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Estimating spatial patterns of wilting point deficit using a water balance model and a geographic information system

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Abstract

A geographic information system was used to integrate soil maps and soils data with a simple climatological water balance model to assess the spatial distribution of soil moisture deficit (accumulated wilting point deficits) over an area of approximately 250 000 hectares on the Canterbury Plains.

Spatial patterns of soil moisture deficit were analysed for 30-year average conditions, dry and wet years, and selected regimes of atmospheric circulation (e.g., El Niño). After dry years, highest deficits occurred in years with predominantly westerly circulation and in La Niña years. El Niño and Easterly years had smaller deficits. The ability of the Geographic Information System to integrate data from sources with varying resolution to show spatial and temporal variations in patterns of soil moisture deficit illustrates the value of this technology in agroclimatic studies.

Introduction

Knowledge of the moisture status of the soil, particularly in drought-prone areas, is important for planning at a regional level. For example, regional assessments of soil moisture deficit are needed to determine water requirements for, and benefits from, irrigation schemes, and for allocating water resources when water shortages occur. Knowledge of variability of soil moisture deficit is also necessary when assessing risks or predicting yields from crop production.

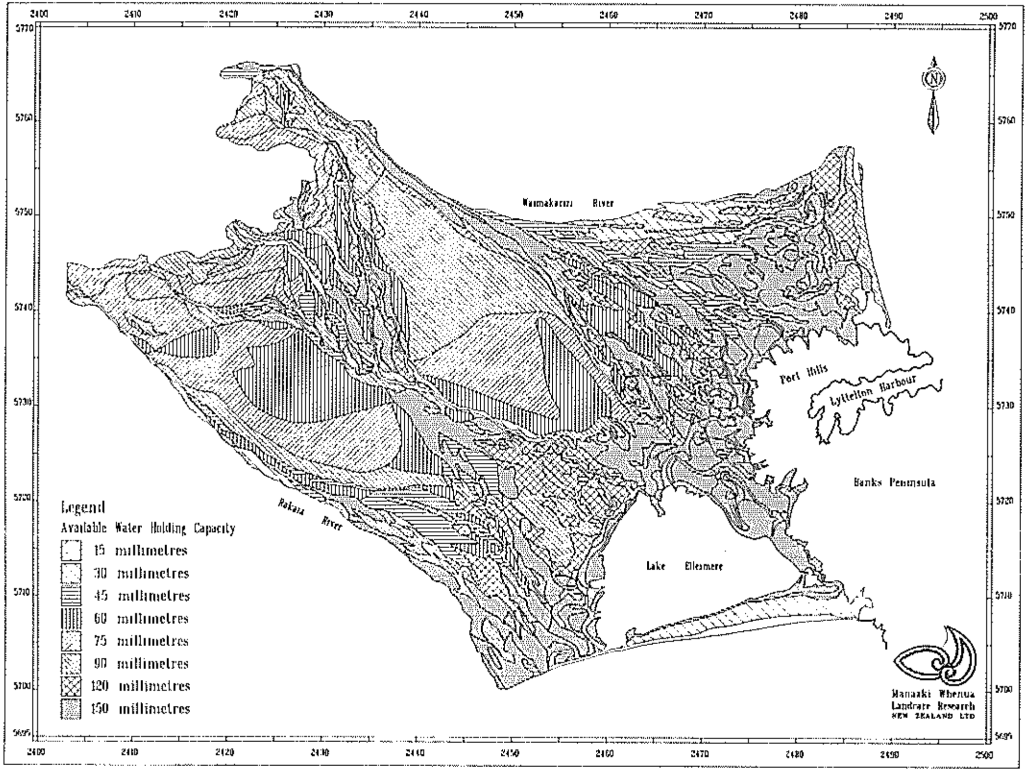
Estimates of regional soil moisture deficit in New Zealand have generally been based on a climatological approach, in which simple water balance models based on rainfall data and estimated evapotranspiration are used to estimate the potential "climatic" moisture deficit. The National Institute of Water and Atmospheric Research (NIWA) uses this method to estimate soil moisture deficit at "representative" sites throughout the country (New Zealand Meteorological Service, 1986). Period mean estimates of wilting point deficit are available for a limited number of climate stations (three on the central Canterbury Plains). This approach does not differentiate spatial patterns of moisture availability at the local or regional scale, or temporal patterns of moisture availability beyond average conditions.

Studies of the spatial variation in soil moisture deficit have generally used either remote sensing technology or a water balance model based on climate and soil data. Thermal (Shih & Jordan, 1993) and microwave (Engman, 1990) remote sensing data have been used for regional soil moisture studies (Jupp et al., 1990), but the convenient spatial nature of the imagery must be offset against the inaccuracies of image interpretation. In New Zealand good quality (minimal cloud cover) high resolution (10 - 30 metre) Landsat and SPOT imagery is available only for limited areas, and temporal coverage is often poor. The NOAA AVHRR imagery, which is readily available, has lower resolution (1000 m) and hence less accurate interpretations. Water balance modelling has been used successfully, but mostly for detailed studies, which require large quantities of point data for interpolating spatial variability of soil moisture deficits. For example Bregt and Beemster (1989) and Stein et al. (1991) used up to 2100 soil borings to establish patterns of soil properties in the same 404-ha study area in the Netherlands. Karnieli (1991) used a Geographic Information System (GIS) in a stepwise overlay approach and a complex model to estimate water budgets over hilly terrain. Such studies provide valuable information on soil-water processes, but the climate data used are generally unsuitable for regional investigations.

Male (unpublished report) started developing a predictive model of regional patterns of soil moisture deficits, based on climate and soil data collected at eight sites on the central Canterbury Plains. It was intended that data from the eight sites could be extrapolated via the model to estimate soil moisture deficits at any point within the study area to provide better information for irrigation scheme design and management. Male had planned to empirically model soil moisture variability, but recognised that this might require measurements at additional sites to adequately explain the spatial variability of soil moisture deficits. However, the project was not completed as Government restructuring lead to the dissolution of the Ministry of Works and Development.

In this study we used existing information on spatial variation of both climate and soil physical properties and a physically based water balance model to estimate wilting point deficits spatially and temporally at a regional scale. Male's (unpublished report) neutron probe data were used to validate the water balance model, and a GIS was used to integrate the soils and climate data with the water balance model. With this method we hope to remedy the shortcomings identified by Male (unpublished report), the lack of validation in previously used climate-based models and the lack of information on

FIG. 1— Estimated available water capacity (AWC) values for the soils of the Canterbury Plains between the Waimakariri and Rakaia Rivers.



regional patterns of soil moisture deficit, and at the same time illustrate the effectiveness of GIS in regional scale studies.

Climate and Soils

Climate

The weather and climate of Canterbury have been summarised most recently by Ryan (1987). The Canterbury Plains receive between 500 and 1000 mm of rain per year. Although mean rainfalls are evenly distributed throughout the year, droughts often occur because Canterbury's rainfall is highly variable (Seelye, 1941), and potential evapo-transpiration exceeds rainfall over summer months. The dominant regional orographic effects of the southwest-northeast trending Southern Alps to the west create a relatively uncomplicated climatic gradient from the coast to the inland foothills. The central Canterbury Plains between the Waimakariri and Rakaia Rivers were chosen for this study because the area is relatively flat, so topographic variations in climate related to elevation, slope, and aspect do not greatly distort the broader regional patterns. The area is also sensitive to large-scale circulation patterns. Climate singularities such as El Niño/Southern Oscillation (ENSO) and Anti El Niño (La Niña) events explain some of the spatial variation in rainfall as they alter regional circulation, which influences the magnitude and spatial and temporal distribution of rainfall (Sturman, 1986).

Northeast and southeast winds predominate on the Canterbury Plains (Ryan, 1987). Northeasterly on-shore sea-breezes are generated by differential heating of the land and ocean. On the plains strong southwesterly and southerly winds are frequently associated with frontal activity (Ryan, 1987). Northwesterly winds are strong, warm and dry, so that evaporation on north-west days can amount to 3 times the seasonal normal (Ryan, 1987), although this is countered to some extent by their low frequency (≈3% days). Northwesters are most common during October and November, when they influence evapotranspiration and soil moisture deficits during the early part of the growing season.

Soils

The Canterbury Plains consist of about 750 000 ha of lowland made up of a series of broad coalescing alluvial fan, terrace, and floodplain systems, with flat and undulating surfaces built up by the major rivers (the Waimakariri, Rakaia, and Rangitata) that flow from the Southern Alps (Fitzharris et al., 1982). Between the larger river/fan systems a number of smaller rivers (e.g., the Selwyn), which flow only from the foothills of the main ranges, have developed smaller fan systems. These fans have characteristic distributions of soils and soil properties (Kear et al., 1967). In the middle and upper plains, the surfaces of the fans and high terraces of the major rivers form large areas

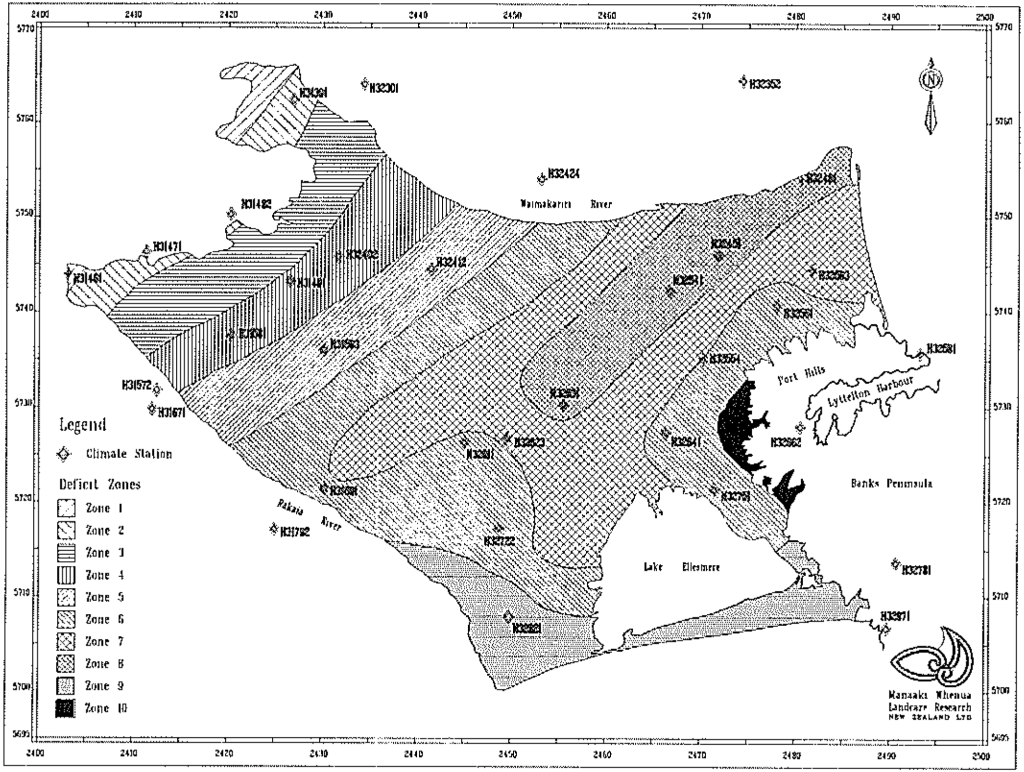


FIG. 2 — "Deficit zones" estimated from analysis of climate data and water balance model assuming a constant available water holding capacity over the study area. Zone 8 represents the highest deficit region and zone 1 the region with lowest deficits.

of generally shallow and coarser textured soils with a thin loess cover (e.g., Lismore and Chertsey Series). On lower terraces and floodplains, soils are generally deeper (although more variable) than on the higher terraces and fans (e.g., Templeton, Eyre and Waimakariri Series). Between the main fan surfaces and the coast, low lying terraces and floodplain areas are characterised by generally finer textured alluvial soils with poor drainage (e.g., Taitapu and Temuka Series). Along the coast the floodplains give way to sand dunes and swampy hollows. Lowland saline flats fringe Lake Ellesmere (e.g., Motukarara Series), which is separated from the ocean by the gravelly Kaitorete Spit (Taumutu Series).

Data Used in Modelling

The soils information from the main regional soil survey (Kear et al., 1967) and from a series of local surveys (Ward et al., 1964; Cox, 1978; Raeside and Rennie, 1974) were updated with more recent unpublished analysis and survey information (T.Webb, *pers. comm.*), then digitised and processed into a GIS vector theme using TERRASOFT, to create area-based soil polygons, with soil attribute data stored in an associated database.

Available water holding capacity plays a key role in linking soils with climate. Available water holding capacity is the "difference between the amount of soil moisture at field capacity and at wilting point, over the rooting zone of the crop", where field capacity is the maximum amount of water the soil can hold after drainage by gravity, and wilting point is the amount of moisture remaining in the soil when the crop has removed what water it can by evapotranspiration and begins to wilt (New Zealand Meteorological Service, 1986). Available water holding capacity depends on both the effective depth of the soil and the rooting depth of the plant species. Because of the variability of available water holding capacity within soil types as well as within specific soil polygons, and the large number of soil polygons defined in this study, it was not practical to make available water holding capacity measurements in every soil polygon in the study area. Instead, we used existing available water holding capacity class estimates for each soil type for a wheat or pea crop with an estimated effective rooting depth of 90 cm (Webb, *pers. comm.*). Each soil type was assigned to one of eight available water holding capacity classes with mean values ranging from 15 mm to 150 mm. These data, which formed the basis for determining the spatial distribution of soil-water holding capacities (Fig. 1), are consistently about 75% of those for pasture, measured by neutron probe over a 90-cm soil depth in similar soil types (Gray and Hutchinson, unpublished data). These values also compare favourably with water extraction values reported by Webb (1989) who found that spring-sown peas and barley extracted 20 to 30 percent less water over a 90 cm soil depth when compared with pasture.

Official daily rainfall data have been collected from approximately 80 locations within 20 km of the perimeter of the study area, with some stations providing records of more than 50 years. Where possible records covering the period 1949 - 1989 with no less than 20 years of rainfall data were used. A total of 30 sites were selected in and around the study area which met these criteria. Of these longer standing stations 11 collect detailed climatological records, including temperature, but only seven collect wind run data, and five sunshine hour data. Most of these 11 stations are near the coast.

Water Balance Model

The soil moisture deficit model used in this study is a simple single-layer model, in which the soil is represented as a water storage reservoir for plants, gaining moisture from rainfall and losing it to drainage and evapotranspiration (New Zealand Meteorological Service, 1986). If the soil reservoir is filled, runoff occurs, but this is not differentiated into surface runoff and subsurface drainage. It is assumed that runoff can occur only when the soil is above field capacity. There is no provision in the model for drainage through macro pores in unsaturated conditions or by surface runoff if the precipitation rate exceeds the soil infiltration capacity. Evapotranspiration is assumed to equal maximum or potential evapotranspiration using Penman's equation (Penman, 1956). The model assumes that evapotranspiration does not vary greatly in

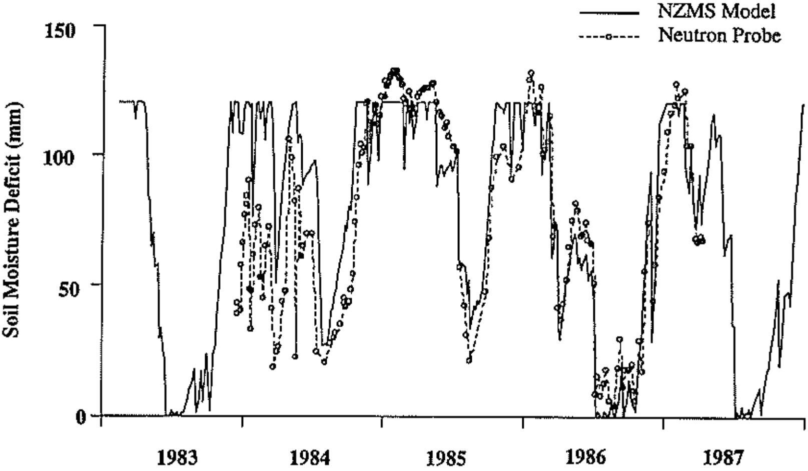


FIG. 3 — A comparison of neutron probe data from near Christchurch Airport and NZMS soil moisture deficit model based on climate data from Christchurch Airport. Available water holding capacity estimated from neutron probe data is 121 mm.

the short term, and hence mean daily potential evapotranspiration is derived directly from mean monthly potential evapotranspiration.

The difference between the actual amount of water in the soil and the wilting point is the available soil moisture. The difference between the available soil moisture and field capacity is the soil moisture deficit. Hence the soil will be at field capacity when soil moisture deficit equals zero and at wilting point when the soil moisture deficit equals the available water holding capacity of the soil. Although the water balance model can be set to output results as millimetres of soil moisture deficit, its primary focus is on water available to plants, so results are usually expressed as a wilting point deficit. This equates to the amount by which potential evapotranspiration exceeds rainfall when the soil is at wilting point (available soil moisture equals zero). The wilting point deficit provides a useful estimate of how much irrigation might be needed over a given period to keep plants from wilting.

Model Validation

To assess the accuracy of the model in predicting wilting point deficits in the study area, we compared output from the water balance component of the model (i.e. soil moisture deficits) with neutron probe data collected by the Ministry of Works Hydrology Centre between late 1983 and early 1987 for sites within the study area (Gray and Hutchinson, unpublished data).

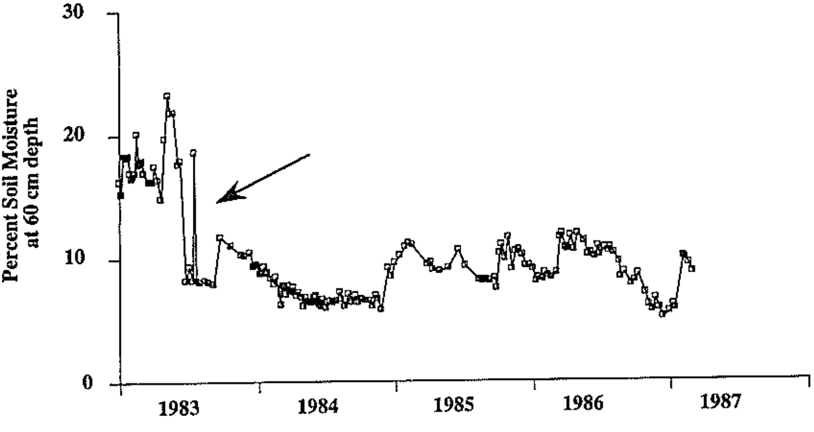


FIG. 4 — The probable error in the neutron probe record is illustrated by this raw data (percentage soil moisture) for Darfield. There is a marked discontinuity in the record in mid-1983, after which maximum moisture values never reach the same levels as in the early part of the record.

Five of seven neutron probe sites were chosen for comparison (Christchurch Airport, Darfield, Hororata, Lincoln, and Templeton). Each site was sufficiently close to a climate station for the records of that station to apply to that site. Firstly, we estimated the available water holding capacity at each site from the neutron probe data using the difference between maximum moisture value (approximately field capacity) and minimum moisture values (approximately wilting point). However, extreme high and low moisture values from the neutron probe were disregarded when it was thought either that high readings may have been due to high water tables, or low readings due to the neutron probe including the air above the soil surface in its sample when making near surface measurements under dry conditions. Based on the estimates of field capacity the data from the neutron probes were converted to millimetres of soil moisture deficit.

The available water holding capacity values estimated from the neutron probe data were also used with the NIWA model to predict water extraction over the four year period that the neutron probe soil water measurements were made at the five sites. The model was set to output soil moisture deficit rather than wilting point deficit for pentades (five day increments - the finest temporal resolution available), and predicted values were compared with the soil moisture deficits derived from the measured soil water values (Fig. 3). All five sites exhibit similar results. The artificially 'flat' model trace at high deficits is caused by the model estimating that wilting point has been reached. The model assumes that no further water can be lost from the soil at this point. The neutron probe data during these dry periods is not constrained by the estimated wilting point, hence the obvious discrepancies between measured and modelled soil moisture deficits. The magnitude of this discrepancy is either due to an error in our estimate of wilting point, or to the possible errors in neutron probe data.

We did not analyse goodness-of-fit between the modelled and neutron probe data, as the regular pentade output from the soil moisture deficit model and the irregular recording dates of the neutron probe data, both of which can vary markedly over time periods of one or two days, can not be properly paired. However, our prime concern is to show that the model accurately predicts the gross trends in soil moisture deficit, giving reasonable estimates of the timing of onset and magnitude of deficits, rather than precisely matching a detailed trace of soil moisture deficit. During the first half of 1984 the fit between the neutron probe records and the modelled estimates of soil moisture deficit was poor at all five sites. However, from about August 1984 onwards the general fit between modelled and observed data appears very good, indicating that the model provides a good simulation of soil moisture deficit at these sites. The neutron probe data show a break in continuity between the early and latter parts of the record at all five sites

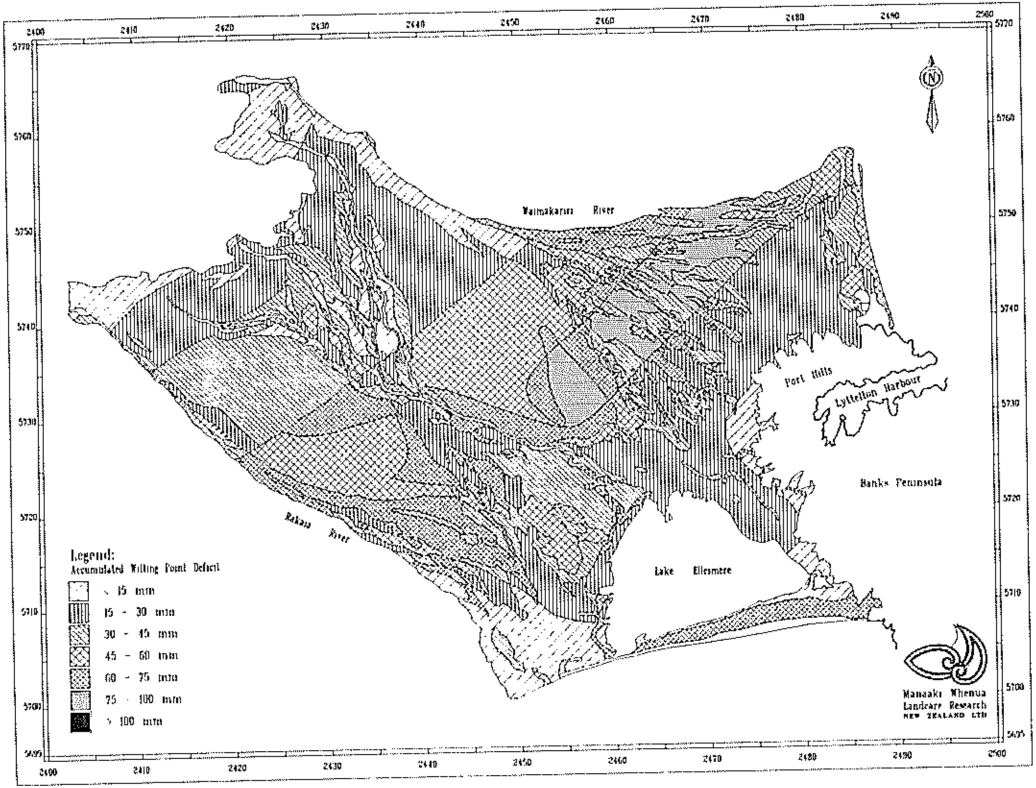


Fig. 5 — Mean accumulated wilting point deficits for period mean November (early summer) conditions. Note the relatively complex pattern and the fact that most of the area experiences wilting point deficits of less than 60 millimetres.

(Fig. 4). Calculations of available water holding capacity excluding data before this break consistently matched measured values more closely than values obtained using the full record, which were much higher than any values measured in the field (T. Webb, *pers. comm.*). We believe that the early part of the neutron probe record may be unreliable, probably because a number of different neutron probes were used early in the investigation, so we excluded this suspect data when calculating available water holding capacity. For the remainder of the period the model accurately mimics all gross variations in soil moisture deficit.

Method Used to Map Wilting Point Deficits

Spatial patterns of wilting point deficit were determined by firstly creating climatic zones then calculating wilting point deficit for each available water holding capacity within that zone and generating a map of wilting point deficit values using the GIS.

Deficit values for the 30 climate stations were calculated using one common available water holding capacity value and running the water balance model for all climate stations for the period mean conditions. The resulting wilting point deficits for each station were plotted on a map and 10 deficit zones, based on 50 mm deficit increments, were drafted by manual interpolation (Fig. 2). Deficit zone 8 in the northeast had the greatest deficit, and deficits decreased approximately linearly both inland and towards the coast. The boundaries of these deficit zones were digitised.

The map of available water holding capacity classes (Fig. 1) and the map of deficit zones (Fig. 2) were combined using the spatial overlay function of the GIS to create a new set of polygons comprising soils with attributes acquired from the two parent themes. The overlay process generated a total of 80 possible combinations from the 8 available water holding capacity classes and 10 deficit zones. A simple coding routine in the GIS database was used to identify each polygon according to its combination of available water holding capacity class and deficit zone.

Standard accumulated wilting point deficits were then calculated using the NIWA water balance model for all 30 climate stations and for the eight possible available water holding capacity values. Where several climate stations fell within the same deficit zone wilting point deficit data were averaged, and in deficit zone 3, which contained no climate stations, wilting point deficits were derived by averaging the data from zones 2 and 4. These data were placed in an attribute table with a unique row of data matched to the code. The final step linked the GIS database to the attribute data (wilting point deficit) using a relational join on the code attribute, and maps of wilting point deficit were generated via ad hoc queries in the GIS, based on each

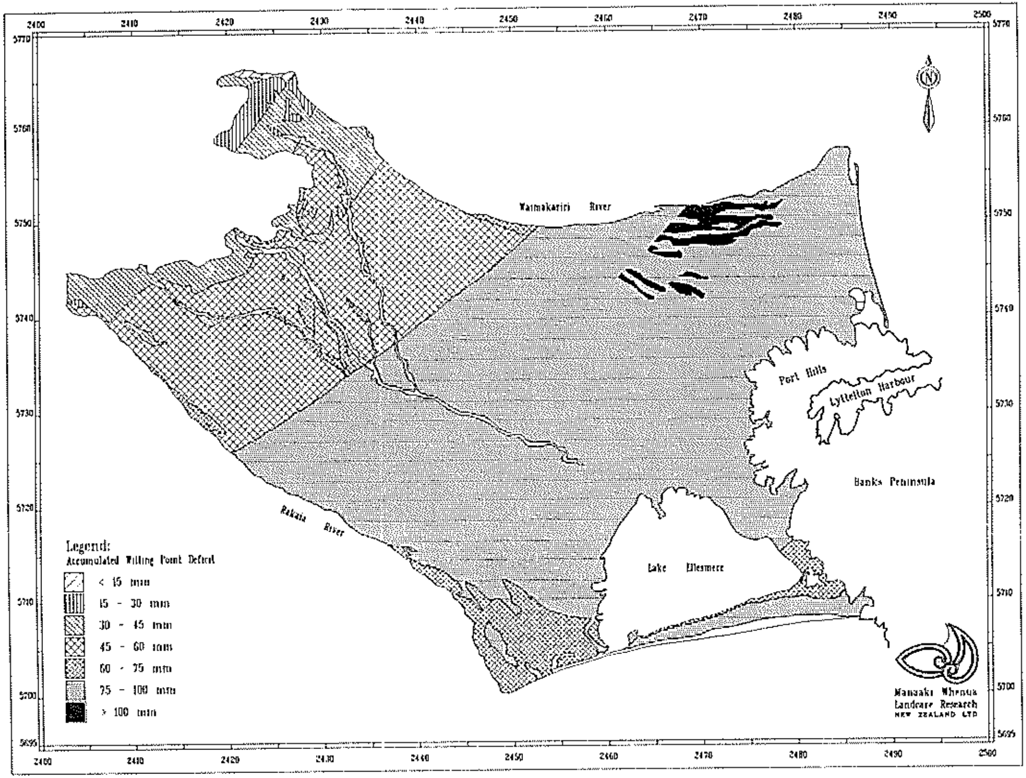


FIG 6 — Mean accumulated wilting point deficits for period mean January (late summer) conditions. The entire region typically experiences wilting point deficits of 75 to 100 millimetres.

polygon's assigned wilting point deficit data for its available water holding capacity and deficit zone (e.g. Fig. 5).

Spatial Patterns of Wilting Point Deficit

On average, early summer (November) wilting point deficits are influenced more by the size of the available soil moisture reservoir rather than broad climatic patterns (see Fig. 5). Thus soils with low available water holding capacities enter deficit conditions earlier than those with high available water holding capacities, illustrating the vulnerability of low-available water holding capacity soils to early drought. Through December and January, rates of evapotranspiration rise and all soils dry out rapidly. By mid-summer the complex wilting point deficit pattern associated with variability in soil available water holding capacity becomes subordinate to the regional climate pattern, with high wilting point deficits over large areas (Fig. 6).

Because changes in regional circulation patterns have a strong influence on regional climate variation, and hence spatial and temporal patterns of soil moisture deficit, we ran the model for the five driest and five wettest years since 1950 (based on mean rainfall over the study area), the five years with strongest easterly and westerly airflows since 1950, and the five years with strongest El Niño and La Niña conditions since 1950

To illustrate the difference between different seasons, we calculated seasonal and monthly spatially-averaged wilting point deficit indices and displayed these data in histograms and line graphs (Figs. 7, 8). Over the whole growing season the dry years had a higher index than seasons with strong westerly circulation and La Niña seasons (Fig. 7). El Niño and Easterly seasons had more moderate wilting point deficits.

Maximum values for monthly spatially-averaged deficit indices for the study area were similar for most years except the Wet years. However distinct temporal patterns of wilting point deficits related to the seasonal progression of circulation patterns associated with climate regimes were also evident (Fig. 8). La Niña seasons are generally associated with summer anticyclones to the east of New Zealand that block circulation, causing long periods with stable anticyclonic conditions and little rainfall, leading to dry conditions over the entire plains between October and December. In late summer, northeasterly rain frequently recharges soil moisture stores in the driest areas in the central plains, leading to a rapid drop in wilting point deficits between January and February (Fig. 8). Despite high deficits in December, La Niña seasons had the shortest period with high deficits during summer, except for the wettest years. In contrast to La Niña, El Niño seasons are characterised by more southwesterly and westerly circulation. The westerly circulation generally results in more frequent passage of fronts,

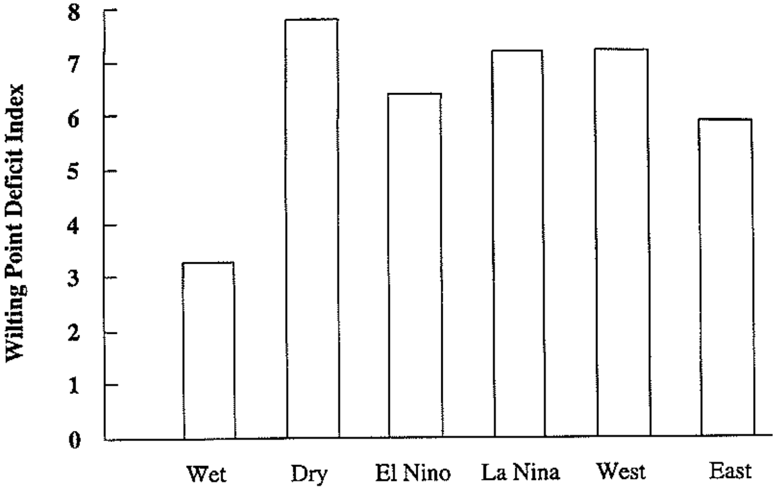


FIG. 7 — An area-weighted mean index of seasonal moisture deficit indicates the relative "dryness" of the types of growing season identified in this study.

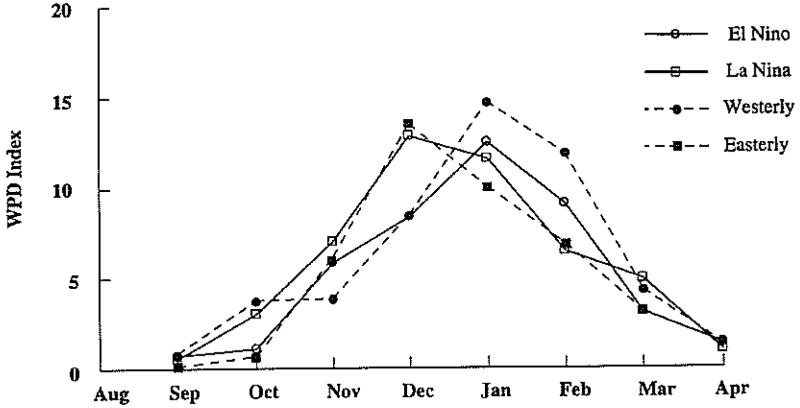


FIG. 8 — An area weighted mean index of monthly moisture deficit illustrates the differences of timing and intensity of deficits during El Niño and La Niña seasons, and growing seasons with predominantly easterly and westerly circulation.

with associated rain in Canterbury. Rainfall is higher than during La Niña conditions in spring, counteracting to some extent the stronger advective drying conditions of westerly katabatic winds blowing over the Southern Alps. Monthly wilting point deficit indices were negatively skewed, with highest deficits in January and February during El Niño seasons (Fig. 8).

When comparing years with predominantly easterly or westerly circulation, the contrast in timing of high wilting point deficits between early summer and late summer is even more evident (Fig. 8). Westerly seasons had low early season wilting point deficits (particularly in November), but high wilting point deficits during January and February. In easterly years, from low wilting point deficits in October, conditions rapidly dried out to maximum wilting point deficit in December, followed by a steady decline in deficits through the late summer (Fig. 8).

The implications for land management and productivity of spatial and temporal variations in wilting point deficit are the subject of another paper (Saunders et. al., in prep). An empirical wheat yield model, one of a number studied by Baird (1986) and Baird and Gallagher (1985), is used to relate moisture deficit to reduction in yield. Although it does not attempt to account for many of the physical details of crop physiology and development, the linear relationship between potential or actual deficits and wheat yields has been extensively validated in Canterbury for estimating gross wheat yields, and has been shown to account for 70% and 80% of variation in yield. The model predicts wheat yield will decrease below potential (either 6 or 8.5 tonnes/ha depending on location) by 0.3% for every 1 mm of deficit. Figure 9 shows the effect of different climatic conditions on area-weighted mean wheat yield (tonnes/ha) assuming dryland conditions, and a simple irrigation scenario which applies up to 400 mm of water. Saunders et al. (in prep.) use the wilting point deficit data derived in this study to estimate wheat yield for two management regimes (autumn and spring planting) both with and without irrigation, and assess profitability and risks for wheat production on the Canterbury Plains, and relate them to variability in climate, production and economic factors.

Conclusions

The methods outlined in this paper involve considerable generalization, first in estimating available water holding capacity classes for soil series with inherently variable water holding capacities, secondly in estimating climatic zones from only a sparse network of climate stations, and finally in overlaying two spatial layers with different spatial resolutions. However the method is consistent with the quality of the input data, and provides output in the form of maps or tables with accuracy and resolution suitable for broad regional

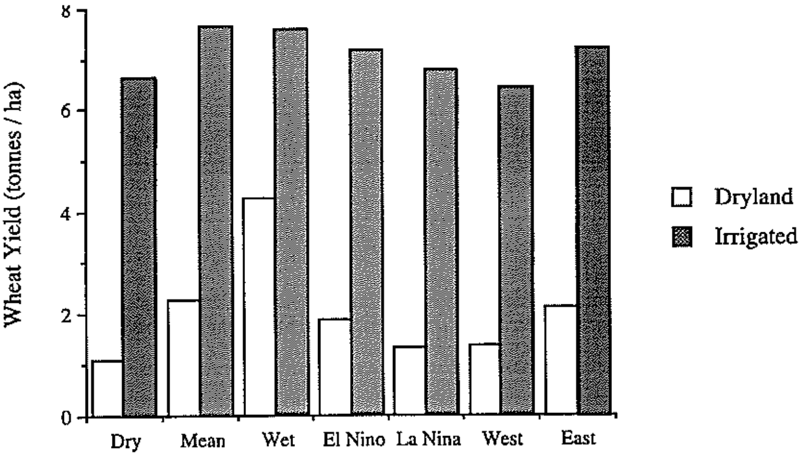


FIG. 9 — A comparison of estimated mean wheat yields (tonnes/ha) for dryland and irrigated conditions, under a range of climatic conditions.

studies of accumulated wilting point deficit. The spatial overlay capability of the Geographic Information System provides a simple but effective method for combining soil and climate attributes which can be linked to the non-spatial water balance model via a relational join. Soil moisture deficit estimates from the water balance model also were validated against 5 years of neutron probe data for five sites.

The complex spatial and temporal patterns of wilting point deficit that have emerged from this analysis are valuable aids to understanding the dynamics of moisture availibility in relation to regional circulation patterns. The methods are useful for regional agricultural planning, including assessment of the potential impact of irrigation and other management practices on yield and gross margins of crops such as wheat, for which yield predictions are correlated to soil moisture availability. Studying the timing and spatial extent of past drought conditions, and monitoring regional drought in real time may be another potential use for this method.

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