Modelling the water budget of Ireland—evapotranspiration and soil moisture

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ABSTRACT

The water budget is one of the most important exchange cycles within the earth-atmosphere system. When applied to a surface it accounts for the partition of precipitation into evapotranspiration, runoff and changes in soil-water storage. While there has been work published on some of these components, few have attempted to evaluate these within the context of the water budget. In this paper a simple model is applied to a 5x5km grid superimposed on the land area of Ireland. The model uses measured monthly values of meteorological variables (precipitation, temperature and sunshine hours) and databases of landuse and elevation to calculate each of the water budget terms. The results for the thirty-year period 1961-1990 are presented and seem to conform to the known climate of the period.

Key index words: water budget, evapotranspiration, climate model.

Introduction

The hydrological cycle is one of the most fundamental of the energy and mass exchange cycles within the earth-atmosphere system. It refers to the passage of water in gaseous, liquid and solid forms between the oceans, atmosphere, lithosphere and biosphere. On land it can be expressed in the form of a water budget which accounts for precipitation (P), evapotranspiration (E), runoff (R) and fluctuations in the water stored in soil (ΔS)—

$$P - E - R = \Delta S.$$

Evapotranspiration includes both the direct evaporation of water from the surface and the exchange of water vapour that occurs at the leaves of plants (transpiration) as a consequence of water extraction from the soil by the root system. The difference between precipitation and evapotranspiration results in changes in the water stored in the soil. If P exceeds E then ΔS will be positive or, if the soil is saturated, will contribute to a surplus that will eventually generate runoff. The saturation value of soil is often represented by its field capacity, the depth of water that can be held in the soil against the force of gravity. If the soil is at field capacity any extra water will either run off rapidly overland or percolate slowly downwards through the soil. As a reasonable approximation runoff can be said to be derived from these two sources, with markedly different response rates. When E exceeds P, vegetation will extract water stored in the soil at a rate that depends upon its ‘need’ and the pressure that the root system is required to exert. As the soil dries, the required pressure increases and plants become less efficient at meeting their water needs. In severe drought conditions the response of the vegetation is to close its stomata, effectively terminating both transpiration and photosynthesis. It is apparent, then, that the water budget incorporates meteorological and soil conditions and vegetational responses.

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If a sufficiently lengthy period (30 years) is considered, it can be assumed that the changes in storage are small and the remaining terms balance. Estimates for Ireland in these circumstances indicate values of 1150mm, 450mm and 700mm for precipitation, evapotranspiration and runoff, respectively (MacCarthaigh, 1996). While there has been some published research on each of these components individually there has been, until very recently, little on the overall water budget. Precipitation has received the most attention with numerous publications on its spatial (for example, Perry, 1970), temporal and seasonal characteristics (for example, Logue, 1990) and synoptic origins (for example, Sweeney, 1985). The research presented here will add little to the existing body of knowledge in this area. Measurements of precipitation are the most extensive both spatially and temporally of all meteorological elements and monthly records are maintained for hundreds of locations (775 in 1990) on the island. By comparison, there are few measurements of the remaining components of the water budget.

Runoff can be examined by measuring stream discharge. In the Republic of Ireland hydrological measurements are made by both private and public bodies (for example, ESB, OPW and Bord Na Móna) and much of this information is compiled by the Environmental Protection Agency (MacCarthaigh, 1997b). There are few general publications on Irish runoff (MacCarthaigh, 1997a) and work has focussed on the response of rivers to heavy rainfall events or on runoff conditions during drought periods (MacCarthaigh, 1996).

Evapotranspiration (E) is notoriously difficult to measure in a spatially representative manner due to complex interactions between site-specific meteorological, vegetation and soil conditions. A commonly taken approach is to measure potential evapotranspiration (Ep), that which occurs if the vegetation experiences no water shortage. Agriculturists are particularly interested in the deviation between actual (E) and potential evapotranspiration (Ep) as this is indicative of a water deficit which, if of sufficient duration, will decrease crop productivity (Burke, 1962; Brereton and Keane, 1982). There are a few methods available for measuring Ep. One of these is the evaporation pan that presents a freely evaporating water surface to the atmosphere. Not suprisingly the resulting values are considered to be overestimates of evapotranspiration and must be adjusted (Keane, 1986). At a few sites in Ireland, Ep is measured using an evapotranspirometer (Guerrini, 1957), an instrument that consists of an isolated depth of soil with a grass cover that is irrigated. Water input into, and percolation from, the soil volume are recorded and Ep is estimated as the difference between the measured inputs and outputs. Monthly values for this variable show a distinctive seasonal pattern (with a summer maximum) associated with available solar radiation and plant growth (Figure 1). Actual evapotranspiration (E) is not directly measured but is usually calculated from measurements of Ep, P and estimates of the maximum ‘useful’ quantity of water stored in the soil.

Research on evapotranspiration in Ireland has attempted to extend spatially Ep measurements by employing estimation methods that rely on generally available data for meteorological variables that are correlated with Ep. Typically, these variables include solar radiation, windspeed, humidity and temperature. These estimators are of varying sophistication and range from statistical to physically-based models. The best known of the latter is the Penman method that provides a physical relationship between all the relevant variables. However, its general application is limited by the relative paucity of windspeed and radiation observations it requires. Comparisons, where possible, between measured and Penman estimates of Ep show statistically significant correlations for the summer months but systematic overestimates in winter months (Guerrini, 1953; Morgan, 1962; Connaughton, 1967).

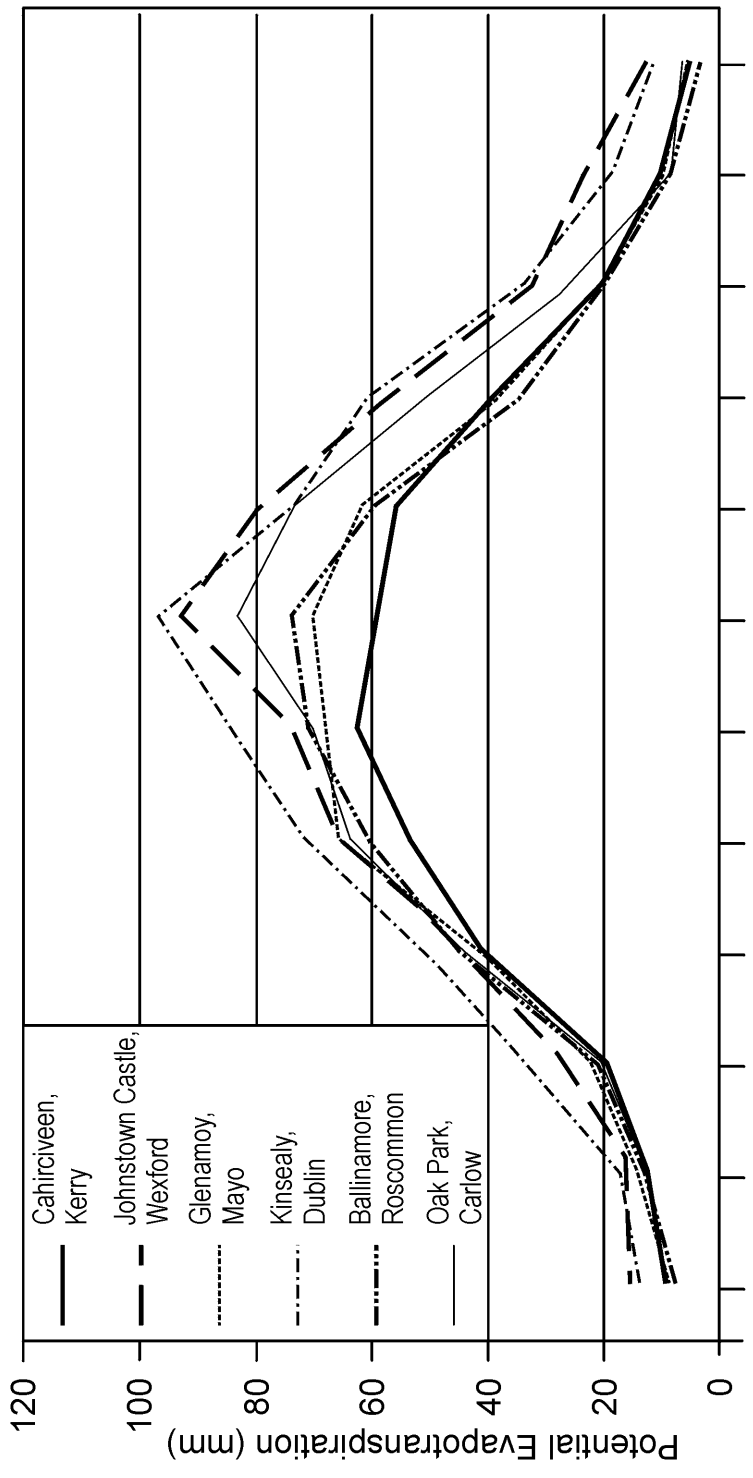

Figure 1: Average monthly evapotranspiration measured at six stations over the period 1971-1990.

In an Irish context there have been few attempts at a comprehensive evaluation of all water budget components. There have been many papers that link two of the components, precipitation and potential evapotranspiration, in an attempt to estimate soil water deficit for agricultural purposes (Burke, 1962; Murphy, 1966; Connaughton, 1967; 1969; Brereton and Keane, 1982). In a broadly similar climate the UK Meteorological Office has established a regular procedure for evaluating agricultural water shortage in Britain using the water budget approach. The MORECS system (Thompson *et al.*, 1981) is applied to grid cells of size 40x40km and employs regularly collected meteorological data to estimate actual evapotranspiration using a modified Penman equation that accounts for both meteorological conditions and vegetation characteristics (including type and growth stage). The depth of water available in soil to plants is estimated from vegetation type. Comparisons of estimated soil water levels show a close correspondence with those measured but the procedure does not attempt to estimate runoff. Recently, Goodale *et al.* (1998a; 1998b) assessed forest productivity in Ireland using meteorological and soil databases. Monthly averages of precipitation and temperature for the period 1951-1980 were interpolated to a dense grid ($1km^2$) using a method based on polynomial regression. This estimation procedure accounted for spatial and topographic variations across Ireland. Although the forest productivity model described in this research evaluates water budget components, it was not the primary interest of the study and no budget results were shown.

The research presented here is based upon a general water budget model that has been derived for the purpose of estimating spatial variations in the monthly values for each component of the water budget. The model is implemented using digital topographic and landuse data and meteorological data for the period January 1961 to December 1990. These data are used in an accountancy procedure (Mather, 1978) that is applied individually to a set of regularly distributed points over Ireland. In this paper the operation of the model is described and some of the results are discussed. Given the extensive research completed on precipitation, this paper concentrates primarily on evapotranspiration and changes in soil moisture storage over the period. In particular, the results of the model during a ‘drought’ year (1976) are compared with published descriptions of the event. The relationship between runoff (as measured by stream discharge) and surplus (as calculated in the present model) is complex and no attempt is made here to link these two variables. In a subsequent paper, the author will present a more formal verification of the model results by comparing estimates of runoff with measurements of river discharge.

The water budget model

Model description

The water budget model is based on the approach developed by Thornthwaite and has been widely employed (Mather, 1978). To apply the model on a monthly basis to any location requires knowledge of just three variables, field capacity, precipitation and potential evapotranspiration. Thereafter, each of the water budget components are calculated by comparing vales for P and Ep and monitoring water stored in the soil.

Potential evapotranspiration represents the maximum E or ‘water need’. To meet this need, vegetation will use water available via precipitation and/or water stored in the soil (S). When P exceeds Ep there is sufficient water and actual evapotranspiration (E) will be equal to Ep. If the opposite occurs, water stored in the soil will be extracted by the root system.

However the efficiency of this extraction will depend on the pressure that the roots are required to apply. When the soil is near field capacity plants experience no stress in accessing this water but as the soil dries, the roots become less efficient. Here it is assumed that the efficiency of extraction is 100 percent when stored soil water is greater or equal to 70 percent of field capacity and thereafter declines in a linear manner (Thompson *et al.*, 1981). If there is insufficient water to meet Ep requirements there is a deficit (D), defined as the difference between Ep and E. When P exceeds Ep the extra water either contributes to increased soil storage or to surplus. In the case of the former, the field capacity sets an upper limit on water stored in the soil. Once storage is equal to field capacity and vegetation need is met, any extra water is considered to be surplus that will eventually become runoff. The precise relationship between surplus and runoff in any given month will be highly variable and depends upon the individual characteristics (such as soil types and slope) of river catchments. There is no attempt in this paper to estimate runoff.

This model is applied to 3348 grid cells, each 5x5km in size, which encompass the land area of Ireland. The choice of cell area (25km^2) was based primarily on the spatial distribution of temperature and sunshine observations. The field capacity of each cell is estimated from its landuse cover and the model is currently run using estimated monthly values for precipitation and potential evapotranspiration for 1961-1990 for each location. For each cell the model proceeds in sequence from month to month calculating actual evapotranspiration, deficit, surplus and change in storage. Initially, in January 1961, it is assumed that the soil is at field capacity (a reasonable assumption in Irish conditions). In the following sections the compilation of the various datasets required for the model is discussed.

Datasets

Meteorological: A meteorological database was compiled from information available from the Irish Meteorological Service and UK Meteorological Office (HMSO, 1961-90; Meteorological Office, 1961-90; Meteorological Service, 1971-90). The data obtained from these sources included station location, monthly precipitation, bright sunshine totals and average temperatures. In the case of precipitation, all stations that had at least a complete year of monthly values were included in the database. Measurements of temperature and sunshine are more limited and consequently all available monthly values were included. Values for the centre of each grid cell were interpolated from these spatially scattered stations using a distance-weighted scheme—

$$\hat{Z}_{i,j} = \frac{\sum_{k=1}^{N} Z_k}{\sum_{k=1}^{N} 1/d_k}$$

where Z refers to any variable (sunshine or precipitation or temperature) and d to the distance between the grid position and the station location. The superscript over Z indicates that it is estimated and the subscripts refer to cell position (row (i) and column (j)). The summation sign refers to the number (N) of neighbouring stations that are included in the estimation. For precipitation the search for neighbouring stations was limited to 50km, and for sunshine and temperature (recognising their fewer number) the radius was 150km. If fewer than six stations were found within the radius, the cell value was treated as missing. Currently there is no attempt to consider the uneven distribution of stations around a grid centre. This could result in errors that are likely to be largest near coastlines where there are no seaward observations.

Both monthly precipitation and air temperature values are closely related to elevation. In the case of precipitation this relationship is highly variable and no attempt is made at this stage to correct for altitude in the interpolation procedure. For temperature, prior to interpolation, the measured values were corrected for station elevation using the average environmental lapse rate of 6.5°C km^{-1} (Thompson *et al.*, 1981). Once these sea-level temperatures were interpolated to the grid, they were adjusted for the mean elevation of the grid cell. These cell elevations were obtained from a global digital elevation dataset (USGS, 1996) that has a spatial resolution of 30 seconds of longitude and latitude (0.598km and 0.927km at 50° latitude). For Europe, the vertical accuracy of the dataset is ±30m (with 90 percent confidence) in absolute terms and its relative accuracy (for slope and aspect calculations) is considered superior to the absolute value. A section of the global database that included Ireland was extracted and the global coordinates were converted to the Irish co-ordinate system used for the model grid. These values were subsequently used to estimate the average elevation of each grid cell.

Soil water availability: There is no survey of the field capacities of Irish soils. The approach taken here is based on the approach of Thompson *et al.* (1981) whereby values for ‘water availability’ are assigned based on the vegetation cover. For Ireland the closest approximation to these characteristics is the landcover dataset, CORINE (O’Sullivan, 1994). The information in this database was compiled from a variety of sources in the early 1990s and uses a minimum mapping unit of $0.01km^2$. The classification of land cover is based upon a hierarchy encompassing 40 types; each represented by a unique code. In Ireland, grassland (63 percent) and peat bogs (14 percent) account for the greater proportion of total land area (79,360 km^2). Water availability values were assigned to each code (Table 1) based on those reported in Thompson *et al.* (1981). The lowest values are associated with impermeable surfaces and the largest with forest cover. Those assigned to grassland landcover (codes 2311-2313) are based upon its productivity.

Table 1: CORINE land surface classifications used in this study, water availability in mm (after Thompson *et al.*, 1981) and area (in square kilometres).

CORINE Codes	Description	Available water	Area
111,331,332	impervious surface and beaches	0	307
121-124,131-133,334,411	non vegetated soils	20	124
2312, 322, 334, 411	low productivity grassland	50	19424
2313	mixed productivity grassland	90	7668
211,241-243	arable, crops	110	7676
141,142,321	highly productive grassland	125	40387
311-313	forests	175	2683

The original CORINE data are stored in vector format. These data were converted to a raster format using a cell resolution of $1km^2$ and the code associated with the dominant landcover was assigned to each cell. Water availability values for the larger model cells are the weighted average values of these $1km^2$ cells. In this study there is no attempt to allow for seasonal variations in water availability associated with vegetation growth nor is account taken of landuse changes that occurred during the time period under study.

Estimating potential evapotranspiration

In Ireland potential evapotranspiration is measured at several climatological stations using evapotranspirometers. The determination of Ep for the model grid is based upon a statistical analysis of the correlation between measured values of Ep and more widely available meteorological parameters. Ideally these parameters would include radiation, windspeed and humidity. However, only measurements of bright sunshine hours and air temperature are available at sufficiently numerous stations. Unfortunately this precludes estimating Ep using a physically based model such as that of Penman. Instead, linear regression is used to establish a relationship between measurements of Ep, estimated direct solar radiation (S) incident on a surface and air temperature (T). Solar radiation receipt was estimated from—

$$S = S_{max} (N / N_{max})$$

where S_{max} represents the maximum amount of solar radiation available at the top of the atmosphere and N/N_{max} is the ratio of measured bright sunshine hours (N) to the potential maximum (N_{max}). The maximum values are obtained from established earth-sun geometric relationships that account for the changing elevation of the sun with time of day, day of month and latitude.

Measurements of Ep for six stations were compiled from monthly reports for a twenty-year period, 1971-1990 (Meteorological Service, 1971-90). Figure 1 shows the average monthly values for each of these stations and although the pattern is consistent there are some differences revealed in terms of total amounts and annual range (Table 2a). The majority of these stations are located in more exposed ‘coastal’ areas (the exceptions are Oak Park and Ballinamore), climate conditions that are likely to generate higher than expected values in winter months. Regression analyses were completed for four of these sites that had corresponding monthly measurements of Ep, S and T and the relationships derived for Oak Park were selected for use in this model. Potential evapotranspiration is estimated at each grid cell using—

for winter months (October to March) and

$$\hat{E}_p = -11.40 + 1.41S + 2.57T,$$

for summer months. These equations account for 81 percent and 86 percent of the variation

$$\hat{E}_p = -29.50 + 1.50S + 4.41T,$$

in Ep measured at Oak Park for summer and winter, respectively.

In order to examine the reliability of these equations when applied generally, the estimated Ep values calculated for the grid cells in which these six stations were located and compared with those measured (Table 2b). The measured and predicted mean monthly values show broad agreement with the exception of Cahirciveen. When all available monthly data are considered the model captures a substantial component of the measured variation (between 89 percent and 90 percent). However, this agreement is significantly reduced when

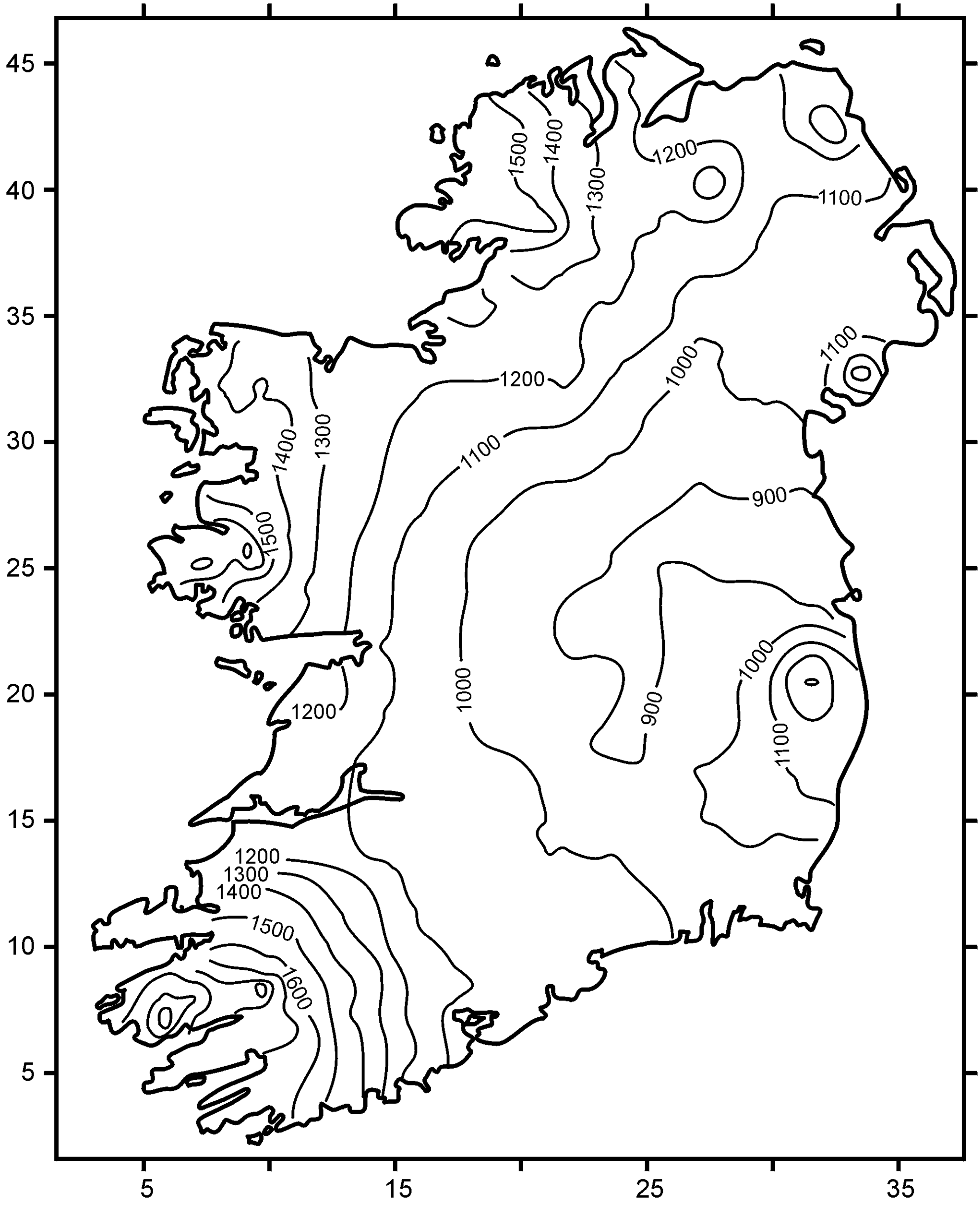

Figure 2: Average annual precipitation (mm) for the period 1961-1990.

the summer and winter months are considered separately. In fact just 13 percent of the variation in Ep at Ballinamore during the winter months is explained. Perhaps a more valuable assessment of the model is the mean absolute error (Table 2b). As a proportion of the monthly values, this is between 30 percent and 40 percent overall and between 15 percent and 30 percent during summer months. Although this error is highest for winter months (71 percent for Ballinamore) bear in mind that this is also when measured Ep values are lowest

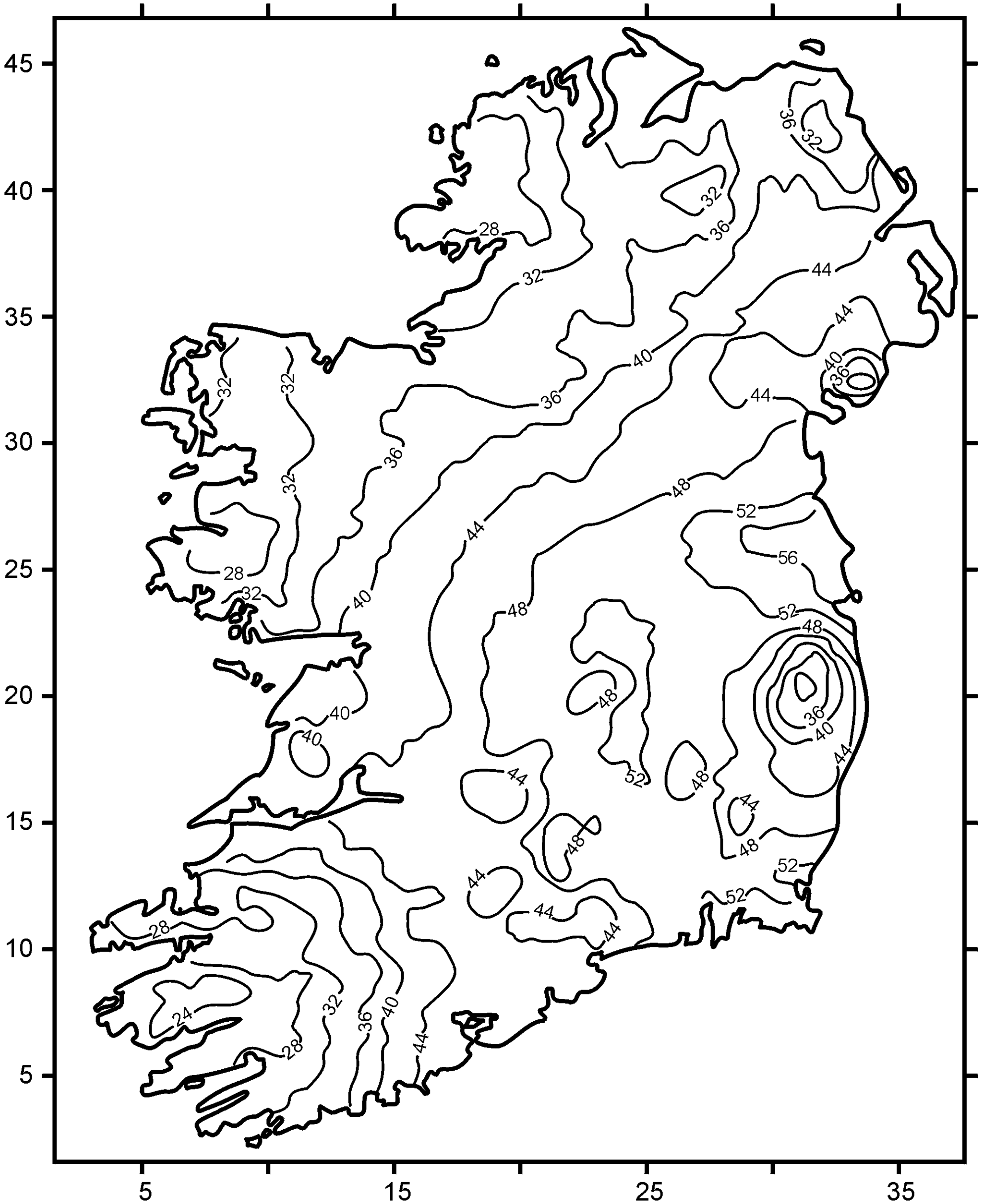

Figure 3: Average estimated actual evapotranspiration as a percentage of annual precipitation 1961-1990.

so that the implications of this error for the water budget are limited. During the winter there is little available radiation and little plant growth, the soil is at field capacity and the majority of precipitation contributes to surplus.

Table 2(a): Potential evapotranspiration (Statistics).

	Year	Summer	Winter
Cahirciveen, Co. Kerry	390	312 (60)	78 (5)
Johnstown Castle, Co. Wexford	543	413 (93)	130 (13)
Glenamoy, Co. Mayo	428	346 (70)	82 (6)
Kinsealy, Co. Dublin	567	439 (97)	129 (11)
Ballinamore, Co. Roscommon	421	345 (74)	76 (6)
Oak Park, Carlow	467	386 (83)	80 (3)

Annual and seasonal measurements of Ep (mm) for 1971-1990. Values in parentheses represent monthly averages for July and December in summer and winter, respectively.

Table 2(b): Potential evapotranspiration (Model comparison).

	Annual			Summer			Winter		
	a	b	c	a	b	c	a	b	c
Cahirciveen	229	.83	33	119	.55	26	110	.24	60
Johnstown Castle	225	.82	20	116	.60	16	109	.26	33
Glenamoy	210	.78	27	112	.49	21	98	.32	55
Kinsealy	233	.79	22	118	.48	18	115	.42	37
Ballinamore	205	.79	29	112	.58	22	93	.13	71
Oak Park	220	.87	21	115	.68	15	105	.37	54

Statistical comparison between model output and station measurements. The columns represent the sample size (a), the coefficient of determination (b) and mean absolute error divided by measured monthly value (c).

Results and Discussion

Figures 2 and 3 show the annual average precipitation and its partitioning into estimated actual evapotranspiration and surplus for the period 1961-90. The precipitation map displays the well-known pattern of higher mountain precipitation superimposed on general west-east and north-south gradients. The percentage of precipitation that is evapotranspired is shown in Figure 3. It will be noticed that the patterns on this map are nearly opposite those established in Figure 2: the lowest values are to be found in the north and west and at higher elevations and the highest values are found in the south and east (with the exception of the lower values over the Wicklows). This relationship is to be expected as areas of higher precipitation will generally be areas of greater cloudiness and less sunshine.

Water shortage or deficit, defined here as a difference between actual and potential evapotranspiration, is shown in Figure 4. The values here are very small, for most of the country there is an annual deficit (accumulated during the summer months) of less than 15mm. These values are less than those presented by Connaughton (1967) for the period 1958-1965 but his deficits were calculated differently as the accumulated differences between Ep and P. While the pattern of deficits here agree with those of Connaughton, Figure 4 identifies some local maxima and minima. The exceptional values on this map are found in

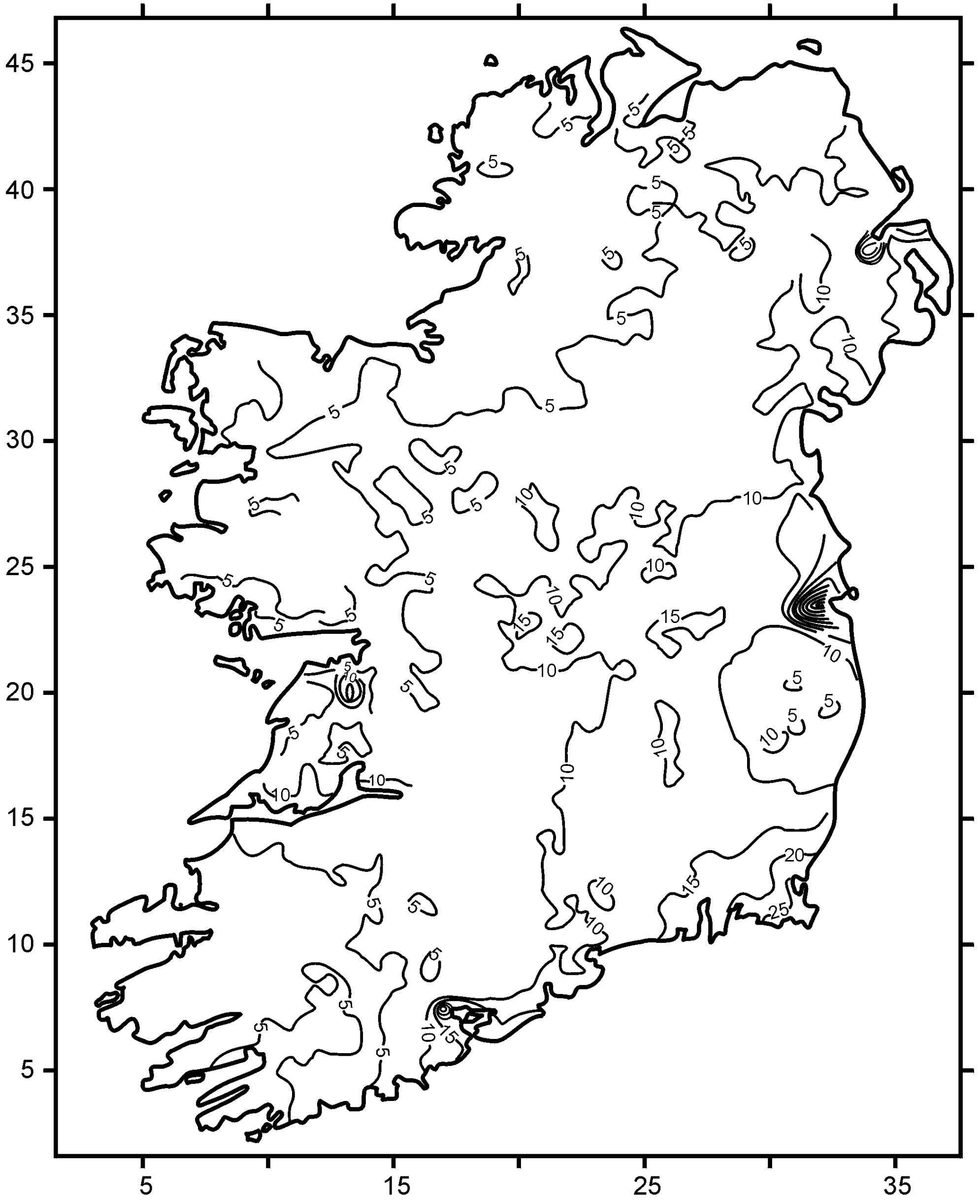

Figure 4: Average annual deficit (mm) 1961-1990.

urban areas where much of the land surface is artifically ‘sealed’ and in the Burren, an area of exposed rock in north Clare. In both cases the relative lack of vegetation means that available water values are low.

The average monthly water budget for the entire island (based on the average cell values for each term) is shown in Figure 5. It clearly shows that, on average, precipitation receipt is sufficient to meet water need. Precipitation amounts are greatest (over 100mm) from

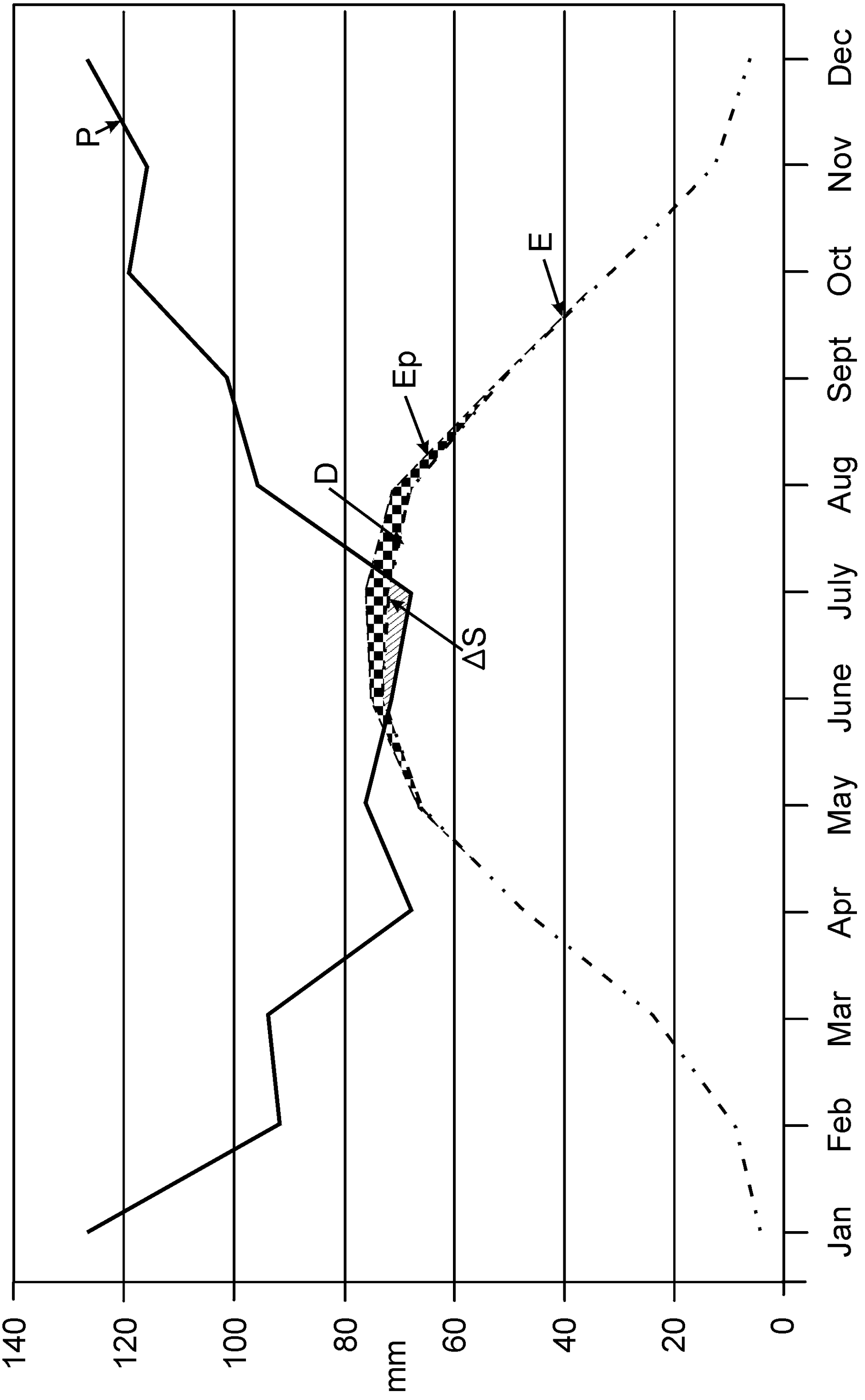

Figure 5: The average monthly water budget for Ireland.

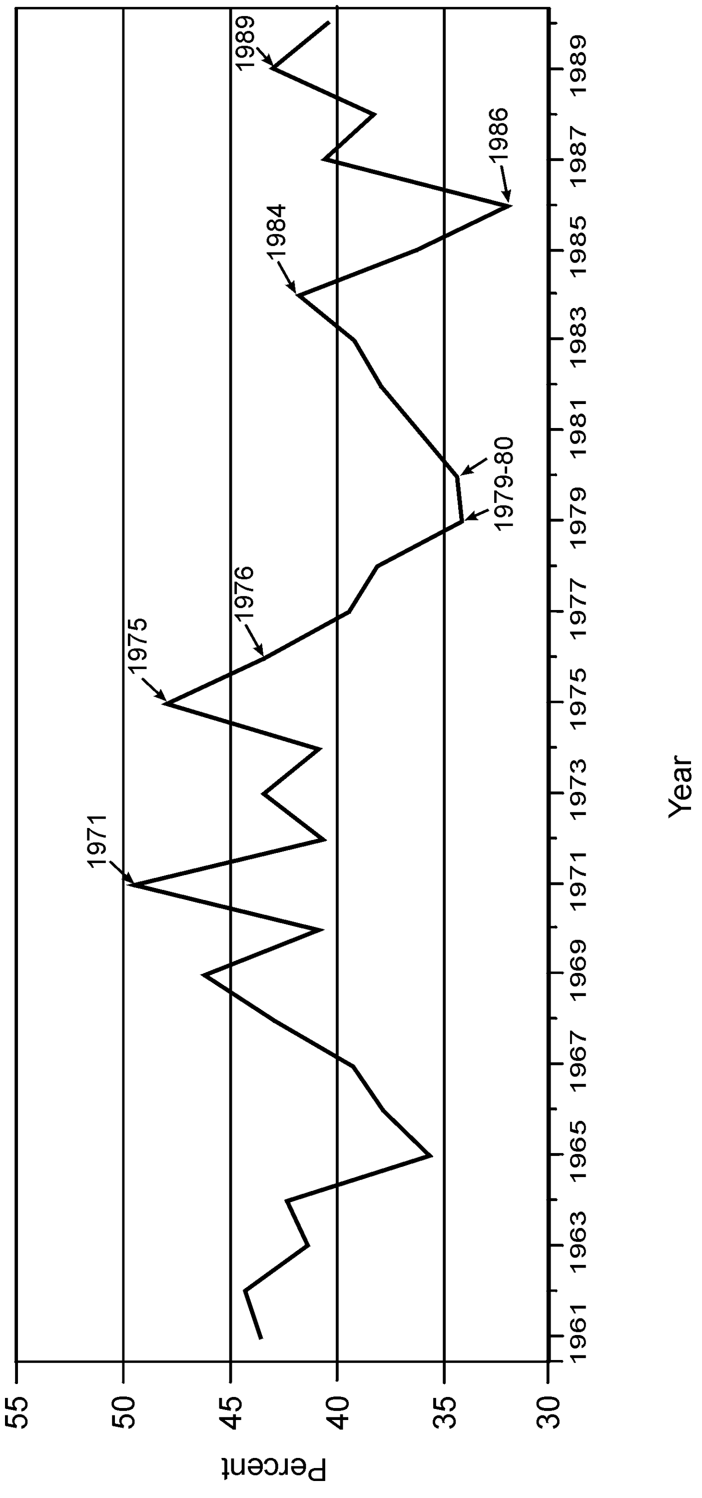

Figure 6: Estimated actual evapotranspiration as a percentage of annual precipitation.

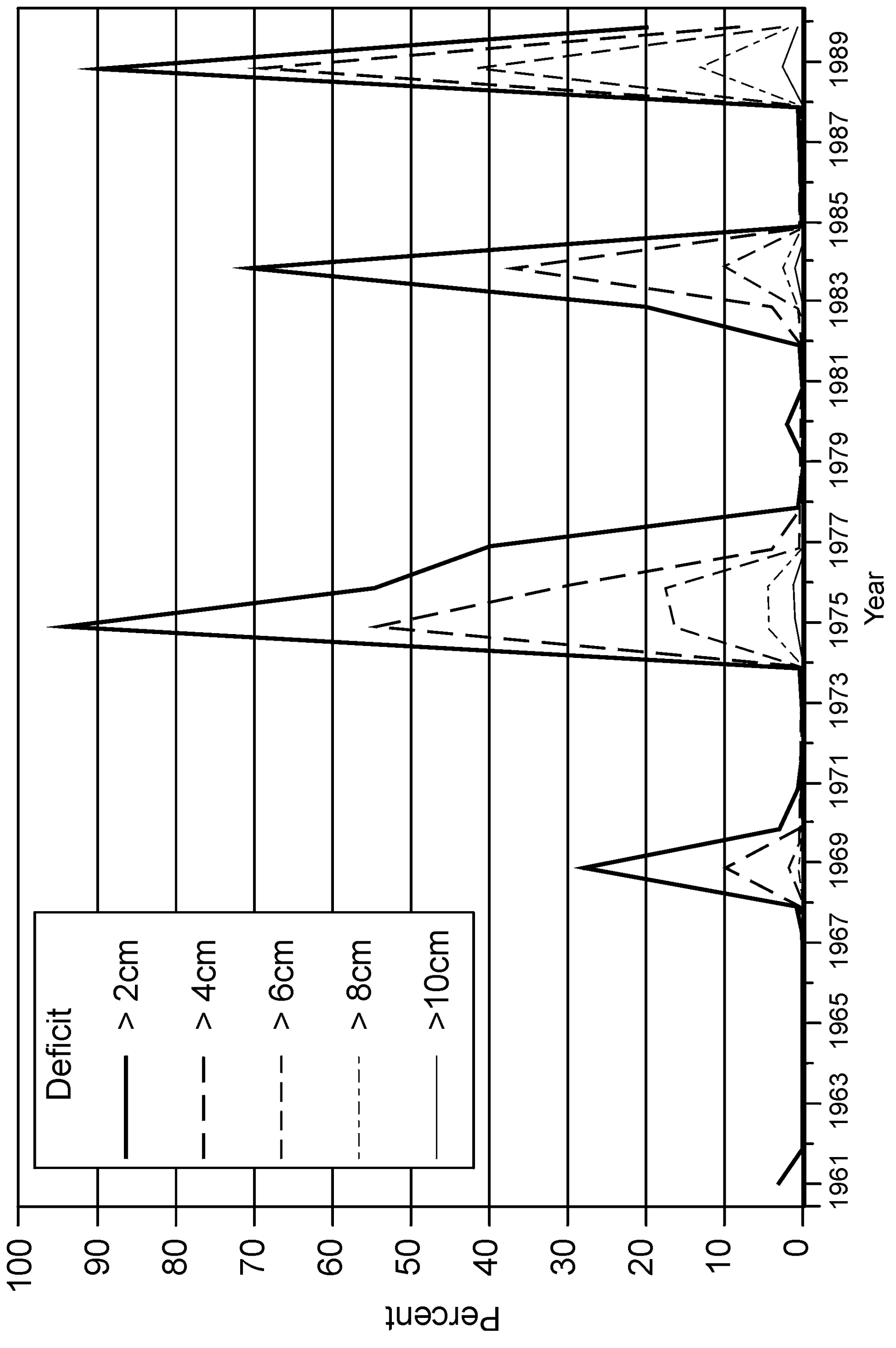

Figure 7: The area of Ireland experiencing deficits of varying magnitude expressed as a percent of the total land area.

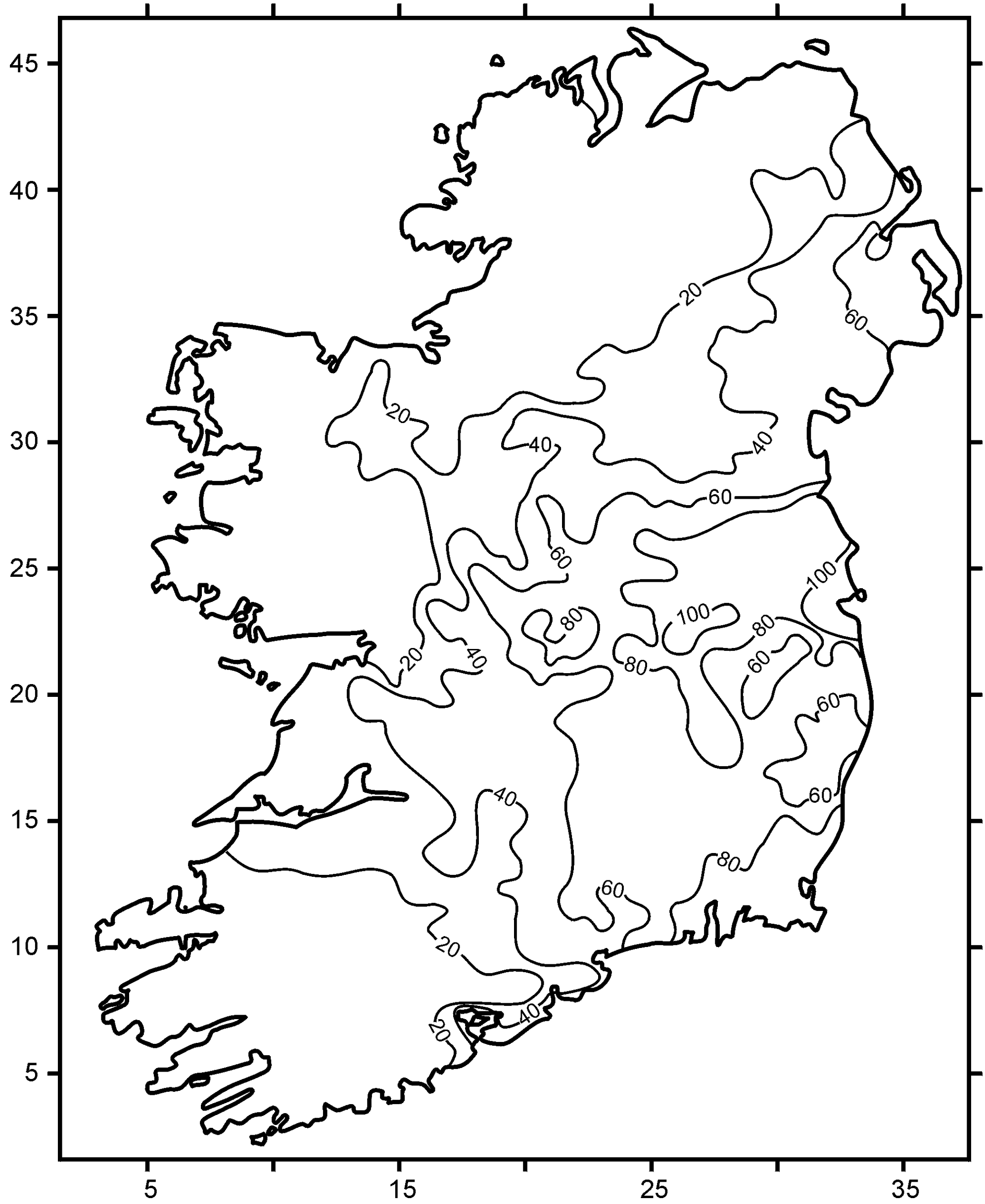

Figure 8: Annual deficit (mm) for 1976.

September to January when evapotranspiration is least, consequently this is when the largest surpluses are generated. During the growing period from April to August, evapotranspiration exhibits a symmetrical pattern with maximum values of 76mm occurring in July. It is in the months of June and July that Ep exceeds precipitation nationally and water is drawn from storage. However, actual evpotranspiration in these months is still less than Ep so that a small deficit occurs. This withdrawal is quickly replaced by the end of August during which P exceeds Ep for most of the country (the deficit in this month is due to the fact that the spatial distributions of P and Ep are not perfectly correlated). From September onwards the surplus generated increases with each month, for example, in December, 119mm of the 126mm of precipitation is surplus. The annual values for precipitation, evapotranspiration and surplus are 1156mm, 464mm and 692mm which compare favourably with those quoted earlier.

Figure 6 shows the percentage of annual precipitation expended in evapotranspiration for the thirty-year period. This figure combines changes in both P and E and masks any intra-annual variation. For example, during 1976 Ireland experienced a drought. However, its value on this graph does not seem exceptional. The lowest value occurred in 1986 which during this time period represented the wettest year (1341mm). By comparison during the driest year (1971) Ep accounted for nearly fifty percent of P (993mm). Perhaps a more effective examination of the time series and the water budget effects is shown in Figure 7. In this diagram the percentages of the land area which experienced deficits of varying amounts are plotted against time. The dry years, in terms of meeting water demand, are now clearly marked as 1969, 1975-1977, 1983-1984 and 1989. During 1975 over 95 percent of the country experienced deficits of more than 20mm, and just less than 25 percent had deficits exceeding 60mm. In the following year the extent of the dry area was considerably reduced but the area with deficits over 60mm remained the same and that with deficits over 100mm increased from 1425km^2 to 1800km^2.

The spatial distribution of the deficit that occurred during 1976 (Figure 8) is the same as that for the average (Figure 4), except that the values are substantially higher. During the summer of 1976 a large ‘blocking’ anticyclone centred off the south-coast of England caused cyclone paths to be diverted northward (Morris and Ratcliffe, 1976). As a consequence, those areas furthest from the high-pressure centre experienced near average amounts of precipitation, while areas in the south-east had a sunny, exceptionally dry summer (O’Laoghog, 1979). One means of assessing the severity of this drought is by estimating its agricultural impact. Brerton and Keane (1982) suggested that the effects of water shortage on yield from managed pasture (assuming the addition of Nitrogen at 250kg per hectare each year) could be evaluated from—

$$\frac{Y}{Y_P} = 0.25 + 0.75\frac{E}{E_P},$$

where Y represents yield and the subscript P indicates potential. The 60mm deficit line on Figure 8 coincides approximately with a yield ratio of 90 percent. The effects of the water shortage in 1976 on agriculture were compounded by the fact that the summers of the preceding two summers were also comparatively dry. In 1989 over half the area of the country experienced deficits greater than 60mm and 5425km^2 had deficits in excess of 100mm. Although the extent of the deficit was greater and more intense in this year compared to those in either 1975 or 1976, it was short-lived.

Summary and Conclusions

The water budget approach offers a comprehensive assessment of precipitation, evapotranspiration, soil water and runoff. This paper has described the development and application of a simple water-budget model applied to Ireland. Although there has been consideration of individual components of the hydrological cycle elsewhere there is no recently published research on the overall budget. This work has provided the most detailed temporal and spatial evaluation of its terms (with the exception of runoff) over a significant period of time. The results indicate that while Ireland as a whole receives sufficient water in all months to meet vegetation needs there can be substantial deficits. While the relative vulnerability of the south-east to drought is well known, the results here show the extent of agriculturally limiting deficits more precisely.

This model has been developed using a variety of meteorological, topographical and landuse datasets and is applied to regularly distributed cells. Of the budget terms, the estimation of potential evapotranspiration is the most problemmatic. The limited number of stations where Ep is measured and the absence of widespread wind and humidity measurements prevents the application or development of more realistic or comprehensive methodologies. The statistical approach employed here appears to overestimate Ep however these errors are proportionately greatest in winter months when evapotranspiration is low and the bulk of precipitation contributes to surplus and runoff. It is doubtful whether another approach to this problem would yield superior estimates. Although the results of the model are broadly in agreement with the work of others, no formal verification has been completed yet. It is the intention of the author to develop and improve the model by incorporating elevation and directional bias into the interpolation procedure and estimating catchment runoff. These estimates will be evaluated by comparing them with measurements of catchment discharge.

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