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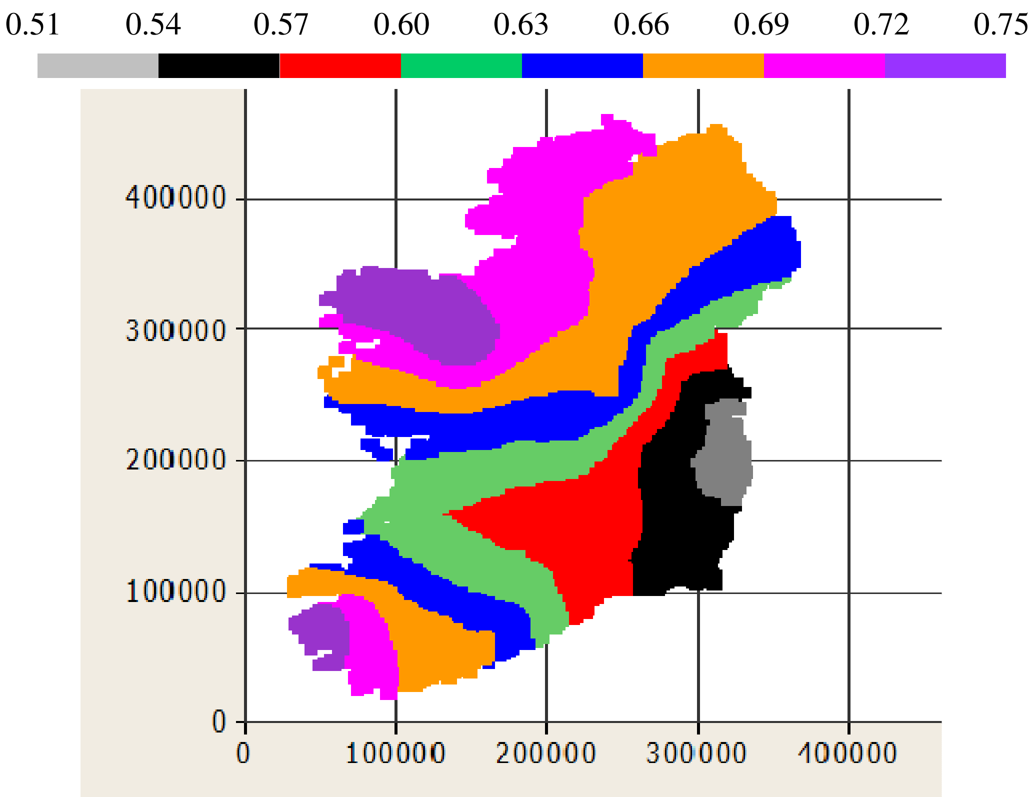
PROPWET for Ireland: a dimensionless index of typical catchment wetness



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Report to OPW

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Flood Studies Update Work-Package 5.4

PROPWET for Ireland: A dimensionless index of typical catchment wetness

1 Introduction

Summary

An index of wetness is relevant to catchment characterisation in the Flood Studies Update. The variable *PROPWET* is the proportion of the time for which soils can be expected to be typically quite wet.

In the study reported here, *PROPWET* has been evaluated from Met Éireann estimates of soil moisture deficit (SMD) at 14 premier climatological stations. The index has been evaluated from 26 years of data (1981 to 2006). A spatial interpolation method has been devised to map the index across Ireland, so that a value of *PROPWET* can be inferred at any site or (with appropriate overlay) averaged across any catchment.

Some background

Meteorological agencies produce standard estimates of soil moisture deficit (SMD) based on climate data. Heavy rainfall that occurs when SMD is close to zero tends to produce significant flood runoff. This is less often the case when heavy rainfall occurs when a marked soil moisture deficit persists. SMD is measured as mm of rainfall deficit, i.e. the depth of rain required to bring soil moisture to a saturated condition.

The *PROPWET* index was developed in the UK Flood Estimation Handbook (FEH) based on estimates of SMD for 1961-1990 calculated by MORECS (Thompson *et al.*, 1981). The index works on the simple premise of distinguishing wet and dry conditions. Bayliss and Morris (1999) came up with a rationale for adopting a threshold of 6 mm to distinguish wet and dry conditions. The choice was reached by balancing Type I and Type II errors in inferring flood dates from SMD data. The sophistication of their scheme – which used flood dates in UK peaks-over-threshold series – was offset by the need to use daily estimates of SMD interpolated from month-end values.

The *PROPWET* index developed here uses Met Éireann estimates of SMD for 1981-2006. The SMD estimates are based on the so-called Hybrid model (see Appendix 1 for details). This model replaces the Makkink model previously used by Met Éireann.

Three sets of SMD estimates were supplied to the work-package. Those designed to represent Well Drained (WD) and Poorly Drained (PD) soils were principally considered. [The third set – representing Moderately Drained soils – was discarded once it was realised that they yielded identical values of *PROPWET* to the WD case.]

The sensitivity of *PROPWET* to the wet-dry threshold was examined for each set of SMD estimates. As reported later, the eventual decision taken was to standardise on the WD estimates of SMD and to adopt a threshold of 8.5 mm to distinguish wet and dry conditions.

To highlight that this definition differs from that used in the FEH, the index developed here is given the full label $PROPWET_{\mathrm{WD},8.5}$.

An auxiliary index of catchment wetness behaviour, $CVWET_{\mathrm{WD},8.5}$, is also investigated. *CVWET* is the coefficient of variation of the length of wet periods, and is a measure of the degree of irregularity in wet/dry sequences at the site.

Motivation

PROPWET and *CVWET* are intended as simple numerical indices of climatic influence on catchment flood behaviour. In addition to appearing in the FEH statistical method of flood frequency estimation, PROPWET has proved useful in post-FEH research to generalise rainfall-runoff models for use on ungauged catchments (e.g. Calver *et al.*, 2005; Kjeldsen *et al.*, 2005).

Given the somewhat coarse basis of the FEH descriptor – not least, the interpolation from month-end MORECS estimates – the success of PROPWET in the UK suggests that indices based on standard estimates of SMD at climate stations provide relevant information that is not well represented in other catchment/climate descriptors, such as the standard-period average annual rainfall (*SAAR*).

This study forms FSU Work-Package 5.4 (WP5.4). It is relevant to note that *PROPWET* and *CVWET* are not the only catchment descriptors used to represent climatic influence. WP1.1 supplies estimates of the 1961-1990 *SAAR*, WP1.2 supplies descriptors of extreme rainfall (e.g. the median annual maximum 1-day rainfall, $RMED_{24\mathrm{h}}$) and WP5.3 will supply altitude and slope information (thereby offering scope to represent orographic effects).

***PROPWET* is only an index!**

The remit of WP5.4 is to develop an index of wetness behaviour based on SMD data. It is sufficient that the derived field of *PROPWET* values represents the variation across Ireland in a locational sense. It is not required that it should represent orographic effects that are more effectively summarised by *SAAR* and/or topographic data.

When interpreting the maps presented here, the reader is urged to see *PROPWET* as an empirical descriptor of climate to be used alongside other indices: not as a free-standing descriptor of typical soil wetness. In particular, it should be noted that the index does not represent *actual soils* other than indirectly through the natural (and exceptionally long-term) link between climate and soil formation.

2 Soil moisture deficit (SMD) data

2.1 Met Éireann Hybrid model

The *PROPWET* index developed here is based on Met Éireann estimates of SMD for 14 premier sites for which full climate data are available. The SMD calculation is based on the Hybrid model (see Appendix 1). Met Éireann provided three sets of SMD estimates, for: Well Drained (WD), Moderately Drained (MD) and Poorly Drained (PD) soils. The SMD estimates are provided as daily values.

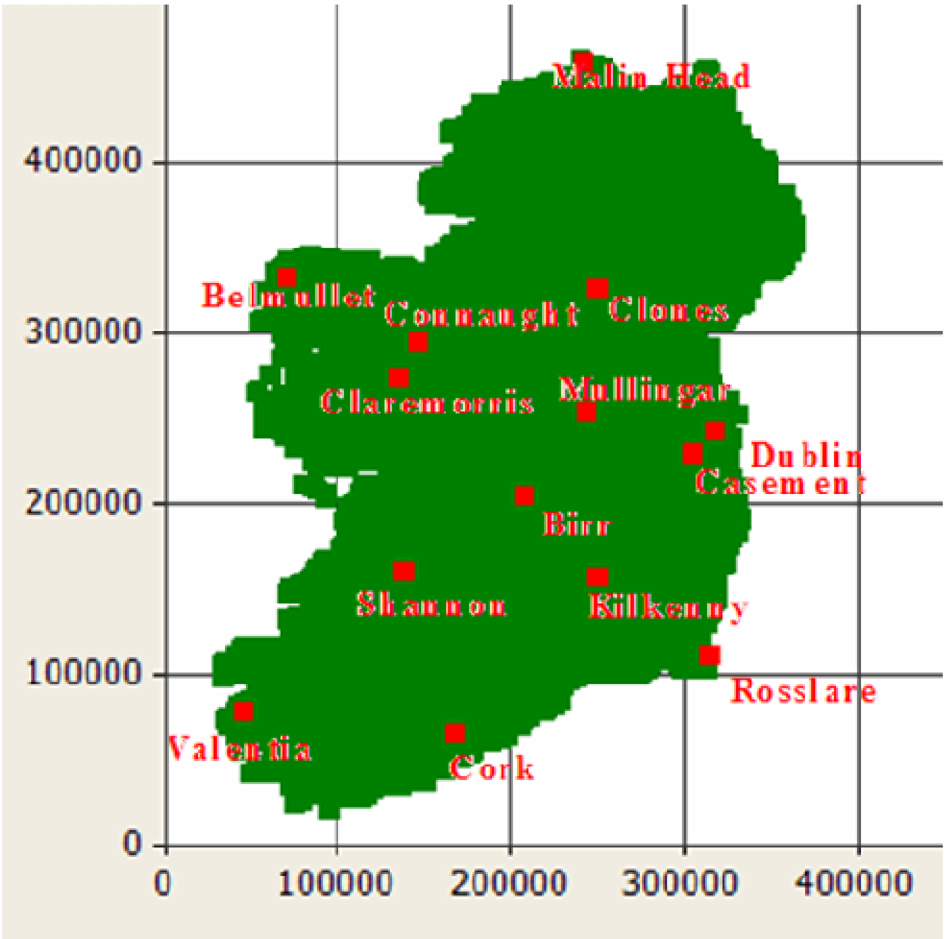
2.2 Gauge network

Table 2 provides some general information, including the formal names of the 14 stations. Hereafter, some of the names are abbreviated. The network is illustrated in Map 1.

Table 2 ***Some metadata for the 14 climate sites***

#	Station name	County	Easting	Northing	Height (mAOD)	Opened	Hydrom[c] Area
305	Valentia Observatory	Kerry	45700	78800	11	1 Jan 1866	5
518	Shannon Airport	Clare	137900	160300	6	1 Jan 1937	18
532	Dublin Airport	Dublin	316900	243400	71	1 Sep 1939	32
545	Malin Head	Donegal	241900	458600	22	1 Jan 1957	45
1034	Belmullet	Mayo	69100	332900	11	16 Sep 1956	34
2437	Clones	Monaghan	250000	326300	89	1 Jan 1950	37
2615	Rosslare	Wexford	313700	112200	26	30 Nov 1956	15
2727	Claremorris	Mayo	134500	273900	71	9 Nov 1943	27
2922	Mullingar II	Westmeath	242300	254300	104	7 Nov 1973	22
3613	Kilkenny	Kilkenny	249400	157400	66	1 Jun 1957	13
3723	Casement Aerodrome	Dublin	304100	229500	94	1 Jun 1944	23
3904	Cork Airport	Cork	166500	66200	154	31 Dec 1961	4
4919	Birr	Offaly	207400	204400	73	1 Jan 1954	19
4935	Connaught Airport	Mayo	146300	295500	203	7 May 1986	35

Map 1



2.3 Periods of record

Data were initially supplied for the period 2 December 1980 to 11 June 2006. It was agreed with OPW that the study should concentrate on data for the 26 calendar years 1981-2006. On request to Met Éireann, the records were updated to March 2007 during the study.

Stations with incomplete data

The Claremorris and Connaught Airport data were known to be incomplete: the SMD series for Station 2727 (Claremorris) runs up to 31 March 1996, with data for Station 4935 (Connaught/Knock Airport) commencing 3 August 1996. The sites are too far apart and at too different an altitude for their records to be merged. It is inevitably something of a challenge to incorporate these data effectively.

It was discovered during the data exploration phase (see next section) that the SMD series for Rosslare lack data for the three years 1997-1999.

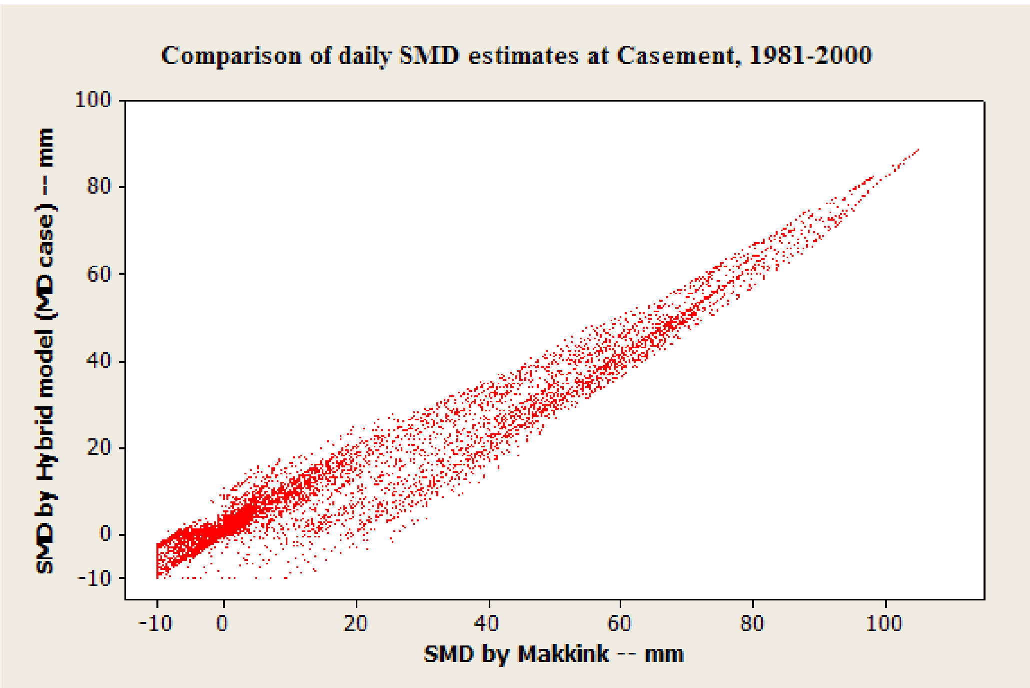
2.4 Exploratory data analysis

Data problems

Some of the daily SMD series were found to lack particular days of record. The nature of SMD modelling is by nature sequential, with one day's evapotranspiration/rainfall increasing/reducing the prevailing SMD. Inspection suggested two problems: the lack of estimates for particular days, and flawed estimates in periods following a missed day.

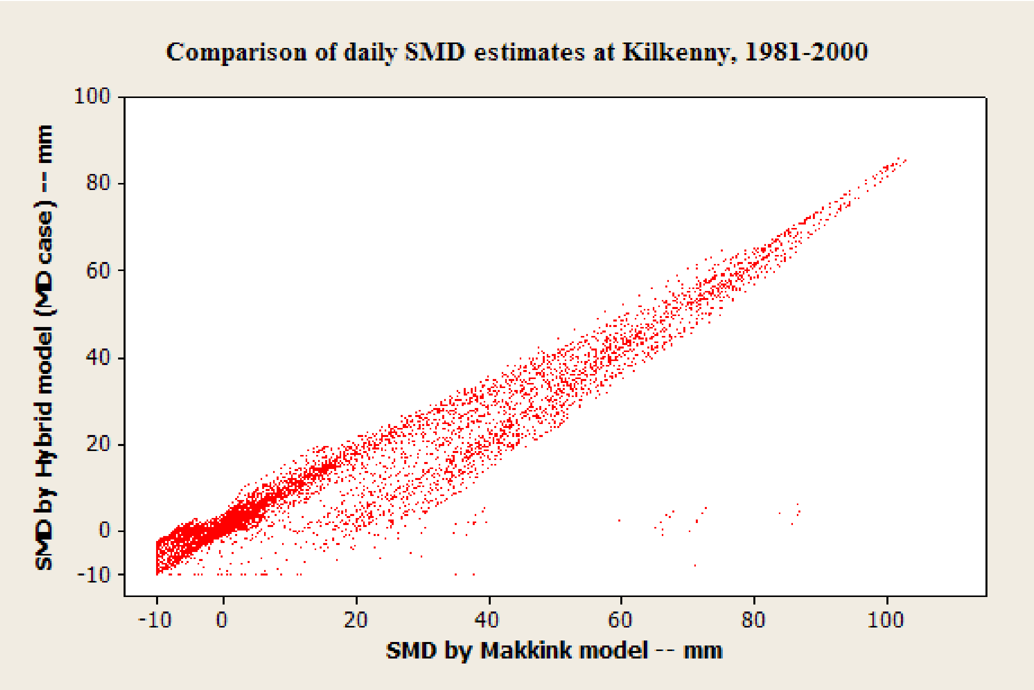
SMD estimates based on the earlier Makkink model were also held, and these were known to be generally complete. Comparison of the two sets of estimates confirmed the extent of the problem. Several stations presented no problem: the Hybrid and Makkink estimates differed, but not unreasonably. Figure 1 compares the Hybrid MD and Makkink estimates for Casement.

Figure 1



However, equivalent plots revealed problems at specific stations such as Kilkenny (see Figure 2). These arise from faulty Hybrid model estimates that have propagated in this instance from two isolated missing days (9 September 1991 and 29 August 1998).

Figure 2



Diagnosing these problems took some considerable time. Once informed of the problem, Met Éireann acted swiftly: re-running the model to fill the gaps, thereby eliminating both the missing values and the propagated errors. One long gap persisted. Met Éireann reported that the 3-year gap in the record at Station 2615 reflected specific concerns about the quality of wind-speed measurements at Rosslare in the period 1997-1999.

Inter-site correlations

The extent of inter-site dependence was examined by correlating the time series of SMD estimates (WD case) across the 14 stations. In each case, the period of common record was used. This yielded correlation coefficients for all station-pairs except Connaught & Claremorris. The seven strongest and seven weakest pairwise correlations were examined for spatial consistency (see Table 3).

Table 3 Station-pairs exhibiting greatest and least correlation in daily SMD (WD set)

Correlation coefficient	Station-pair	Correlation coefficient	Station-pair
Seven greatest		*Seven least*	
.940	Casement & Dublin	.643	Cork & Malin Head
.924	Mullingar & Clones	.650	Kilkenny & Malin Head
.917	Mullingar & Birr	.653	Rosslare & Malin Head
.911	Birr & Shannon	.661	Dublin & Malin Head
.900	Mullingar & Shannon	.661	Casement & Malin Head
.896	Claremorris & Belmullet	.664	Connaught & Rosslare
.895	Birr & Kilkenny	.678	Connaught & Dublin

There are no particular surprises in the lists. The pairings generally reflect inter-site distance. The strong SW-NE correlation evident between Mullingar–Birr–Shannon is a feature of the later wetness maps (see Sections 4.3 and 4.4). That Malin Head is the most disassociated record is perhaps to be expected given its unique exposure and distance from other stations.

Sensitivity of *PROPWET* to the period of record

At ten years, the record at Connaught is the shortest. $PROPWET_{WD,6.0}$ was evaluated over this specific 10-year period (1997-2006) and compared with $PROPWET_{WD,6.0}$ calculated over the full period-of-record (1981-2006) at the 11 stations with complete records (i.e. excluding Claremorris and Rosslare, as well as Connaught).

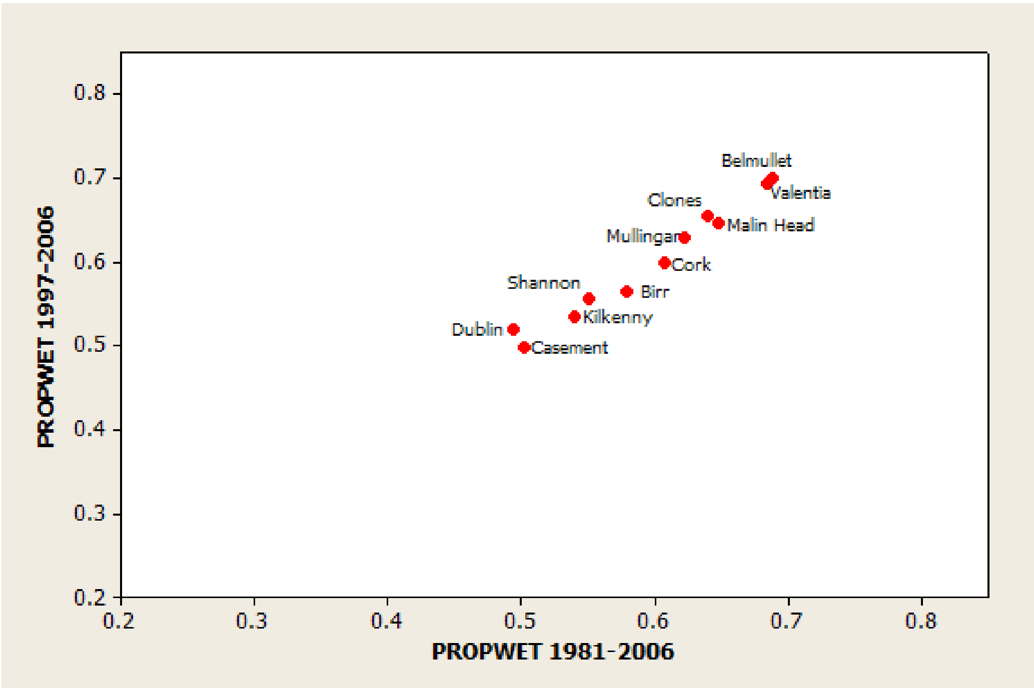
No systematic pattern was detected (e.g. Figure 3). $PROPWET_{WD,6.0}$ for the short period was found to be 5.1 % higher at Dublin but 2.4 % lower at Birr. In a linear regression, the intercept was found to be not significantly different from zero, yielding the relation:

$$PROPWET_{WD,6.0}^{(1997\text{-}2006)} = 1.006\ PROPWET_{WD,6.0}^{(1981\text{-}2006)}$$

Near identical results were found for the $PROPWET_{PD,6.0}$ variable, yielding:

$$PROPWET_{PD,6.0}^{(1997\text{-}2006)} = 1.007\ PROPWET_{PD,6.0}^{(1981\text{-}2006)}$$

Figure 3



None of the stations close to Connaught indicated a large adjustment factor. Similar explorations revealed nothing of significance. It was therefore concluded that period-of-record adjustments to the *PROPWET* values were not required.

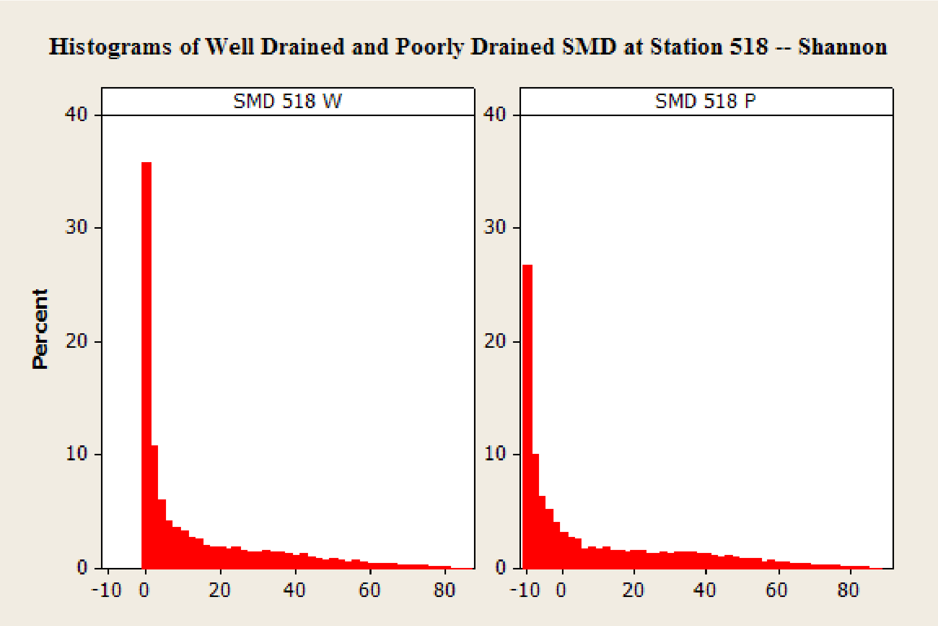
In the later mapping, the derived wetness indices at Connaught and Claremorris (and, to a lesser extent, Rosslare) are down-weighted to reflect their shorter periods of record.

Choosing which set of SMD estimates to focus on

It had initially been intended to focus on either the Moderately Drained (MD) estimates or the Poorly Drained (PD) estimates of SMD. However, it was found that the *PROPWET* index was insensitive to the difference between the two datasets. Consideration of the MD estimates therefore ended on completion of the exploratory data phase.

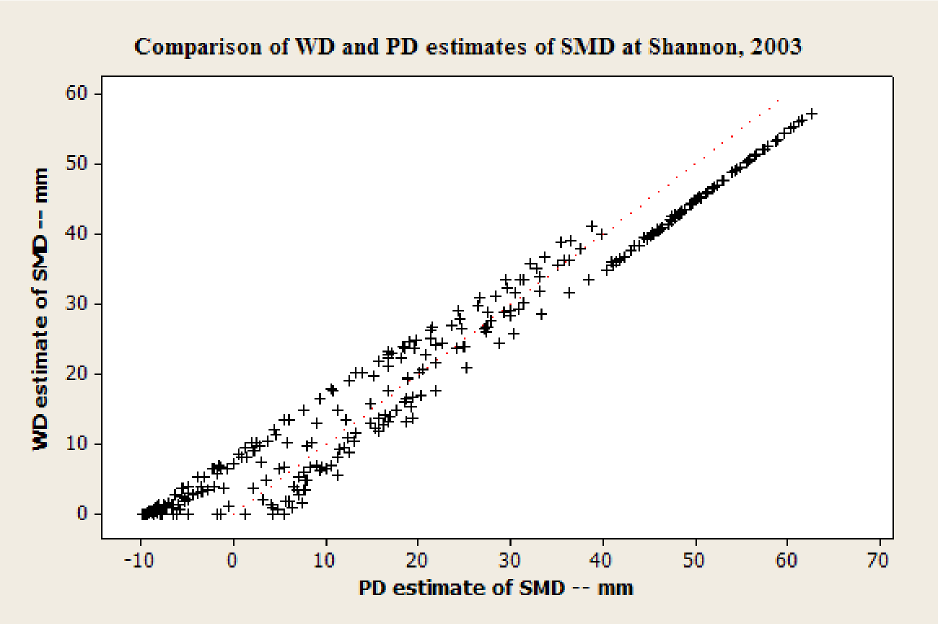
Comparison of the PD and WD estimates of SMD led to some surprises, and an eventual preference for the WD estimates. Figure 4 illustrates that, in the PD case, the model correctly represents periods of saturation, i.e. periods when there is an excess of soil moisture (indicated by a negative value of SMD). In contrast, in the WD case, the SMD never drops below zero. These features are as expected.

Figure 4



The disconcerting feature of the PD model is that it provides larger estimates of SMD in long dry periods. As illustrated for Shannon in 2003 in Figure 5, the PD model tends to produce larger SMDs (than the WD model) once deficits become large. This is counter-intuitive.

Figure 5

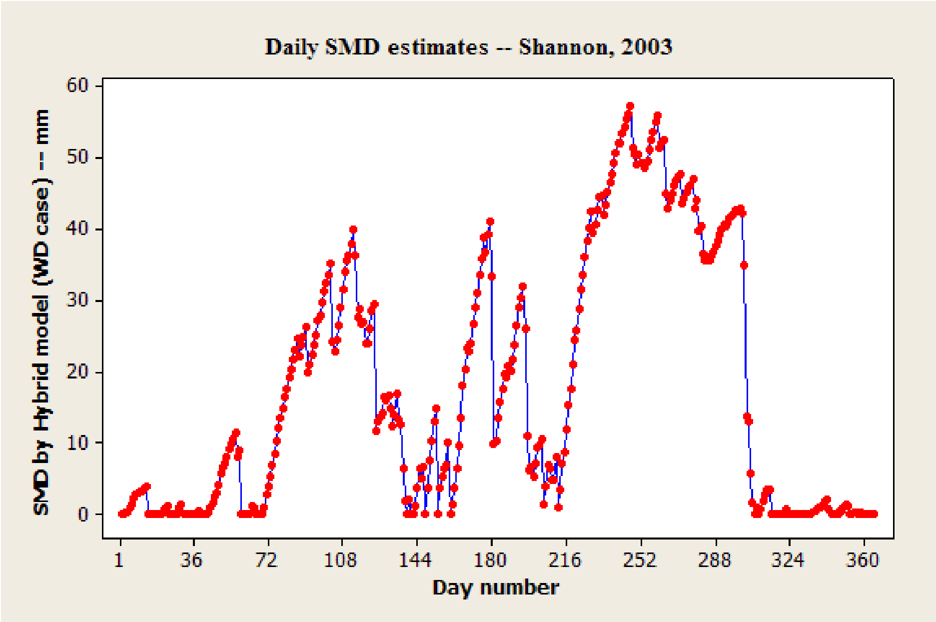


This puzzling feature of the PD version of the model was later confirmed to be quite general. Consequently, as the study progressed, a preference built up to adopt the simpler estimates based on the WD version of the model.

2.5 Deciding which periods of record to use at which stations

The calendar year is appropriate for studying SMD, since SMD is typically close to zero at 1 January. Use of the water-year would be less appropriate because significant SMDs occasionally persist beyond 1 October as, for example, in 2003 at Shannon (see Figure 6). [1 October is Day 274 in a non-leap year.]

Figure 6



The objective of WP5.4 is to produce *PROPWET* estimates across Ireland. Thus, spatial interpolation plays a major role in the research. Changes in the gauge network inevitably complicate the interpolation considerably. It is helpful at the outset to summarise the records analysed in the project in the chronological format of Table 4.

Table 4 Summary of the records to be analysed

Set	Years	# stations	Stations absent	Commentary	File of Voronoi weights
1	1981-1995	13	Connaught	Connaught not yet started	*vweight1.txt*
2	1996	12	Connaught & Claremorris	Claremorris has ended; Connaught still not started	*vweight2.txt*
3	1997-1999	12	Rosslare & Claremorris	Connaught has started but Rosslare gone missing	*vweight3.txt*
4	2000-2006	13	Claremorris	Rosslare returns	*vweight4.txt*

The final column is relevant to the mapping work reported in Section 4.

3 Analysis of wetness at gauged sites

Three descriptors of wetness behaviour are examined: *PROPWET*, *CVWET* and *SMDBAR*. It is convenient to discuss *SMDBAR* first, since it derives directly from the SMD estimates. For the 11 stations with complete data, the values reported here refer to the main period of analysis: 1981-2006. For Rosslare, the values derive from the main period less 1997-1999. For Claremorris and Connaught they refer to the shorter periods 1981-1995 and 1997-2006, respectively.

3.1 *SMDBAR*

SMDBAR denotes the long-term mean SMD. [While this is the definition used in the 1999 Flood Estimation Handbook, it should be noted that the *SMDBAR* mapped in the 1975 Flood Studies Report had a different (and rather obscure) definition. This is discussed further in Section 5.2.] Table 5 reports the values found. Entries in red indicate stations with incomplete records.

Table 5 **SMDBAR *at gauged sites***

Gauge	$SMDBAR_{WD}$	$SMDBAR_{PD}$	**Altitude**
	mm	*mm*	*m*AOD
Valentia	7.219	-0.028	11
Shannon	13.262	8.644	6
Dublin	15.372	11.601	71
Malin Head	8.154	1.731	22
Belmullet	7.211	0.702	11
Clones	9.392	3.474	89
Rosslare	16.777	12.423	26
Claremorris	8.574	2.018	71
Mullingar	10.701	5.150	104
Kilkenny	14.468	9.957	66
Casement	15.712	11.864	94
Cork	11.023	4.970	154
Birr	12.181	7.489	73
Connaught	5.481	-2.180	203

As expected, *SMDBAR* is appreciably higher in the Well Drained (WD) case than in the Poorly Drained (PD) case. The two versions of *SMDBAR* are very closely related (Figure 7), with the regression:

$$SMDBAR_{WD} = 6.97 + 0.745\ SMDBAR_{PD}$$

explaining 99.4 % of the variation in $SMDBAR_{WD}$.

It is relevant to check for any pronounced altitudinal effects. The regression line shown in Figure 8 is not at all significant, explaining 0.0 % [sic] of the variation in $SMDBAR_{WD}$.

Figure 7

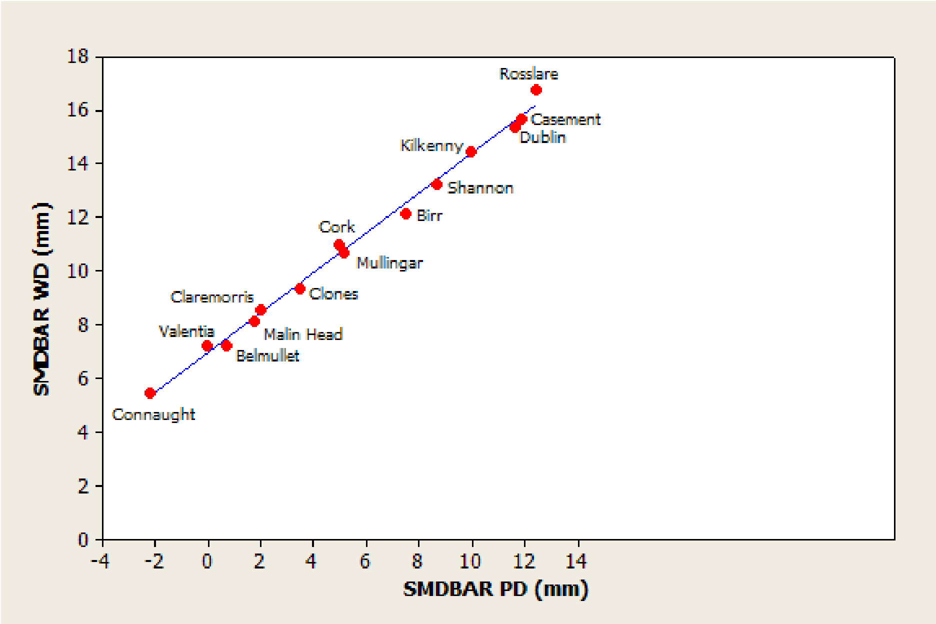
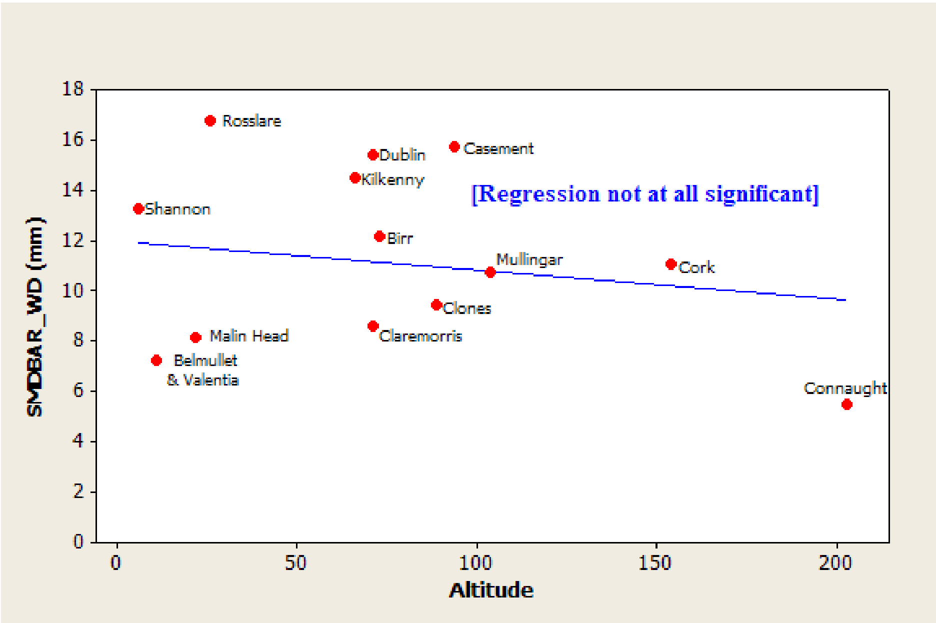


Figure 8



3.2 *PROPWET*

The variable *PROPWET* is the proportion of the time for which soils can be expected to be typically quite wet. The variable works by distinguishing wet/dry conditions according to whether the SMD is less/greater than a given threshold.

Choice of wet-dry threshold

The choice of wet-dry threshold is rather arbitrary. The Flood Estimation Handbook (FEH) contrived a way of fixing the threshold by reference to the dates of peaks-over-threshold events. This was based on the expectation that floods should generally occur, and only occur, when catchment soils are wet. A more pragmatic approach is followed here. The threshold is chosen to maximise inter-site variation in *PROPWET* across the 14 gauged sites.

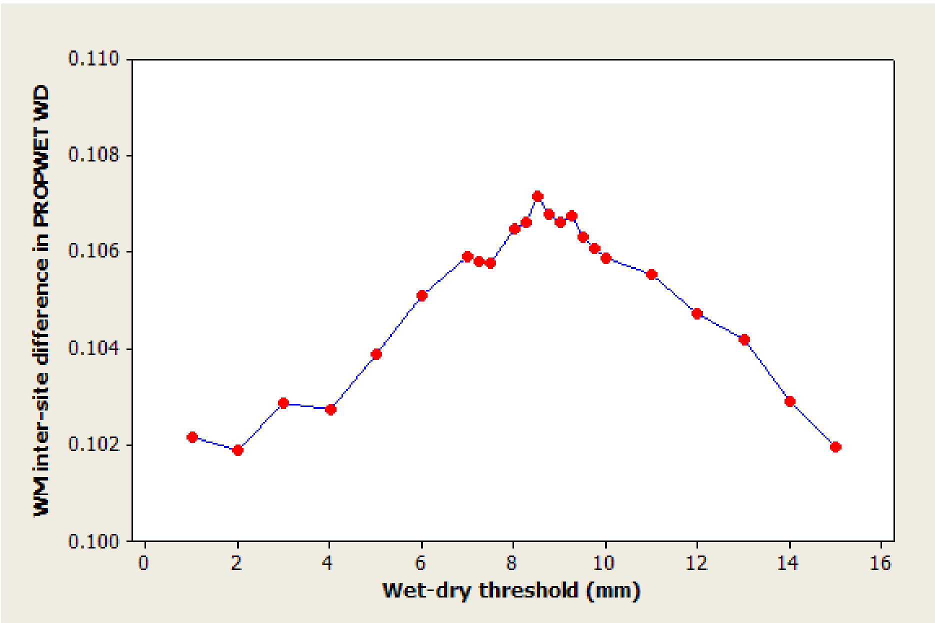
Thinking behind choice of wet-dry threshold

The unexpected success of the catchment descriptor *PROPWET* – both in the FEH and in later work to generalise UK rainfall-runoff models – leads one to consider why this may be. The variable is inevitably rather sketchy spatially, given the sparse coverage of climate datasets. Moreover, experience in using the FEH has revealed some rather harsh edges in the field of *PROPWET* values supplied. Yet the descriptor has proved valuable in the generalisation of hydrological models for use on ungauged catchments.

One explanation for its success is that *PROPWET* is supplying information of a distinctly different character to descriptors such as *SAAR* and *SPRHOST*. Another explanation is much simpler: perhaps *PROPWET* is proving useful in part because it is neat dimensionless index, defined to take values in the range [0,1]. [The FEH *PROPWET* values – based on a 6 mm wet-dry threshold – spanned a fair swathe of the theoretical range, with values from about 0.20 to 0.85.] It is the latter thought which prompted the highly empirical approach of choosing the wet-dry threshold to maximise inter-site

Figure 9 reveals a relatively well-defined optimum value for the wet-dry threshold in the WD case. A threshold of 8.5 mm maximises the weighted mean pairwise inter-site variation in *PROPWET*. The weighting takes account of the shorter records at Rosslare, Claremorris and Connaught. A similar optimisation indicated a wet-dry threshold of 0.8 mm for use in the PD case. These thresholds are adopted in the *PROPWET* values and maps presented later.

Figure 9



Derived values of *PROPWET*$_{WD}$ and *PROPWET*$_{PD}$

To emphasise the specific wet-dry thresholds underlying these PROPWET values, the variables are given the full names *PROPWET*$_{WD,8.5}$ and *PROPWET*$_{PD,0.8}$. The entries in red in Table 6 highlight the stations with incomplete data.

Table 6 **PROPWET** ***at gauged sites***

Gauge	*PROPWET*$_{WD,8.5}$	*PROPWET*$_{PD,0.8}$	Altitude (m)
Valentia	0.7370	0.7166	11
Shannon	0.5964	0.5529	6
Dublin	0.5411	0.4923	71
Malin Head	0.7057	0.6717	22
Belmullet	0.7322	0.6913	11
Clones	0.6852	0.6489	89
Rosslare	0.5466	0.5203	26
Claremorris	0.7192	0.6838	71
Mullingar	0.6625	0.6257	104
Kilkenny	0.5809	0.5403	66
Casement	0.5480	0.4973	94
Cork	0.6585	0.6322	154
Birr	0.6235	0.5803	73
Connaught	0.8001	0.7768	203

Checks were made for systematic variation of *PROPWET* with gauge altitude. In both cases (see Figures 10.WD and 10.PD), the regressions explain 0.0 % [sic] of the variation in *PROPWET*. [This does not mean that *PROPWET* is free from altitudinal effects, or that it would be appropriate to remove such effects if found. It is just an observation. *PROPWET* is only being developed as an index to be used in conjunction with other descriptors of catchment properties. It does not need to make perfect sense.]

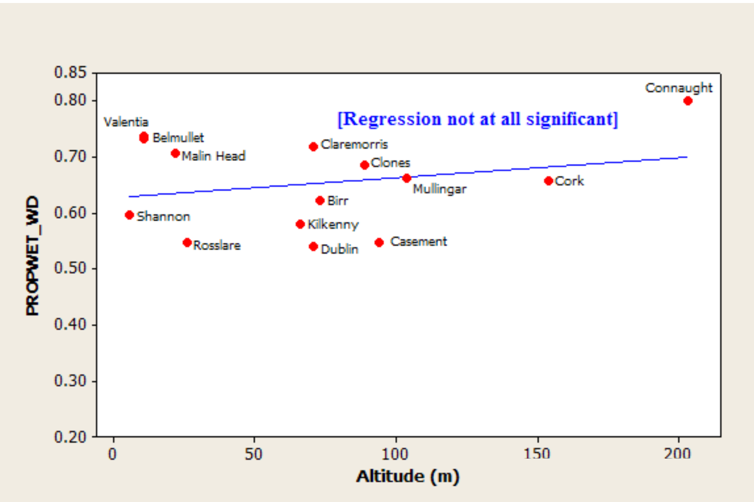


Figure 10.WD

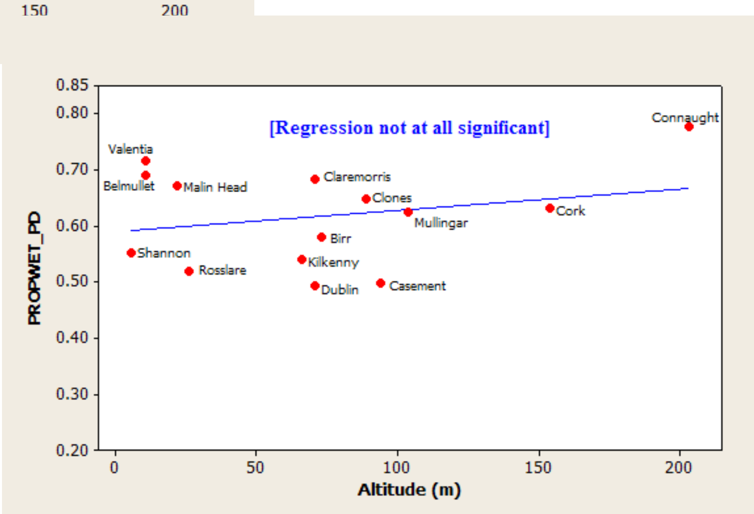


Figure 10.PD

4 Mapping wetness

across Ireland

The requirement is to be able to estimate the wetness indices (e.g. *PROPWET*) for any catchment in Ireland. The approach to meeting this requirement taken here is to generate estimates of the variables across a regular grid. From the gridded dataset, it will be possible to derive a catchment value of the descriptor by averaging values of the index across all the grid-points within the catchment. An alternative scheme would adopt the index value for the grid-point nearest to the catchment centroid. [This might be a useful back-up method to apply on any small catchment bereft of a grid-point.]

Mapping requires some kind of spatial interpolation.

4.1 Methods

Choice of grid system

The grid scheme used by Met Éireann in WP1.2 was adopted. This constructs a 2-km grid across the whole of Ireland, based on Irish Grid References. The scheme comprises 172 by 222 grid-points. In response to a specific request, Met Éireann kindly supplied a flag to indicate which of these 38184 grid-points lie on sea, and which (of those on land) lie in Northern Ireland. 21002 of the grid-points lie on land, of which 3551 are in Northern Ireland.

Stage at which to perform the spatial interpolation

One approach would simply interpolate the wetness index from values at the gauged sites (see Section 3) to the grid-point. This is termed below *index interpolation*.

However, the approach principally favoured here is to *interpolate SMD values on each day of the analysis period*, and to calculate the wetness index at the grid-point as if it were gauged. This method is termed below *SMD interpolation*. It is preferred because it exploits the available daily SMD data more fully.

Method of spatial interpolation

Going into the research project, there was some uncertainty about the choice of an appropriate method of spatial interpolation. This doubt dissipated once the merits of Voronoi interpolation had been fully appreciated. British Standards Institution guidance (BSI, 1996) is unequivocal:

> *Voronoi interpolation is a very attractive method of establishing a regular square grid of [rainfall] estimates. It is easy to program, produces a smooth surface and is logically consistent. Essentially it is a development of the Thiessen polygon approach. … However, where the surface produced from Thiessen polgons is a series of plateaus [sic] with sharp steps between them, the Voronoi method provides a gradually varying surface.*

Trial use of the method led to interpolations that did indeed appear logically consistent. It should be noted that the method fully respects the gauged values of the index at the sites with complete records, i.e. no unnecessary smoothing is introduced.

How Voronoi interpolation works

A network of polygons is constructed about the gauged sites, in the manner of Thiessen polygons. Each point on the national grid is allocated to the gauge to

Voronoi weights

Each grid-point was treated in turn and each assigned a unique set of Voronoi weights. Because of the differing numbers of gauges operating in different eras (see Table 4 earlier), it was necessary to construct four sets of Voronoi weights for each grid-point, one set for use in each of the sub-periods: 1981-1995, 1996, 1997-1999 and 2000-2006.

A feature of Voronoi interpolation is that the weights depend only on the number and configuration of gauges. Thus, the same sets of Voronoi weights might be used to interpolate other climate variables from data at these sites. Files holding the Voronoi weights (stored to five decimal places to maintain accuracy in the interpolation) can be supplied on request.

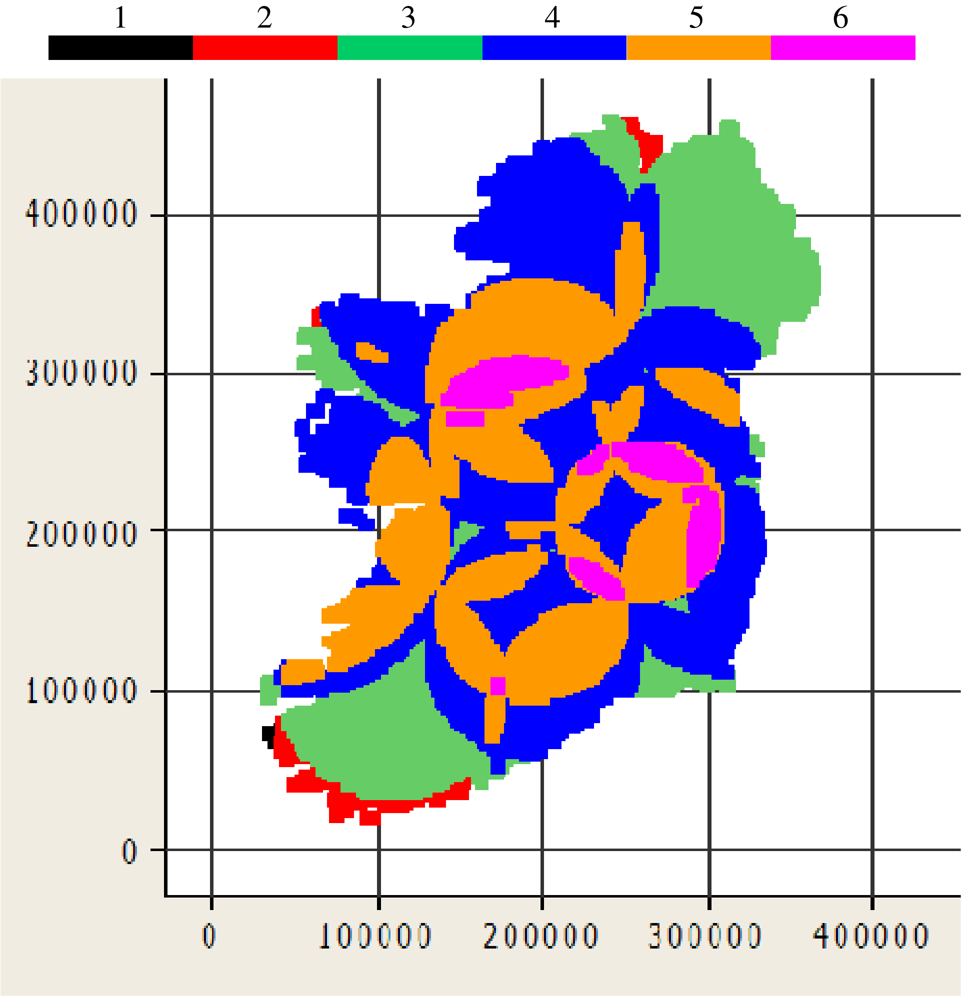
4.2 Features imposed by the gauge network

Three maps summarise the features imposed by the gauge network.

Map 2 shows the number of gauges used in interpolation. The number mapped is non-integer, being the weighted mean number of gauges used across the four sub-periods. In a very small zone immediately west of the Valentia gauge – shown in black – only one gauge is used. Thus index values interpolated to grid-points there take on the value gauged at Valentia. More typically, the number of gauges used in interpolation is between three and six (see also Figure 11). It is re-iterated that the non-integer values reflect that the number of gauges used in interpolation to some grid-points changes in particular years: as the Claremorris record ends, the Connaught record begins, and the Rosslare record goes on leave.

Map 3 is of the gauge accorded the greatest weight. [This has been judged from the weighted mean of the Voronoi weights applying in each sub-period.] The map shows the relative dominance of the different gauges. The Connaught gauge commands only a very small area because of its relatively short record. The large zone over which Clones is the gauge accorded the greatest weight would have been smaller had one or more gauges in Northern Ireland been introduced.

Map 4 indicates the size of the largest Voronoi weight.



Map 2

Number of gauges used in interpolation

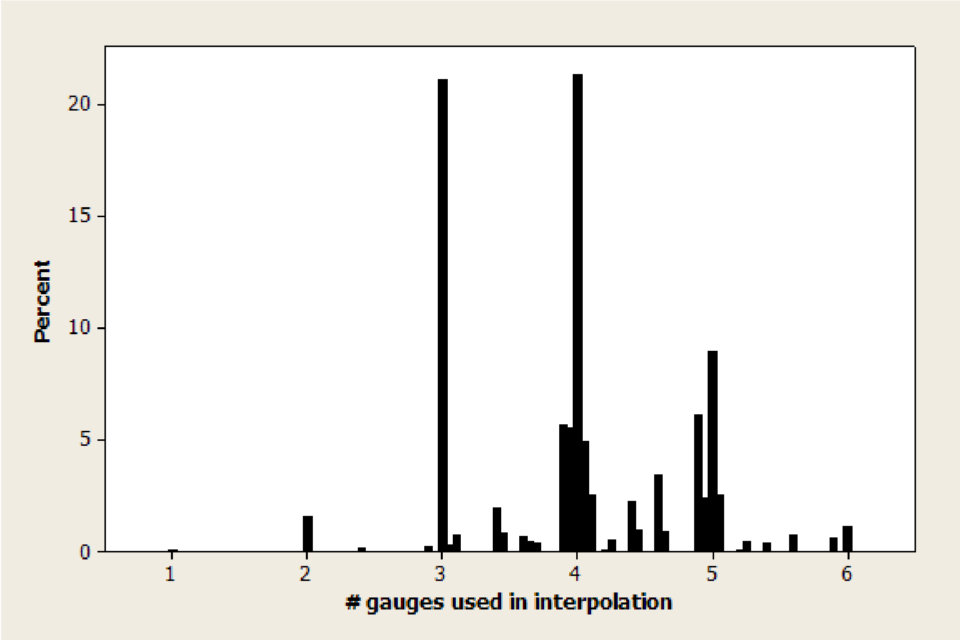
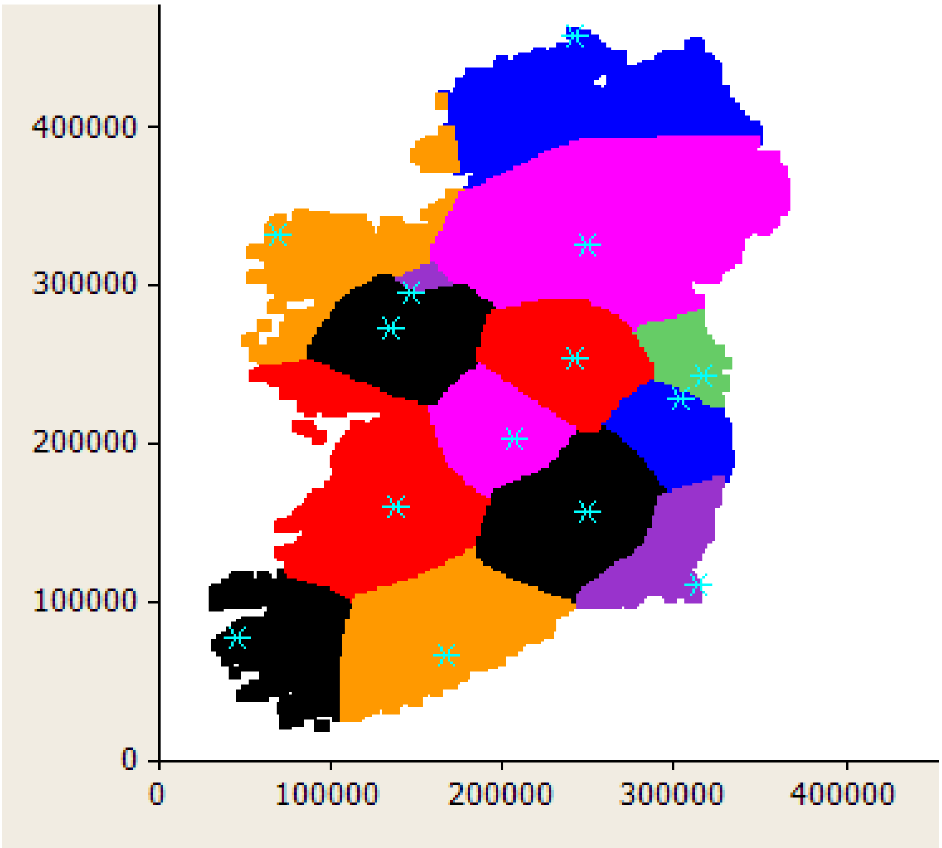


Figure 11

Relative frequency distribution of number of gauges used in interpolation

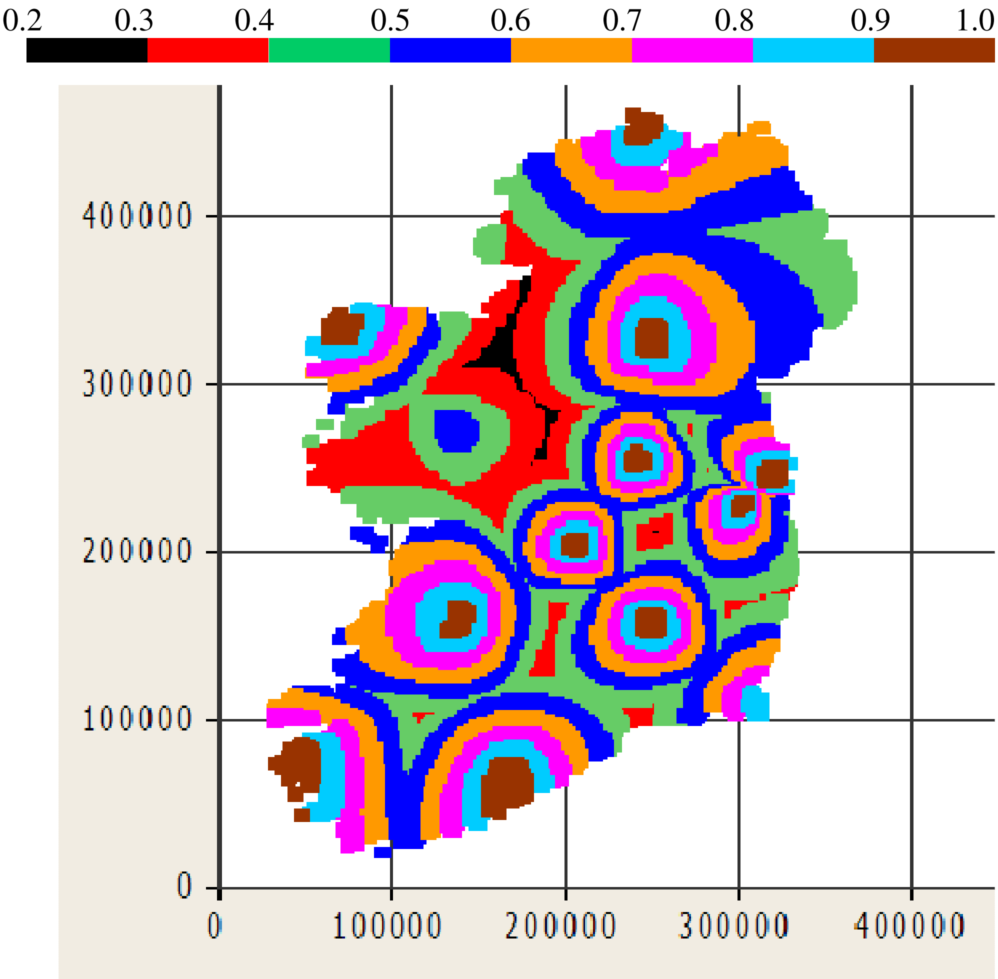
Map 3

Gauge accorded greatest weight



Map 4

Magnitude of greatest weight

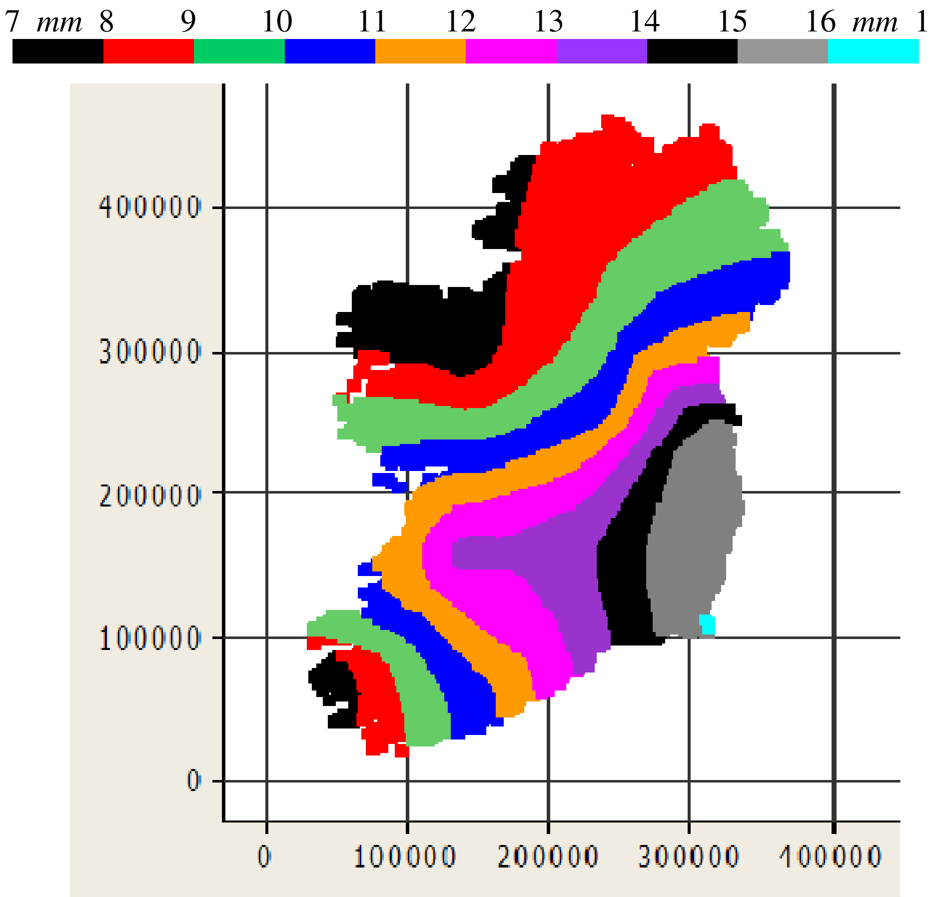


4.3 Maps of *SMDBAR*

Although the maps are rather similar in appearance, note that the numerical values of $SMDBAR_{WD}$ (Map 5.WD) and $SMDBAR_{PD}$ (Map 5.PD) are very different.

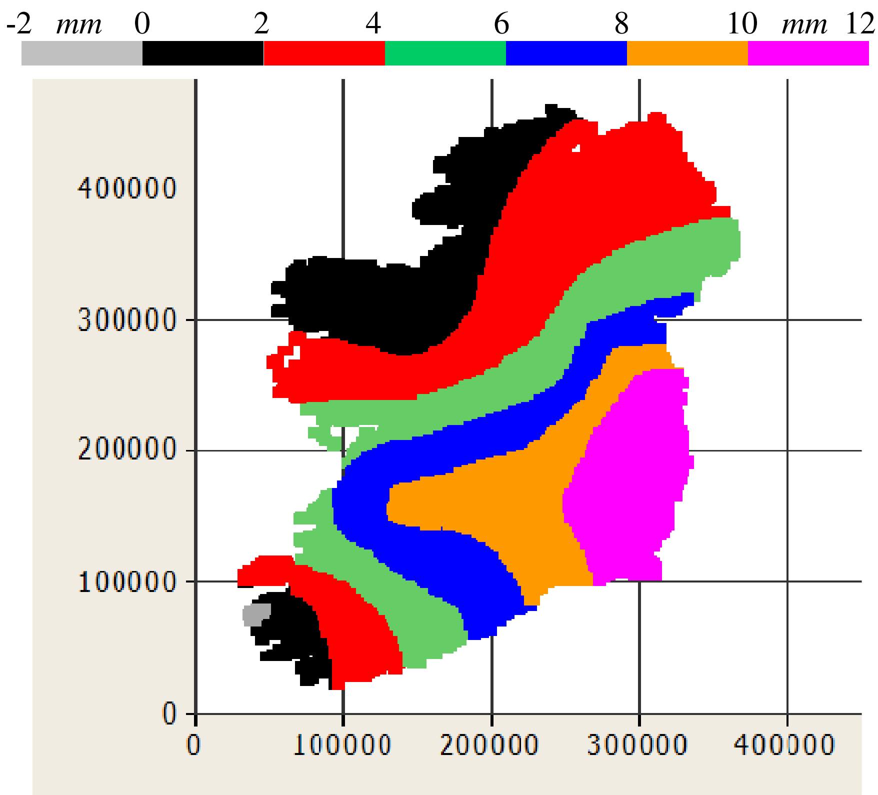
Map 5.WD

SMDBAR



Map 5.PD

SMDBAR

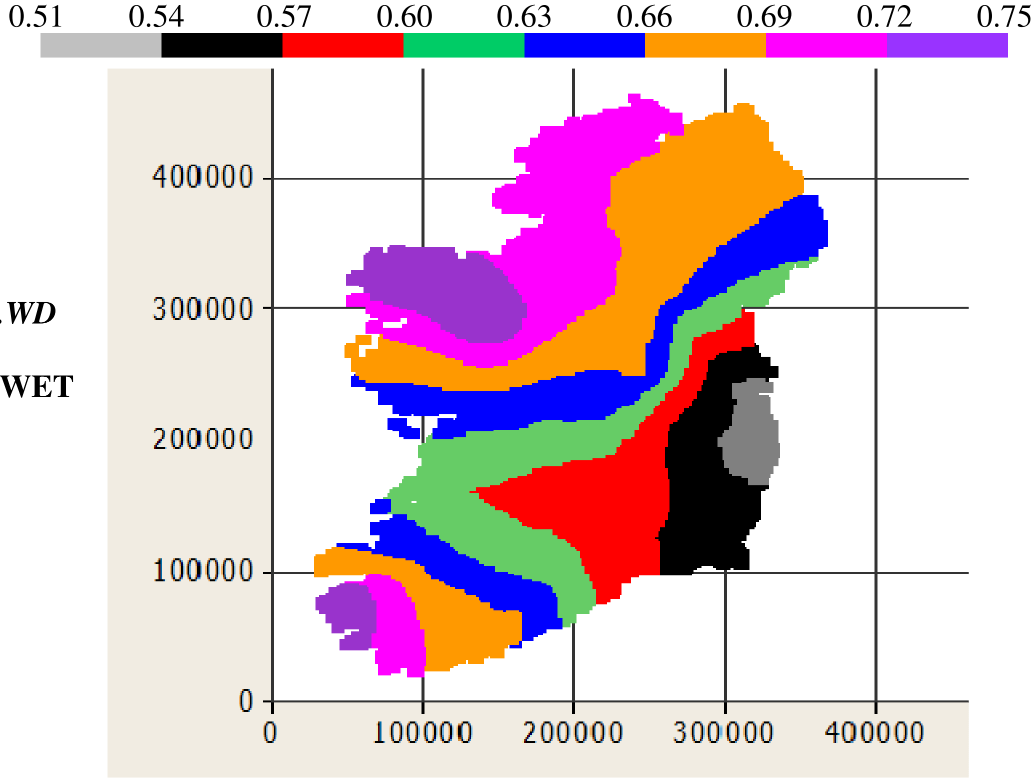


4.4 Maps of *PROPWET*

The acute close-packing of $PROPWET_{PD,0.8}$ contours west of Dublin is an undesirable feature of Map 6.PD in comparison to the map of $PROPWET_{WD,8.5}$ (Map 6.WD).

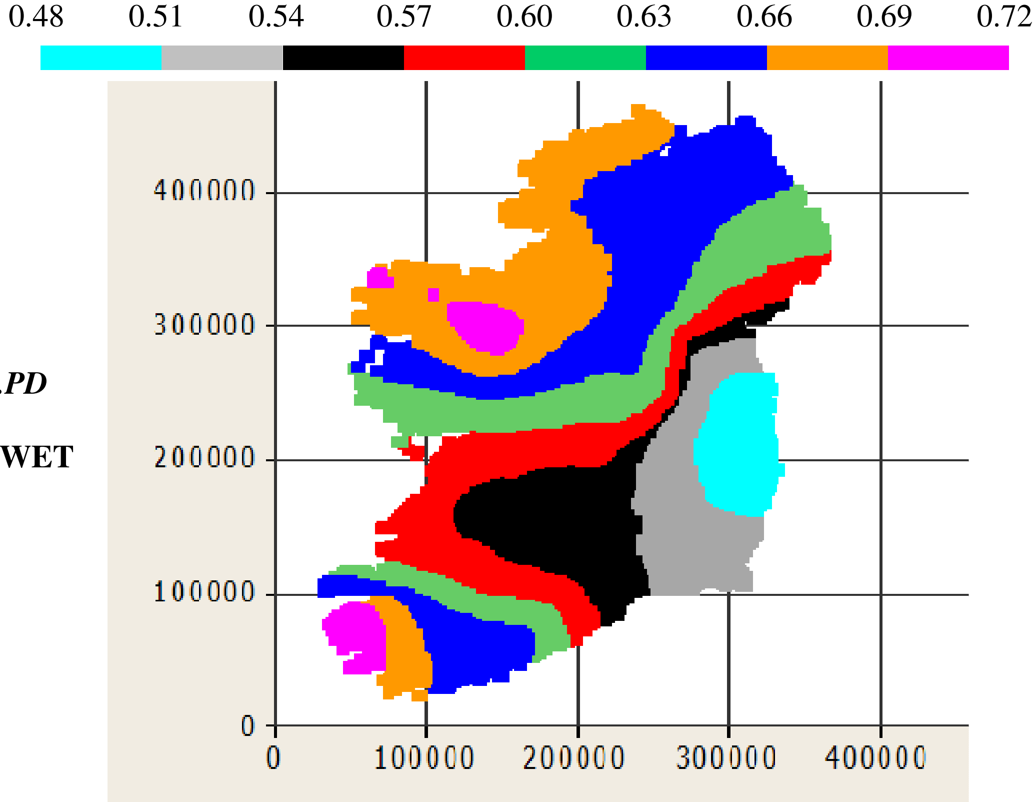
Map 6.WD

PROPWET



Map 6.PD

PROPWET



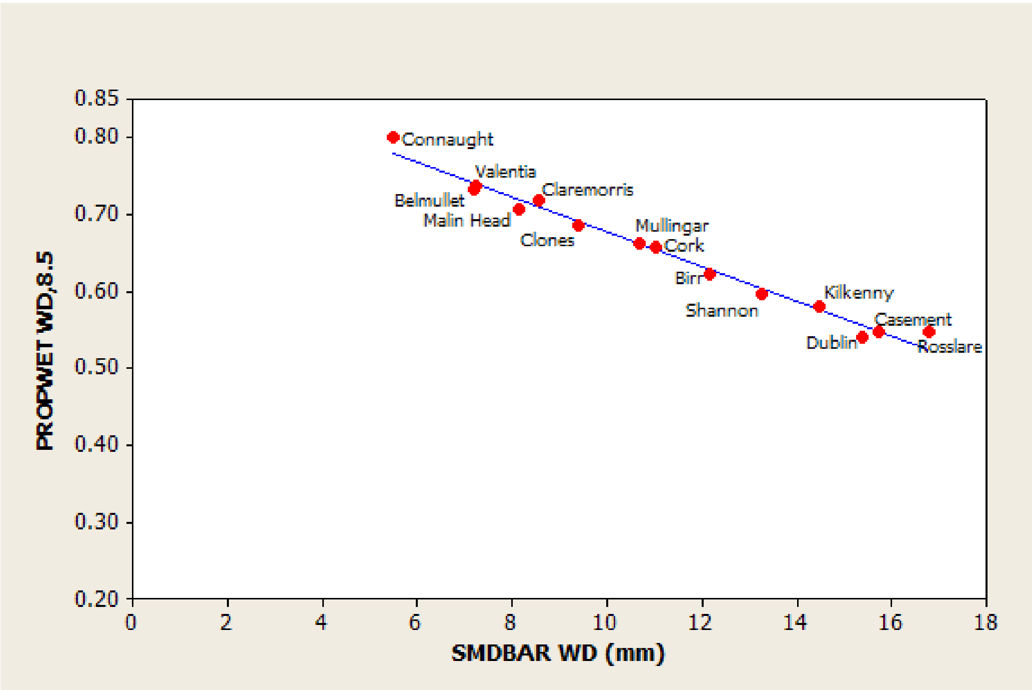
5 Discussion and comparisons

The descriptor-values for stations with complete records are fully honoured in the mapping of wetness variables reported in Section 4. Those for Connaught, Claremorris and Rosslare are replaced by values calculated after the SMD data for missing years have been filled by interpolation from other sites. This is implicit in the methods described in Section 4.1.

5.1 Association between *PROPWET* and *SMDBAR*

A striking feature of the maps presented in Sections 4.3 and 4.4 is the visual similarity of the *SMDBAR* and *PROPWET* maps. This had not been fully anticipated. It transpires that estimates for the gauged sites (see Section 3) reveal a very strong inverse correlation between *SMDBAR* and *PROPWET* (e.g. Figure 12).

Figure 12



Linear regression yields:

$$PROPWET_{\mathrm{WD,8.5}} = 0.903 - 0.0225\ SMDBAR_{\mathrm{WD}},\ \text{with an adjusted } r^2 \text{ of } 98.0\ \%$$

and

$$PROPWET_{\mathrm{PD,0.8}} = 0.717 - 0.0180\ SMDBAR_{\mathrm{PD}},\ \text{with an adjusted } r^2 \text{ of } 97.9\ \%.$$

The mapping (spatial interpolation) process weakens the association slightly. Regression on the 21002 grid-point values yields:

$$PROPWET_{\mathrm{WD,8.5}} = 0.873 - 0.0212\ SMDBAR_{\mathrm{WD}},\ \text{with an adjusted } r^2 \text{ of } 97.2\ \%.$$

These results suggest that there is considerable duplication between the *SMDBAR* and *PROPWET* descriptors of catchment wetness, and that one or other of the descriptors may prove redundant. The equivalent wetness descriptors used in the FEH (denoted here as $PROPWET_{6.0}$ and *SMDBAR*) were also highly correlated, although less strongly (with an r^2 of about 0.94).

A final check was made for correlation between $PROPWET_{WD,8.5}$ and average annual rainfall (*SAAR*). Using 1961-1990 *SAAR* values abstracted from http://www.met.ie/climate/30year-averages.asp, linear regression of $PROPWET_{WD,8.5}$ on *SAAR* yielded:

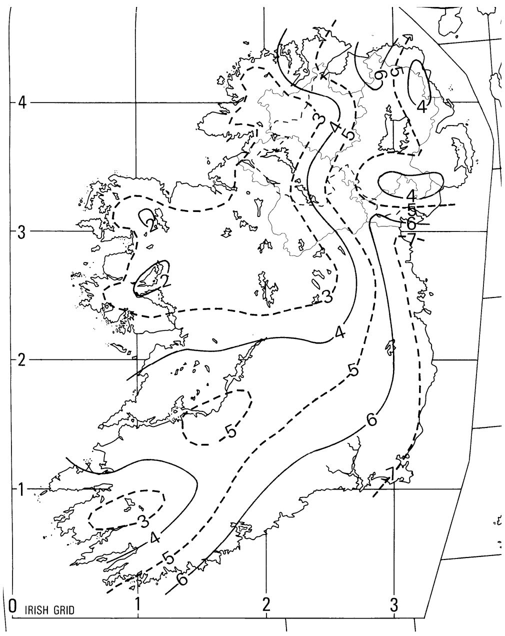
$$PROPWET_{WD,8.5} = 0.286 - 0.326\ (SAAR/1000), \text{ with an adjusted } r^2 \text{ of } 73.1\ \%.$$

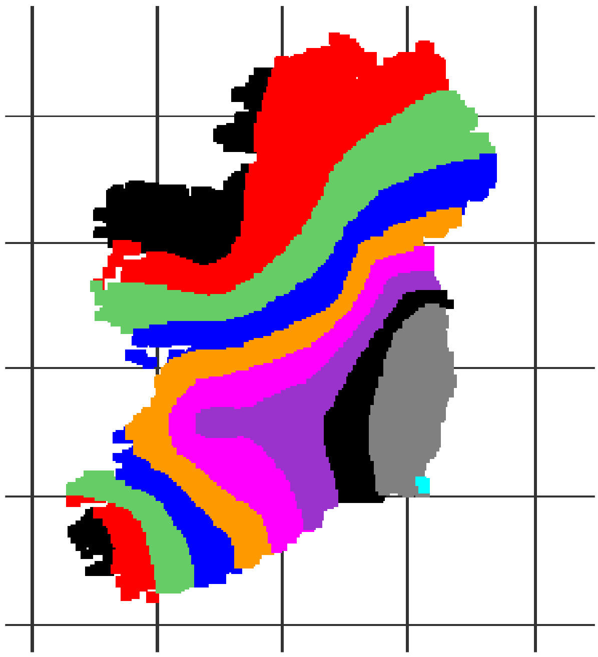
[This result is based on data for 13 stations. Reflecting its commencement in May 1986, an estimated 1961-1990 *SAAR* value could not be found for Connaught.] The suggestion from the above analysis is that there is no undue redundancy between $PROPWET_{WD,8.5}$ and *SAAR*.

5.2 SMDBAR

Ireland

The map of *SMDBAR* presented in the 1975 Flood Studies Report (FSR) is of a different variable (see FSR **I** pp 306-7 & p 311 and Figure **I** 4.19 in FSR **V**). Abstrusely, *SMDBAR* was defined as the difference between estimates of the 5-year maximum rainfall and the 5-year maximum rainfall excess. A detailed comparison is therefore inappropriate. However, it is heartening that some of the spatial traits in the FSR map are broadly similar. The map shown here for comparison is that of $SMDBAR_{WD,8.5}$ (Map 5.WD).





🡅 ***Map 7*** **SMDBAR** ***from the 1975 FSR***

Although based on a similar number of Irish stations, and somewhat shorter records, the FSR representation is rather more intricate. This suggests that the FSR contouring was aided by climatological interpretation, as well as by the incorporation of data for a number of gauges in Northern Ireland.

Northern Ireland

The Flood Estimation Handbook (FEH) covers Northern Ireland. For various reasons, the FEH descriptors of wetness developed in Northern Ireland were based on MORECS v2.0 rather than on MORECS (see Bayliss and Morris, 1999).

SMDBAR values are not amongst the data published on the FEH CD-ROM. However, Bayliss (1999) gives values of *SMDBAR* for 42 Northern Ireland catchments. These values lie in the range 10.0 to 17.5 mm. Grid-point values derived here are smaller: the WD estimates indicating *SMDBAR* values of 8 to 11 mm in Northern Ireland (see Map 5.WD).

Comparison with Map 5.PD indicates that the PD estimates of *SMDBAR* are much too small to be at all compatible with the FEH *SMDBAR* values.

5.3 PROPWET

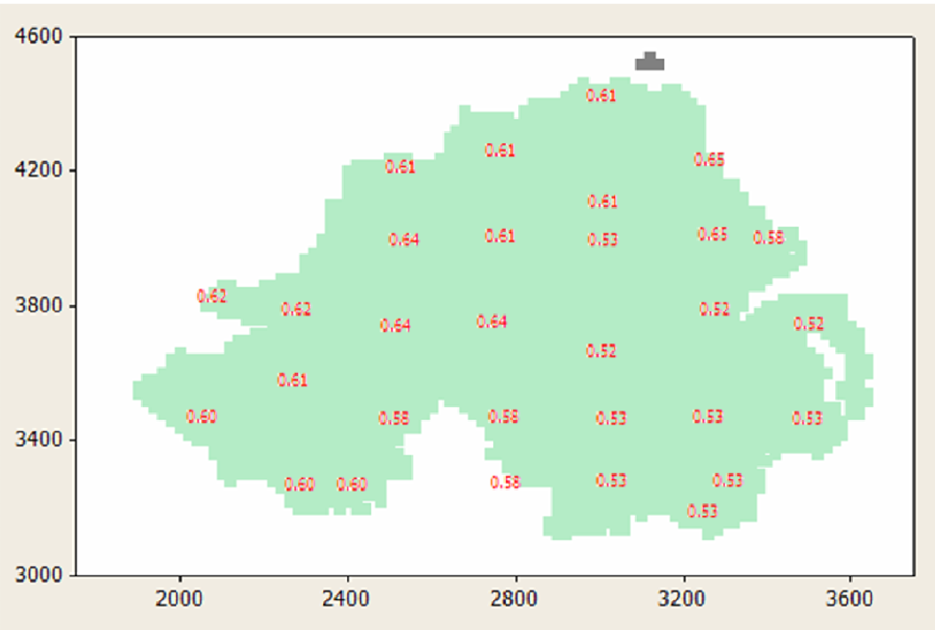
Northern Ireland

The FEH covers Northern Ireland and *PROPWET* values are published on the FEH CD-ROM. A sample of catchment values of *PROPWET* was extracted for small ungauged catchments (typical size 0.5 to 1.0 km^2) in Northern Ireland using FEH CD-ROM v2.0. [Version 2.0 provides catchment centroids, allowing the derived *PROPWET* values to be located relatively precisely.]

The FEH values of *PROPWET* illustrated in Map 8 range from 0.52 in the E to 0.62 in the W but with higher values in some central and NE areas. Overall, the pattern is rather irregular, confirming experience elsewhere that the FEH fields of *PROPWET* include some "cliff edges". It should be recalled that the FEH *PROPWET* is based on a wet-dry threshold of 6 mm rather than 8.5 mm.

Map 8

***FEH* values of PROPWET**



A comparison was done for these 30 grid-points by extracting relevant values from a map of $PROPWET_{WD,6.0}$ derived in the present study. In a linear regression, the intercept was found to be not significantly different from zero, yielding the relation:

$$PROPWET_{FEH} = 0.953\ PROPWET_{WD,6.0},$$ with an adjusted r^2 of 51.6 %

Thus the two sets of values are found to be broadly comparable, but with the FEH descriptor giving (on average) slightly lower values of *PROPWET*.

5.4 Why WD is preferable to PD

As the study progressed, a number of reasons were found for preferring adoption of the WD estimates of SMD rather than the PD ones.

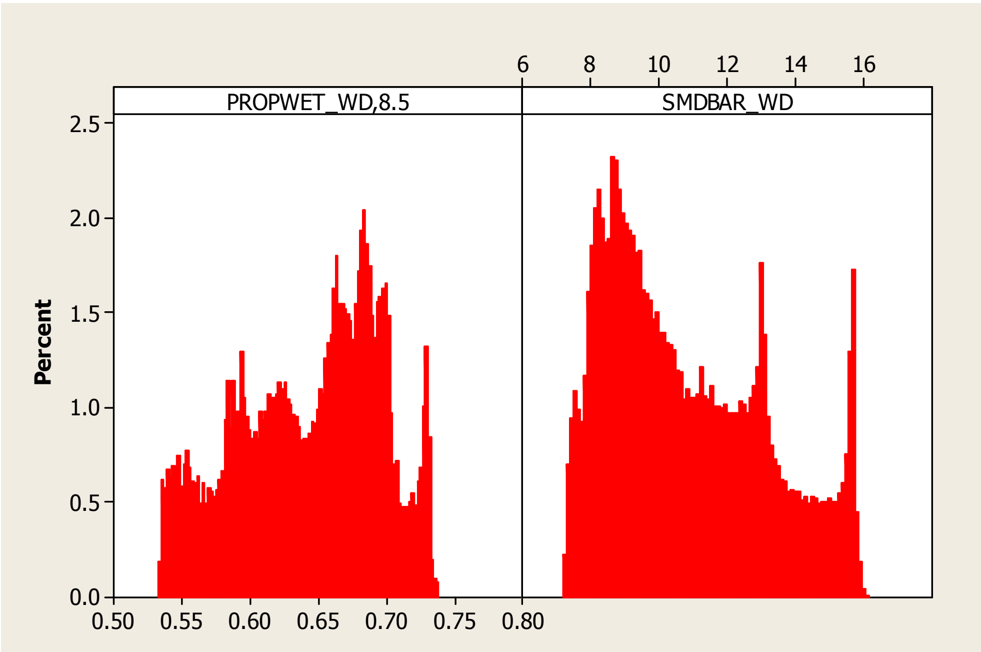
First, it seems odd that, in prolonged dry conditions, estimates of SMD for Poorly Drained soils should indicate larger SMDs than those for the Well Drained soils. Second, the numerical values of *SMDBAR* appear unrealistically low in the PD case. Third, there is nevertheless considerable association between the WD and PD estimates of *SMDBAR* and *PROPWET*, suggesting that little is to be lost by adopting one set over the other. The acute close-packing of contours west of Dublin in the PD-based *PROPWET* map (Map 6.PD) provides a fourth and final reason for preferring the wetness descriptors based on the WD estimates of SMD.

5.5 Relative frequency distributions

As an illustration of the data outputs from WP5.4, Figure 13 presents relative frequency distributions of $PROPWET_{WD,8.5}$ and $SMDBAR_{WD}$ for the 21002 grid-points on land (strictly, land means "not at sea").

Figure 13

***Histograms of recommended fields for* PROPWET *and* SMDBAR**



6 The auxiliary descriptor, *CVWET*

The FEH developed, but did not really exploit, the auxiliary wetness descriptor, *CVWET*. This is the coefficient of variation (CV = σ/μ = standard deviation / mean) of the length of wet spells, calculated over the analysis period.

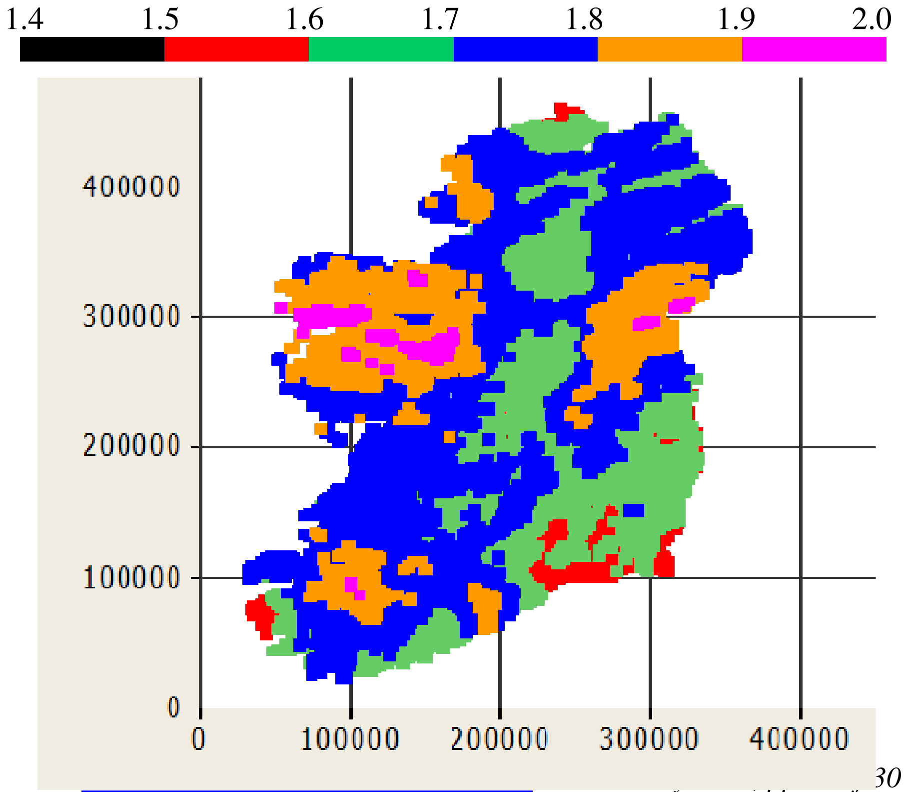
There are again two possible approaches to interpolation. In the *SMD interpolation* method, the wetness descriptor is derived from a long-term daily SMD series interpolated at the grid-point. In the *index interpolation* method, the interpolation is made directly from estimates of *CVWET* at the gauged sites.

6.1 Use of SMD interpolation method

The mapping of *SMDBAR* and *PROPWET* reported above favoured the SMD interpolation method, and found it generally satisfactory. Extension of the study to apply the SMD interpolation method to *CVWET* proved relatively straightforward.

Interestingly, the SMD interpolation method was found to perform poorly when used to map *CVWET*. Map 9 shows the map of $CVWET_{WD,8.5}$ produced by SMD interpolation. It can be seen to be strikingly different to the other wetness indices mapped in this research. This in itself is promising. However, closer inspection of Map 9 reveals that the interpolation is unsatisfactory.

There is just one grid-point with a *CVWET* of less than 1.5. This is grid-point 228000 102000, which is roughly intermediate to Kilkenny, Cork and Rosslare. Some of the other areas of low *CVWET* are close to the Malin Head, Valentia and Rosslare gauges. The unsatisfactory nature of the interpolation is more evident in the areas of high *CVWET*. With the possible exception of Claremorris, all these areas are intermediate to gauged locations. This suggests that the high values are an artefact of the interpolation process. Use of the map cannot be supported.



Map 9

***$CVWET_{WD,8.5}$* by SMD interpolation – do not use**

6.2 $CVWET_{WD,8.5}$ at gauged sites

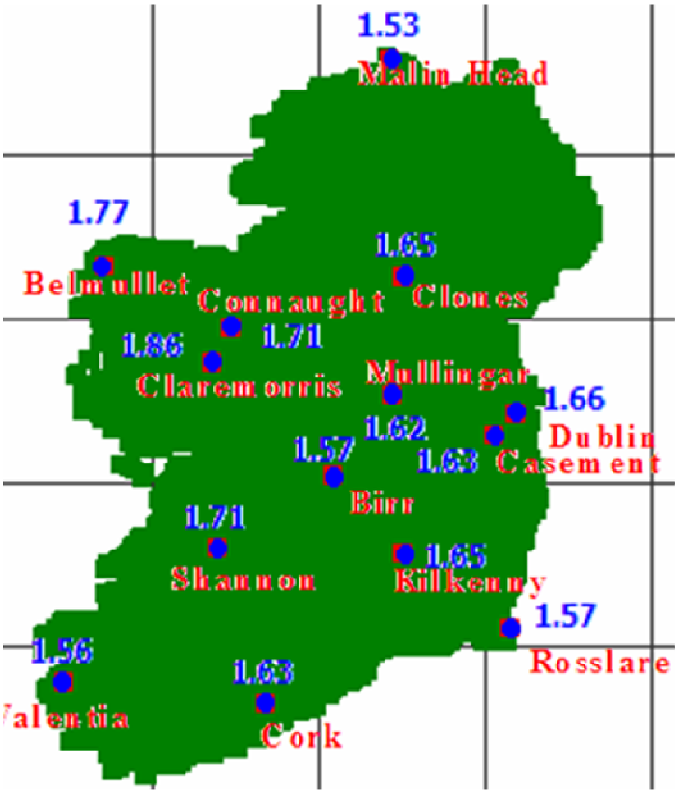
Table 7 lists values of $CVWET_{WD,8.5}$ for the grid-point closest to each gauged site. These are thought to provide good estimates of *CVWET* at those gauged sites with complete data, a usable estimate at Rosslare, and rather doubtful estimates at Connaught and Claremorris. The doubt arises because of the reliance there on interpolation from other sites, which has been shown in Section 6.1 to be suspect for *CVWET*.

Table 7 Inferred estimates of $CVWET_{WD,8.5}$ at gauged sites

Station name	Nearest 2-km grid point	$CVWET_{WD,8.5}$ at grid-point
Valentia	9,31	1.5564
Shannon	55,72	1.7136
Dublin	144,114	1.6640
Malin Head	107,221	1.5260
Belmullet	21,158	1.7672
Clones	111,155	1.6475
Rosslare	143,48	1.5657
Claremorris	53,129	1.8554
Mullingar	107,119	1.6229
Kilkenny	111,71	1.6504
Casement	138,107	1.6291
Cork	69,25	1.6271
Birr	90,94	1.5746
Connaught	59,140	1.7111

None of the correlations of $CVWET_{WD,8.5}$ with $PROPWET_{WD,8.5}$, Altitude or SAAR is at all significant. This suggests that the *CVWET* descriptor may be providing new information.

From Map 10, the geographical pattern is seen to be somewhat erratic. But there is a suggestion of generally higher values in the mid-west.



Map 10

Estimates of CVWET$_{WD,8.5}$ at gauged sites

6.3 Recommendation for further work

It is recommended that the index interpolation method be used to map $CVWET_{WD,8.5}$. Further development and programming is required to implement this method.

There are several complicating factors. Most of these stem from the need to make effective use of the stations with incomplete data. The suggested approach is to seek best estimates of $CVWET_{WD,8.5}$ at each gauged site in turn. The estimates shown in Table 7 may suffice for all stations except Connaught and Claremorris, although the broken record at Rosslare may merit special treatment.

Interpolation of the required *CVWET* field would then be based on a special (fifth) set of Voronoi weights: one appropriate to the network with all 14 gauges operating. [The alternative approach of evaluating *CVWET* separately for each sub-period, and averaging/integrating those values, is unattractive.]

A particular challenge will be to determine how to arrive at the special set of Voronoi weights. The system must ensure that the estimates of *CVWET* at Connaught and Claremorris (and, to a lesser extent, Rosslare) are given no more than appropriate weights in the mapping. A plausible approach may be to form the special set of weights as a weighted average of the separate sets of Voronoi weights that apply to each of the four sub-periods (see Table 4).

A further 20 hours' work would be needed to execute, test and report this refinement.

7 Conclusions

7.1 Summary of outputs

The recommended wetness descriptor is $PROPWET_{WD,8.5}$ (Map 6.WD). Values of $SMDBAR_{WD}$ (Map 5.WD) are also supplied, although it is not thought that these will add much useful information, given the very strong correlation between the two variables. In contrast, it is thought that $CVWET_{WD,8.5}$ will offer valuable new information if a way can be found to map the variable satisfactorily (see Section 6.3).

Gridded outputs from the study are presented in the *FSUwetness* MS Excel Worksheet accompanying the report. The grid is rectangular, encompassing the whole of Ireland. It comprises 38184 grid-points. The contents of the spreadsheet are summarised in Table 8. Full names are given for the FSU descriptors to reduce the chance that they are mistaken for similar (but different) FSR/FEH descriptors.

Table 8 ***Contents of* FSUwetness *spreadsheet***

Column	Variable name	Variable type	Comment
A	Easting	Integer	6-digit easting of grid-point
B	Northing	Integer	6-digit northing of grid-point
C	PROPWET_WD8.5	Real	$PROPWET_{WD,8.5}$ at grid-point
D	SMDBAR_WD	Real	$SMDBAR_{WD}$ at grid-point
E	Land	Integer	1 if not at sea, 0 otherwise
F	NI	Integer	1 if in N Ireland (& not at sea), 0 otherwise

Copies of the four sets of gridded Voronoi weights developed in the study can be supplied on request.

7.2 Quality assurance

Because all DWRconsult work is done personally, quality assurance is based on Dr Duncan Reed's reputation for producing outputs only of the highest quality and repute. As a professional scientist, chartered member of CIWEM, member of the British Hydrological Society and Fellow of the Royal Statistical Society, he is aware of the need to live up to high standards of professional conduct: personal, technical, managerial, financial and ethical.

Some specific checks made during the study are noted in relevant sections of the report.

Acknowledgements

Séamus Walsh and Liam Keegan of Met Éireann are thanked for supplying (and later updating) the SMD data, and for filling minor gaps in the series found during the study. I am immensely indebted to Séamus for providing a flag to distinguish grid-points lying on sea.

The derivation of catchment wetness descriptors for the UK Flood Estimation Handbook was undertaken by Susan Morris and Adrian Bayliss. Adrian (until 31 May 2007, CEH Wallingford) is thanked for supplying a copy of FEH Note 31, and Susan (now of Jacobs) for suggesting Voronoi interpolation.

I am grateful to JBA Consulting for contractual arrangements.

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Appendix 1 Some notes on the Hybrid Soil Moisture Deficit Model

[Amalgamated and edited extracts from Met Éireann accounts of the Hybrid SMD Model. See also: http://www.met.ie/climate/data02.asp. Please check primary sources before quoting from this account. Use of the model became operational in Met Éireann on 18th May 2006.]

Drainage is the amount of water lost from the topsoil through either percolation or overland flow and is dependent on the soil drainage capacity. In the new model (Schulte *et al.*, 2005), three soil drainage classes – well drained, moderately drained and poorly drained – are defined as follows:

> ***Well Drained***: Soil never saturates, remains at field capacity even on very wet days in winter. Minimum SMD is zero. When SMD > 0 mm, Actual Evapotranspiration (AE) is less than Potential Evapotranspiration (PE), decreasing linearly to zero when SMD is at a theoretical Maximum of 110 mm.
>
> ***Moderately Drained***: Soils may saturate on wet winter days, but return to Field Capacity on first dry day. Minimum SMD is –10 mm. When SMD > 0, AE is less than PE, decreasing linearly to zero when SMD is at a theoretical Maximum of 110 mm.
>
> ***Poorly Drained***: Soils saturate on wet winter days, water surplus is drained at very slow rates, in the order of 0.5 mm per day. Minimum SMD is –10 mm. When SMD > 10 mm, AE is less than PE, decreasing linearly to zero when SMD is at a theoretical Maximum of 110mm.

Daily SMDs and calculated PE and AE are available for the three different soil drainage classes for synoptic stations. Soil moisture deficits and surpluses are computed from the differences between rainfall, AE and drainage. Soil moisture surpluses are assumed to be removed by drainage and surface run-off over time.

Soil moisture deficit (SMD) calculation

The SMD is calculated as follows:

$$SMD_t = SMD_{t-1} - Rain + ET_a - Drain$$

where:

- SMD_t and SMD_{t-1} are the SMDs on day t and day t-1 respectively (mm),
- *Rain* is the daily precipitation (mm d^{-1}), ET_a is the daily actual evapotranspiration (mm d^{-1}),
- *Drain* the amount of water drained daily by percolation and/or overland flow (mm d^{-1}).

Potential (reference) evapotranspiration calculation

The potential evapotranspiration (PE) is calculated according to the FAO Penman-Monteith Equation (Allen *et al*., 1998) for a reference grass crop at an assumed height of 0.12 m:

$$PE = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where:

- PE is the potential evapotranspiration (mm d^{-1}),
- R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1}),
- G is the ground heat flux density (MJ m^{-2} d^{-1}),
- T is the air temperature at 2 m height (°C),
- u_2 is the wind speed at 2 m height (m s^{-1}),
- e_s and e_a are the saturation vapour pressure and the actual vapour pressure, respectively (kPa),
- Δ is the slope of the vapour pressure curve (kPa $°C^{-1}$),
- γ is the psychrometric constant (kPa $°C^{-1}$).

Actual Evapotranspiration (AE)

For each soil drainage class, a critical Soil Moisture Deficit, SMD_c, is defined. When the current SMD is less than this critical value, moisture is not limiting respiration and Actual Evapotranspiration (AE) equals Potential Evapotranspiration (PE):

i.e. when $SMD \le SMD_c$, $AE = PE$

When the current SMD is greater than this critical value, moisture available is no longer unlimiting. As a result, AE is less than PE. In this case it is assumed that AE decreases linearly to zero as the SMD approaches a theoretical maximum value, SMD_{max}.

i.e. when $SMD > SMD_c$, $AE = PE \cdot \frac{SMD_{max} - SMD_{t-1}}{SMD_{max} - SMD_c}$

The value of SMD_c for well and moderately drained soils is zero, and 10 mm for poorly drained soils. The value of SMD_{max} is 110 mm for all three soil types.

Drainage

It is assumed that drainage by means of percolation or overland flow only occurs when soil moisture exceeds field capacity (i.e. SMD < zero).

Well Drained soils: These remain at field capacity even on very wet days and are never saturated, all water in excess of field capacity is drained immediately.
Moderately Drained soils: These carry water surpluses on wet days but return to field capacity on the first subsequent dry day. This corresponds to a maximum drainage rate in excess of 10 mm d^{-1}.

Poorly Drained soils: These can carry surplus water for a number of days, water drains at the maximum rate of 0.5 mm d^{-1} when SMD is –10 mm, decreasing linearly to zero when SMD > zero.

Effective Drainage is the total drainage amount, i.e. through percolation and overland flow.

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