paddocks. However, the cost of obtaining the additional information must be compared with the improvement in accuracy of the map. For most purposes, errors of 10% would be acceptable. This is particularly true for mapping waterlogged crops as there are no alternative mapping methods.

The spectral classifier would be expected to vary between seasons and major landforms. However, the bands would be expected to remain constant. For remote sensing scenes from other areas and years it would be possible to use the classifier developed in this study to provide a first approximation. The accuracy could then be checked in the field and training areas chosen to account for discrepancies.

On the Amiga 2000 microcomputer we used it would take about 20 minutes to classify a farm of 1500 ha. It is necessary to acquire the remote sensing scene at the right time of the year (i.e. August or September) and to have the classified image available for checking in the field before the crop ripens. It is feasible that the method developed in this study could be used routinely to map areas of waterlogged crop for farm planning purposes.

General discussion and conclusions

LANDSAT TM is potentially very suitable for mapping waterlogging in crops over extensive areas. It can give regional estimates of the extent of the problem and it can map waterlogged areas as small as 50 m across making it relevant to farmers considering drains or farm planning.

The 1988 rainfall in the west central Upper Great Southern Statistical Division had an exceedence probability of about 0.3 (i.e. we would expect it to be exceeded about three times in ten years on average). From the statistical method, such a year would be expected to result in at least an $8.0 m loss in wheat yields and at least an $2.2 m loss in oat yields (total loss of $10.2 m excluding barley losses). Using remote sensing, the loss in 1988 from all cereal crops was estimated to be about $23.3 m. The estimates differ by a factor of about two.

While the difference between the two estimates is considerable, they show the order of magnitude of losses caused by waterlogging. Both estimates are based on extrapolation from known data. The statistical method is known to be very conservative and estimates minimum rather than actual losses. We believe that the remote sensing estimate is more accurate as it measures all waterlogged areas, rather than relying on waterlogging affecting average crop yields.

It is difficult to extrapolate the estimates obtained using remote sensing to other years (unlike the statistical method which uses rainfall distributions). If the statistical method underestimates by a factor of two then the average annual crop losses in the central Upper Great Southern Statistical Division during a ten year period (with wet and dry years) will be about $20 m for wheat, $3 m for oats and $1 m for lupins.

The Upper Great Southern Statistical Division is not the only division that is likely to be adversely affected by waterlogging. The costs of waterlogging need to be extrapolated to adjacent divisions. McFarlane and Barrett-Lennard (1987) surveyed experienced advisers and used rainfall probability data to estimate the probability of widespread waterlogging. The Narrogin Shire had a probability of 40%; the Esperance Shire had a probability of 85% and Northam Shire had a probability of 15%. Therefore significant losses due to waterlogging are likely in the Statistical Divisions of Upper and Lower Great Southern, the South West, the west Midlands and the southern South East. It is likely that waterlogging is a major reason why crops and pastures in the > 400 mm rainfall zone are not achieving their potential yields.

The estimates of financial losses made in this report ignore losses of winter pasture production, which have been shown to be significant even in a year with below average rainfall. Pasture areas are much more common in the high rainfall areas. However, there is no easy method of converting lost or delayed pasture production to financial losses as there is for cereals. Investigations into the effect of waterlogging on pasture production are urgently needed. Further work is needed on agronomic methods (e.g. choice of variety, time of sowing, timing and level of fertilizer) of obtaining crop production from waterlogged areas not amenable to drainage.

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References

Armstrong, W. (1979). Aeration in higher plants. *Advances in Botanical Research* **7**: 225-332.

Barrett-Lennard, E.G. (1986). Effects of waterlogging on the growth and NaCl uptake by vascular plants under saline conditions. *Reclamation and Revegetation Research* **5**: 245-261.

Barrett-Lennard, E.G., Leighton, P.D., McPharlin, I.R., Setter, T. and Greenway, H. (1986). Methods to experimentally control waterlogging and measure soil oxygen in field trials. *Australian Journal of Soil Research* **24**: 477-483.

Campbell, N.A. and Wallace, J.F. (1987). The A-Image image processing system. User Manual. CSIRO, Australia.

Cox, J.W. (1988). Seepage interceptor drainage of duplex soils in south-western Australia. Ph.D. Thesis, Geology Department, The University of Western Australia.

Francis, C.M. and Devitt, A.C. (1969). The effect of waterlogging on the growth and isoflavone concentration of *Trifolium subterraneum* L. *Australian Journal of Agricultural Research* **20**: 819-825.

Francis, C.M. and Poole, M.L. (1973). The effect of waterlogging on the growth on annual *Medicago* species. *Australian Journal of Experimental Agriculture and Animal Husbandry* **13**: 711-713.

Grable, A.R. (1966). Soil aeration and plant growth. *Advances in Agronomy* **18**: 57-106.

McArthur, W.M., Churchward, H.M. and Hick, P.T. (1977). Landforms and soils of the Murray River Catchment area of Western Australia . CSIRO (Aust.) Land Resources Management Series No. 3.

McDonald, G.K. and Gardner, W.K. (1987). Effect of waterlogging on the grain yield response of wheat to sowing date in south-western Victoria. *Australian Journal of Experimental Agriculture* **27**: 661-670.

McFarlane, D.J. and Barrett-Lennard, E.G. (1987). Survey of research needs in water erosion, waterlogging and flooding in south-western Australia. Division of Resource Management Technical Report No. 61, Department of Agriculture Western Australia.

McFarlane, D.J. and Setter, T.L. (1990). Waterlogging is reducing the growth of your pastures when you need it most. In: Pushing Pastures Conference Proceedings (Ed. G.J. Parlevliet). Miscellaneous Publication No. 18/90, Department of Agriculture Western Australia .

McFarlane, D.J., Barrett-Lennard, E.G. and Setter, T.L. (1990). Waterlogging: a hidden constraint to crop and pasture production in southern regions of Australia. *In*: Proceedings of the 5th Australian Agronomy Conference, Perth. Australian Society of Agronomy.

Negus, T.R. (1983). The effect of waterlogging on cereal yields. Farmnote 60/83, Department of Agriculture Western Australia.

Northcote, K.H. (1979). A factual key for the recognition of Australian soils. Rellim Technical Publications Pty. Ltd., Adelaide, South Australia.

Ponnamperuma, F.N. (1984). Effects of flooding on soils. *In:* Flooding and plant growth (Ed. T.T. Kozlowski). Academic Press Inc.

Poole, M.L. (1971). Don't crop areas liable to waterlogging. *Journal of Agriculture Western Australia.* **12**: 108-109.

Sieben, W.H. (1964). Relationship between drainage conditions and crop growth for young light clay soils in the Nordost polder. *Van Zee tot Land* **40**.

Watson, E.R., Lapins, P. and Barron, R.J.W. (1976). Effect of waterlogging on the growth, grain and straw yield of wheat, barley and oats. *Australian Journal of Experimental Agriculture and Animal Husbandry* **16**: 114-122.

APPENDICES

1. Areas ('000 ha) used for growing grain crops in the central Upper Great Southern Statistical Division, 1982/3 to 1986/7. Source: Australian Bureau of Statistics

Year	Bro.	Cub.	Dum.	Nar.	Pin.	Wag.	Wick.	Cor.	West	East	Total
Wheat											
1986/7	20.1	10.8	70.2	9.7	23.3	23.5	49.5	92.0	87.4	211.7	299.1
1985/6	22.1	13.0	71.0	13.6	24.0	26.0	54.9	81.1	98.7	207.0	305.7
1984/5	24.3	13.6	71.5	14.7	26.0	26.4	56.2	96.1	105.0	223.8	328.8
1983/2	22.4	12.6	68.4	13.8	25.4	25.2	51.3	96.5	99.4	216.2	315.6
1982/3	22.2	13.0	70.5	15.4	26.7	26.7	48.0	102.7	104.0	221.2	325.2
Average	22.2	12.6	70.3	13.4	25.0	25.5	51.9	93.68	98.9	215.9	314.8
Oats											
1986/7	9.0	6.2	5.9	15.7	5.5	10.7	7.5	3.2	47.1	16.6	63.7
1985/6	7.2	5.7	6.0	13.3	5.3	8.9	7.0	3.3	40.4	16.3	56.7
1984/5	7.7	6.1	5.7	13.5	5.8	11.3	7.5	3.9	44.4	17.1	61.5
1983/4	9.0	5.6	5.5	14.9	5.8	12.1	8.9	5.0	47.4	19.4	66.8
1982/3	10.1	7.1	6.0	13.1	6.2	11.3	10.1	5.3	47.8	21.4	69.2
Average	8.6	6.1	5.8	14.1	5.7	10.9	8.2	4.1	45.4	18.2	63.6
Barley											
1986/7	3.8	2.7	6.1	3.2	4.0	5.2	1.8	5.0	18.9	12.9	31.8
1985/6	7.0	4.9	9.6	5.7	5.5	9.0	3.8	9.9	32.1	23.3	55.4
1984/5	7.1	5.3	11.5	7.4	5.3	10.0	3.5	10.6	35.1	25.6	60.7
1983/4	5.0	4.6	10.4	6.1	5.3	8.9	2.6	9.7	29.9	22.7	52.6
1982/3	5.0	4.4	9.9	6.0	4.5	8.6	3.6	7.6	28.5	21.1	49.6
Average	5.6	4.4	9.5	5.7	4.9	8.3	3.1	8.6	28.9	21.1	50.0
Lupins											
1986/7	4.8	1.4	3.1	1.1	1.7	2.4	5.3	8.7	11.4	17.1	28.5

Bro. = Brookton
Cub. = Cuballing
Dum. = Dumbleyung
Nar. = Narrogin
Pin. = Pingelly
Wag. = Wagin
Wick. = Wickepin
Cor = Corrigin

2. Probability of receiving different amounts of rainfall (mm) in August. Source: Australian Bureau of Meteorology

Shire	Exceedence probability 0.6 (6 years in 10)	0.5 (1 year in 2)	0.4 (4 years in 10)	0.3 (3 years in 10)	0.2 (1 year in 5)	0.1 (1 year in 10)
Narrogin	57	65	74	85	100	125
Cuballing	58	66	75	87	102	128
Pingelly	49	56	65	75	91	116
Brookton	49	56	65	76	91	116
Wagin	48	56	65	76	91	116
Corrigin	37	44	50	59	72	93
Wickepin	42	49	56	65	78	100
Dumbleyung	37	43	49	58	69	88

Glossary of terms

allocation map - a map in which the pixels have been allocated to classes or superclasses using a classification procedure.

band, spectral band - an interval of wavelengths from the electromagnetic spectrum over which integrated reflected energy is recorded by a sensor.

canonical variate analysis (cva) - a multivariate statistical technique which summarises the separation between groups of pixels ('classes') in the multi-dimensional spectral space.

classification - the process of assigning individual pixels to categories or classes.

exceedence probability - the probability that an amount of rainfall will be equaled or exceeded in any year. For example, a rainfall amount with an exceedence probability of 0.1 has a 0.1 probability of being equaled or exceeded in any one year and would be expected to be equaled or exceeded in one year in ten on average.

pixel (picture element) - an image datum element on which the spectral values are recorded. Also used to refer to the area on the ground which the image pixel represents.

superclass - a combination of spectral classes formed by grouping together training areas with the same ground condition.

training area - an area which is considered to be typical of the ground condition of interest. Training areas are selected for the crop conditions and land uses which are relevant to the study.

typicality - a probability value calculated for each pixel which represents its 'confidence level' of membership to a particular class.

typicality threshold - a confidence level chosen by the user at the display stage. Pixels with class typicality below this level are considered not to belong to the class and are usually displayed in black.

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GARRY L. DUFFIELD, Government Printer, Western Australia

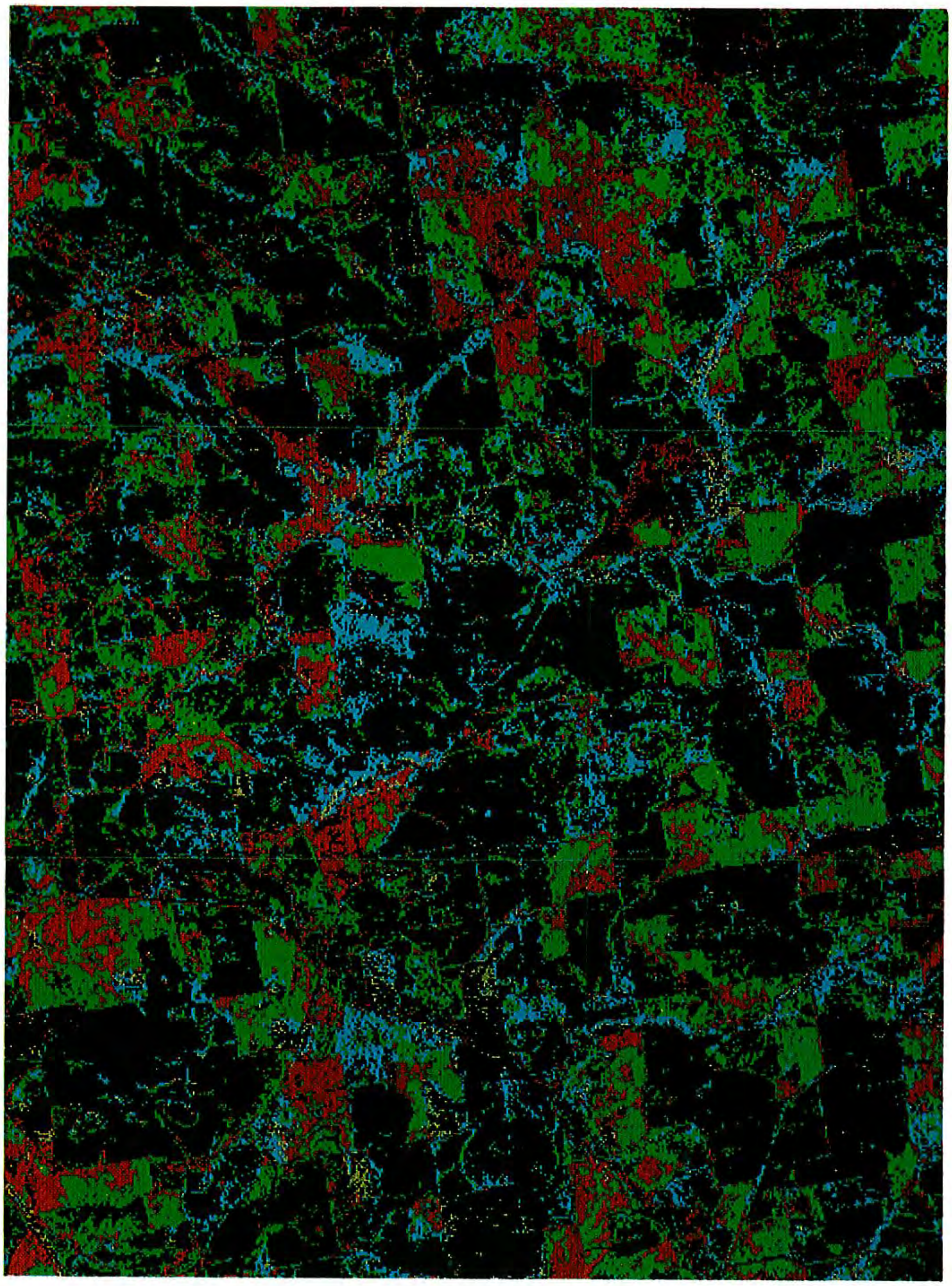

Figure 28: Classification map of the East Yornaning Catchment and surrounding area with a 2 per cent typicality threshold. Green = non-waterlogged crop, brown = waterlogged standing crop, some yield possible, blue = waterlogged (and saline areas) - severe depression of growth, weedy understorey, minmum. yield, grey = waterlogged - crop failure, black = atypical (mainly pasture paddocks and remnant vegetation).