Historic record of pasture soil water and the influence of the North Atlantic Oscillation in south-west England

Anita Shepherd, Wellen Atuhaire, Lianhai Wu, David Hogan, Robert Dunn and Laura Cardenas

ABSTRACT

The North Wyke Farm Platform for sustainable grassland research in south-west England contains infrastructure measuring soil moisture and field runoff. Its time series of sensor data is used to validate the parsimonious SH_2O-NW model for soil water at field-scale. Thirty-four years of daily soil moisture and runoff is simulated, and used to detect long-term trends and produce a risk analysis. The model accounts for wetter periods of soil moisture and the main summer soil deficit and autumn re-wetting; limitations involve short-term, rapid changes in drying and re-wetting. The soil moisture sensor observations however do not reflect field variability. Analysis of more than one field allows an assessment of unexpected sensor anomalies. The paper recommends that soil moisture sensor confidence levels be provided, for comparison against modelled data. The simulations show a historic reduction in the occurrence of summer soil moisture deficits above a third of water capacity, while the winter precipitation and runoff simulation shows a stable long-term trend, matching the direction and magnitude of the North Atlantic Oscillation Index. A large runoff of 400 m^3/day from a 1.75 ha pasture has a 0.07% probability, having a return period of once in 4 years during the 34-year period.

Key words | farm platform, flooding risk, North Atlantic Oscillation, runoff, soil moisture

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INTRODUCTION

Soil moisture is a major component of agricultural systems. In limiting amounts, it limits transpiration, plant photosynthesis and soil nutrient cycling. A balance of moisture encourages microbial decomposition of organic matter and encourages movement of macro-invertebrates such as earthworms. This not only increases nutrient availability but also creates soil structure.

Soil water causes problems in limiting amounts and in excessive amounts. The Dartmoor region in south-west England receives the second highest precipitation in the country, and focus is often placed on problems caused by winter floods, detection of their frequency and management put in place to mitigate their effects.

The UK winter climate is affected by the North Atlantic Oscillation (NAO), being located between regions of high pressure west of Portugal (the Azores high) and low pressure centred over Iceland (the Icelandic low). The NAO leads to changes in the intensity and location of the North Atlantic jet stream (Met Office 2015). The jet stream brings moist air with the potential for stormy weather so its path of travel influences rainfall. The winter (December to March) station-based index of the NAO has been based on the difference of normalized sea level pressure between Lisbon, Portugal and Stykkishólmur/Reykjavik, Iceland since 1864 (Hurrell & NCAR Research Staff 2015).

The year 2010 tied with 2005 was the warmest year on record globally (NOAA 2011). Rising frequency of heavy

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downpours is an expected consequence of a warming climate. Some areas will see more droughts as overall rainfall decreases and other areas will experience heavy precipitation more frequently, or see rain come in rarer, more intense bursts (Huber & Gulledge 2011).

Field investigations between 2001 and 2011 identified widespread structural degradation of 38% of intensively managed agricultural soil surveyed in south-west England (Palmer & Smith 2013). Findings showed surface water runoff was enhanced, increasing the risk of flooding. The loamy stagnogley soils were one of the most frequently damaged soils. Soil moisture is a medium for studying the overall balance of changes in precipitation with changes in temperature. Runoff data, on the other hand, can allow us to analyse how frequently to expect overland flow constituting a risk.

Soil water models are often categorized in terms of their degree of complexity based on the treatment of the soil profile, in addition to the number of processes employed (Ranatunga *et al.* 2008). Relatively simple models may have a fixed number of soil layers and a tipping bucket approach to water inflows and outflows, while relatively more complex models seek to incorporate a continuous soil profile. Within the simple (or fixed soil layer) modelling category, models are divided into single layer or multiple layer approaches. The simplest types of soil water flow models act as tipping buckets. They ignore the vertical moisture gradient within the root zone (Feddes & Raats 2004), to discharge water from one layer to another when the water carrying capacity of the soil layer is exceeded. It is generally accepted that the Richards' equation (Richards 1931) is used to improve upon tipping bucket models incorporating Darcy's law for solute transport and capillary action (Feddes & Raats 2004).

Nonetheless, tipping bucket or cascading models are still in use, and have been operating worldwide for years, for example DSSAT (Decision Support System for Agrotechnology Transfer) (Hoogenboom *et al.* 2010), AWBM (The Australian Water Balance Model) (Boughton 2004) and an example seen in Walker & Zhang (2002) and others listed in Zhang *et al.* (2002).

At a field scale with sufficient observation data for calibration and validation, a tipping bucket model with minimal requirements of parameterization can be useful (Walker & Zhang 2002). Our hypothesis is that a simple model can do a satisfactory job to track the yearly and seasonal variation and trends in soil water. We also want to test if the climate, and winter runoff, is influenced by the trends of the NAO.

A soil water model (Shepherd *et al.* 2002) running on a daily timestep, parameterized for the North Wyke soils and named SH$_2$O-NW, uses the tipping bucket approach together with the Soil Conservation Service–curve number method (SCS–CN) for runoff. This is a popular method, widely used because of its simplicity. Although there is some disagreement in its physical basis, the empirical USDA-SCS curve number technique for runoff has been widely and successfully employed in agricultural modelling, such as APSIM-SoilWat (McCown *et al.* 1996), and used in other simple tipping bucket water models, such as GLEAMS (Leonard *et al.* 1987). Probert *et al.* (1997) evaluated the APSIM-SoilWat model simulation of water and nitrogen, finding the runoff to be satisfactory.

Van der Ent *et al.* (2013) suggested that selection of the best method for a process model depends on the application, the spatial extent, the assumptions made and the level of detail. Ranatunga *et al.* (2008) used a hierarchy of soil water models from simple to complex including tipping bucket models and concluded that all were useful depending on the scale and application.

The application in this study does not require deep drainage since the soil depth is 30 cm. In each field a few hectares of relatively homogenous land with the same land use, crop and management are hydrologically isolated from other fields. Furthermore, no change in management has occurred during the measuring of the soil moisture and runoff. From a modelling aspect that is a suitable site to test a simple model which does not account for changes in field management and terrain.

Time series of consistent ground-based soil moisture measurements to calibrate soil moisture models are not common; however, electrical conductivity measurements in soils are in increasing use (Adelakun & Ranjan 2013; Harris *et al.* 2015) and are becoming the state-of-the-art application in agriculture for irrigation scheduling and in hydrological observation.

It is proposed to use automated instrumentation to provide good quality, continuous observations, to allow a robust model calibration. Without any change in land use or field management, this field-scale study assesses the extent to which a relatively simple water model can be used requiring minimal parameterization. Applying the model to create long-term soil moisture and runoff datasets, the historic trends of soil moisture deficit and runoff are determined and a risk assessment is produced for the probability of runoff occurrence.

The main study of observed and simulated data is carried out on a field, using Longlands South as a case study; however, Wyke Moor is used as a secondary check of the simulation accuracy.

MATERIALS AND METHODS

Site description and data sources

The North Wyke Farm Platform (NWFP) (Orr *et al.* 2011; Griffith *et al.* 2013) is located at the North Wyke grassland site of Rothamsted Research to the north of Dartmoor National Park, the largest area of upland in south-west England. This UK experimental site (50.46.30 deg. N–3.54.54 deg. E, 150 m a.s.l.) has a 30-year mean (1986–2015) annual rainfall of 1,043.4 mm and an annual average air temperature of 10.1 °C (North Wyke weather station records).

The NWFP fields in this study are located on clay or silty clay loams of the Halstow and Hallsworth series. Hallsworth soil is shown in Figure 1, but the separate horizons above and below the clay layer look similar at the same depth for both soils. Both Halstow and Hallsworth soils have surface horizons with a finer blocky structure and dense impermeable clay subsoils with coarse prismatic soil structure. The slightly better drained Halstow soils are classed as typical non-calcareous pelosols in England and Wales (Avery 1980). In contrast, the wetter Hallsworth soils, classed as pelo-stagnogley soils, have traditionally received runoff from upslope (although in this case study of Hallsworth soil it would mean upslope within the same sloping field, as it has no higher ground above it). Seasonal saturated flow is more prolonged in Hallsworth series soil.

Figure 1 | Both Halstow and Hallsworth soil series at North Wyke have clay loam soil to 30 cm depth (soil horizons marked A) over a dense impermeable clay subsoil with coarse prismatic soil structure (soil horizons marked B). Photo shown is of a Hallsworth soil.

All fields of the NWFP are, since 2011, hydrologically sealed units, effectively making them catchments, on which the fluxes of soil water are measured. The fields drain naturally to a clay subsoil of low permeability below 30 cm depth. Runoff leaving individual fields flows into surrounding drainage ditches and is channelled to a flume. Surface flow cannot be measured separately from lateral flow, so the term runoff comprises all field water flow to the flume. The flume is fully instrumented to enable flow rates to be measured and water samples to be automatically collected and analysed. Runoff flow is measured in litres per second at 15 minute timeslots, measured at a V-notch ceramic weir with connection to a Teledyne ISCO 4230 bubbler flow meter. The flume measures in terms of level of water, and the flow meter has a lookup table of 256 equally spaced levels for conversion from level to flow rate. The accuracy for the flow level is ±6 mm for flow between the 0.03 and 1.6 m level. Fifteen minute interval data were scaled up to the daily timestep of the soil water model, and used for runoff validation.

Adcon SM1 capacitance soil moisture sensors with an accuracy of ±2% of volumetric soil moisture are located in the centre of NWFP fields at 10, 20 and 30 cm depth, and data are telemetried to a server every 15 minutes. Collated soil moisture data scaled up to the daily timestep of the soil water model were used for the calibration and validation of soil moisture simulation.

The NWFP site is 1.5 by 2 km (Figure 2). Longlands South is a long-term pasture of the NWFP, 1.75 ha (186 × 94 m, 2–3 degrees slope) and maintained with ryegrass (*Lolium perenne*). Wyke Moor consists of two fenced pastures of the farm platform, but sealed as one isolated hydrological unit of 7.02 ha (292 × 240 m, 3–6 degrees slope) with all runoff running to one flume, and with the soil moisture sensor located centrally in one of the pastures. Wyke Moor pastures were reseeded in 2013 with a mix of white clover (AberHerald) and high sugar ryegrass (AberMagic). Longlands South is not immediately surrounded by, nor accepts drainage from any upland; Wyke Moor is an upland with no surrounding higher ground, and

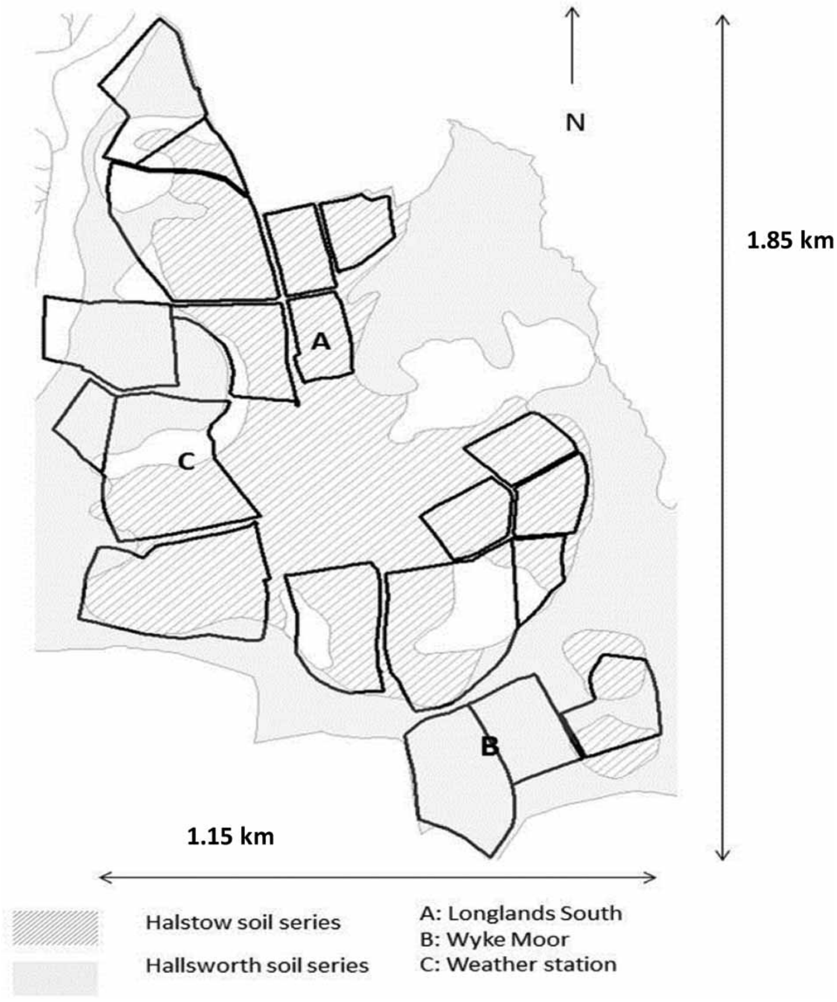

Figure 2 | Map of NWFP showing the relative location of Longlands South and Wyke Moor and the weather station.

the single source of runoff was from rainfall before these fields were hydrologically isolated. The fact that they have been isolated and runoff can be measured merely means, in respect of this study, that we are able to calibrate the simulated–observed runoff during the years observed.

Observed soil moisture and runoff were obtained for the relatively wet and dry years 2012 and 2013 from the open source data repository of the NWFP (http://www.rothamsted.ac.uk/farmplatform).

For parameterization of the model, proportions of sand, silt and clay in the Halstow soil of the North Wyke site were obtained from Harrod & Hogan (2008), who used results from soil surveys of North Wyke. From these values field capacity and available water capacity were determined using the Saxton hydraulic properties calculator (Saxton & Rawls 2009) developed from statistical correlations between soil texture, soil water potential and hydraulic conductivity (Saxton *et al.* 1986). Although Halstow is normally better drained, all fields of the NWFP vary to some extent with compaction, and in this case the available water capacity for the Hallsworth series soil was lower than the Halstow soil (Table 1).

Long-term historic climate data 1982–2015

Daily climate data were collated from historic hand-written archives from 1982 to 1999, plus values recorded by the Met Office since 2000 at the central weather station located on the NWFP (station domain DLY3208 DEVON, Met Office).

Table 1 | Key parameters for model input from field surveys

	Longlands South Wyke Moor	
	Halstow	**Hallsworth**
Soil		
Volumetric field capacity as % (or as mm/dm)	36% (36 mm/dm)	36%* (36 mm/dm)
Vol. permanent wilting point as % (or as mm/dm)	16% (16 mm/dm)	19% (19 mm/dm)
Runoff curve number at field capacity	99	99
Runoff curve no. at permanent wilting point	74	76
Crop		
**Crop growth coefficient for ryegrass, Kc		
Initial/late season (75 < day of year > 200)	0.25	0.25
Mid-season (day of year between 75 and 200)	1.05	1.05

*Field capacity is taken from common high moisture values of sensor during winter.
**Following FAO guidelines, Kc × reference ET = crop ET (Allen *et al.* 2004), where ET is evapotranspiration.

Climate parameters collated for the historic record were max temperature (deg C), min temperature (deg C), precipitation (mm), windspeed (m/s), relative humidity, sunshine hours and solar radiation (KJ/m^2/day). Climate data were infilled using median values, and outliers were checked.

The climate parameter datasets all range from 01/01/1982 to 31/12/2015. From 01/01/1982 to 31/12/2011 sunshine hours were converted to solar radiation using recommended FAO methods (Allen *et al.* 2004) involving the Angstrom formula relating solar radiation to extra-terrestrial radiation and relative sunshine duration. The 2001–2011 climate data has overlap where both sunshine hours and solar radiation were recorded, the conversion of sunshine hours to radiation was validated against observed radiation.

Climate parameters were tested for trends using a Mann–Kendall analysis (Gilbert 1987).

The station-based NAO Index (Hurrell & NCAR Research Staff 2015) termed winter (December to March) was obtained to compare against winter precipitation, temperature and runoff. The NAO Index termed seasonal (June to August) was additionally obtained for soil moisture.

The SH$_2$O-NW water model

SH$_2$O-NW (Shepherd *et al.* 2002) has been used because it requires a relatively small number of soil parameters. It has been parameterized for North Wyke soil types, validated and proven effective when used in previous unpublished field studies, operates on a daily timestep and determines soil moisture, and also drainage and runoff from soil.

Soil moisture in the root zone is determined by a water balance:

- The model assumes that rainfall is the only source of water input to the soil.
- The effective rainfall is calculated by subtracting surface runoff from rainfall, surface runoff is calculated according to SCS runoff curves (USDA-SCS 1985) created using the observed precipitation and observed field runoff.
- Water loss from evapotranspiration (ET) is subtracted from the effective rainfall calculated using a modified Penman equation multiplied by a crop coefficient, Kc (Allen *et al.* 2004) whereby the extraction rate of water depends on a combination of net radiation at the crop surface, mean daily air temperature, humidity and wind speed. The remaining effective rainfall then infiltrates the soil. Kc is dynamic (Table 1), changing with the day number of the year to account for seasonal stages of grass production.
- A tipping bucket mechanism is employed, i.e., if the effective rainfall is higher than potential ET it replenishes the soil moisture. Soil moisture above field capacity becomes drainage and is lost from the system, and the soil remains at full water holding capacity.

- If the effective rainfall is lower than potential ET, there is soil water deficit which may or may not be met by extracting some of the soil water in the root zone. If the crop demand cannot be met (at the empirical threshold soil water that can be depleted from the root zone before moisture stress), the relative reduction in crop ET (employed in the model through a water stress coefficient) is related to the ratio of the available water and the water holding capacity.

The soil moisture is output in volumetric units. Simulated vertical drainage and surface runoff output in units of mm water per day are added and termed runoff, because the NWFP soil has an impermeable layer at 30 cm and drainage around the edge of the field so all surface runoff plus vertical drainage to 30 cm is measured together.

Daily weather input consists of solar radiation, maximum and minimum temperature, precipitation, windspeed and humidity. Soil parameters required (Table 1) consisted of field capacity and permanent wilting point, runoff curve number (USDA-SCS 1985) and crop coefficient for rye grass (Allen *et al.* 2004) for determination of potential crop ET from Penman ET.

SH_2O-NW uses a single reservoir over the site's 30 cm soil depth. A depth weighted average for field capacity and permanent wilting point was taken over soil horizons to 30 cm depth.

Simulation testing

A sensitivity analysis was conducted with the model on rainfall, curve number and runoff, determining the change in runoff with the change in precipitation, and the results calibrated against a separate dataset of rainfall and runoff.

A model validation was carried out for soil moisture and runoff. Mean observed soil moisture from 10, 20 and 30 cm sensors and runoff from drainage flume measurement each produced a daily dataset 2012–2013 with which to validate the simulation.

The set of statistical methods suggested by Smith *et al.* (1997) and Smith & Smith (2007) were used to evaluate and compare simulated and observed soil moisture and runoff. A set of seven statistical parameters is included: correlation coefficient (R), root mean square error (RMSE), modelling efficiency (EF), the coefficient of determination (CD), relative error (RE), mean deviation (MD) and maximum error (ME). The RMSE, RE and ME give an indication of error. The ME and CD indicate if the model describes the observed trend better than the mean of the observations. The mean difference is tested (Student's *t*, two-tailed, 5% confidence limit (CL)) to see whether there is any significant bias in the simulated values compared to the observed values.

Frequency analysis

Since the NWFP was created in 2011, its high quality continuously measured data are excellent for validation of a model, but the time period covered will, for a long time, be too short to use the data directly in a daily frequency analysis. Long-term records, or simulations from applying long-term climate records, are essential for risk assessment.

A risk assessment provides a likelihood of occurrence to the modelled impacts, and puts 34 years of soil moisture and runoff data into context. The two issues are that there is an increasing risk of a soil moisture deficit (most commonly occurring on a short-term basis during summer) and conversely that there is an increasing risk of runoff during winter.

A cumulative frequency analysis is used (Oosterbaan 1994) to determine the risk of exceedance of the data thresholds:

1. Twenty-two data threshold intervals between 30 and 690 m^3 runoff per day chosen for the amount of volumetric soil moisture deficit below field capacity, and for daily runoff. As the frequency of events is 1 or 0 near the upper limit of runoff, the intervals are wider.
2. The frequency of occurrence is determined for values in each interval during the full 34-year range of values and the relative cumulative frequency of increasing severity calculated as a percentage. The number (mi) of data (x) are counted in each interval. The relative cumulative frequency is mi divided by the number of data (n) to obtain the frequency (F) of data (x) in the ith interval, expressed as a percentage, i.e., $Fi = mi/n \times 100$.
3. For each interval, the sum of the frequencies is calculated for all values below the interval value. This cumulative percentage frequency is also referred to as the frequency of non-exceedance.

4. The frequency of exceedance, or occurrence is 100 minus the frequency of non-exceedance.
5. The return period (T) is an estimate of recurrence of a value of a specific interval and calculated in terms of the number of new data that have to be collected, on average, to find a value again of that severity. The return period is calculated as T = 1/frequency of exceedance.

RESULTS AND DISCUSSION

Long-term historic climate

Meteorological parameters measured during a 34-year daily climate record (1982–2015) for North Wyke were collated. Simulated solar radiation compared against observed radiation produced a correlation coefficient of 0.97, a RMSE of 16.7%, a MF of 0.93 and a CD of 1.18. There is some bias with the simulated radiation slightly under-predicting at higher values, and this was confirmed by Student's *t*-test of mean difference higher than the 95% CL. In general the simulated time series of solar radiation compared satisfactorily, and thus was added to the daily climate record.

To detect for a progressive change in the climate record, the full dataset of 34 years was divided up into three 11-year periods (1982–1992, 1993–2003 and 2004–2015) and compared. The record was also divided into two halves prior to 1998, and post-1998. The daily records of precipitation, maximum and minimum temperature do not show any extremes occurring predominantly for the latter third of the record. There are however indirect indications of warmer minimum monthly and yearly temperatures by their lack of extreme low temperatures. Eight out of the ten lowest monthly minimum temperatures occur before 1998 (first half of the record). Nine out of the ten lowest yearly minimum temperatures occur before 1998. Temperature frequency distributions show a shift to warmer temperatures over the three periods (Figure 3(a) and 3(b)).

Seven of the ten highest rainfall years occur after 1998.

A Mann–Kendall test for trend detection was performed on annual and seasonal precipitation totals and temperature averages. Annually, the Mann–Kendall test gave over 99% confidence of an increase of average minimum temperature from 1982 to 2015, no trend was detected for average maximum temperature or precipitation totals.

Seasonally, the Mann–Kendall test gave over 95% confidence of an increase of autumn minimum temperature and autumn maximum temperature over the 34-year period. There is a likely 94% confidence of increasing minimum temperature in summer. There were no trends detected in winter or spring temperatures or with precipitation.

In terms of agricultural management, the progressive trends described above could mean a change in degree–days, and subtle modification to management timings and applications. In terms of the biological system, an increasing minimum temperature should affect plant growth, soil microbial activity, nutrient cycling and gaseous soil emissions.

The UK winter climate is influenced by the NAO. The positive NAO phase is a strong difference between the high and low pressure regions creating a strong jet stream. Westerly winds bringing warm moist air, and stronger and more frequent storms travel across the Atlantic producing stormy and wet winter conditions in northern Europe. The negative NAO phase is a weak difference between the high and low pressure regions. Easterly and north-easterly winds dominate, and bring cold air, while a weak meandering trajectory of the jet stream leads to weaker and less frequent storms. Europe and the eastern US are more likely to experience cold, calm and dry winters. Positive and negative phases and magnitude are described by production of a Met station-based NAO Index (Hurrell & NCAR Research Staff 2015). North Wyke total winter precipitation (for months DJFM) and mean winter maximum and minimum temperatures (for months DJFM) follow the pattern of the NAO Index (Figure 4(a) and 4(b), respectively). The winter NAO Index appears on the plot to be out of synch by a year. In fact, the winter NAO predicts the trend and magnitude of change of the following winter precipitation reasonably well (correlation coefficient of 0.33, $P < 0.05$), and even better for minimum temperature (correlation coefficient of 0.74, $P < 0.05$) and maximum temperature (correlation coefficient of 0.75, $P < 0.05$). This is supported by the findings of Monteith *et al.* (2016) who found a similar correlation coefficients, r^2 of 0.45 (Pearson correlation of 0.67) for precipitation using data from a different weather station about 2 km away from the one used in this study. Rainfall frequency distributions of the three periods show no difference.

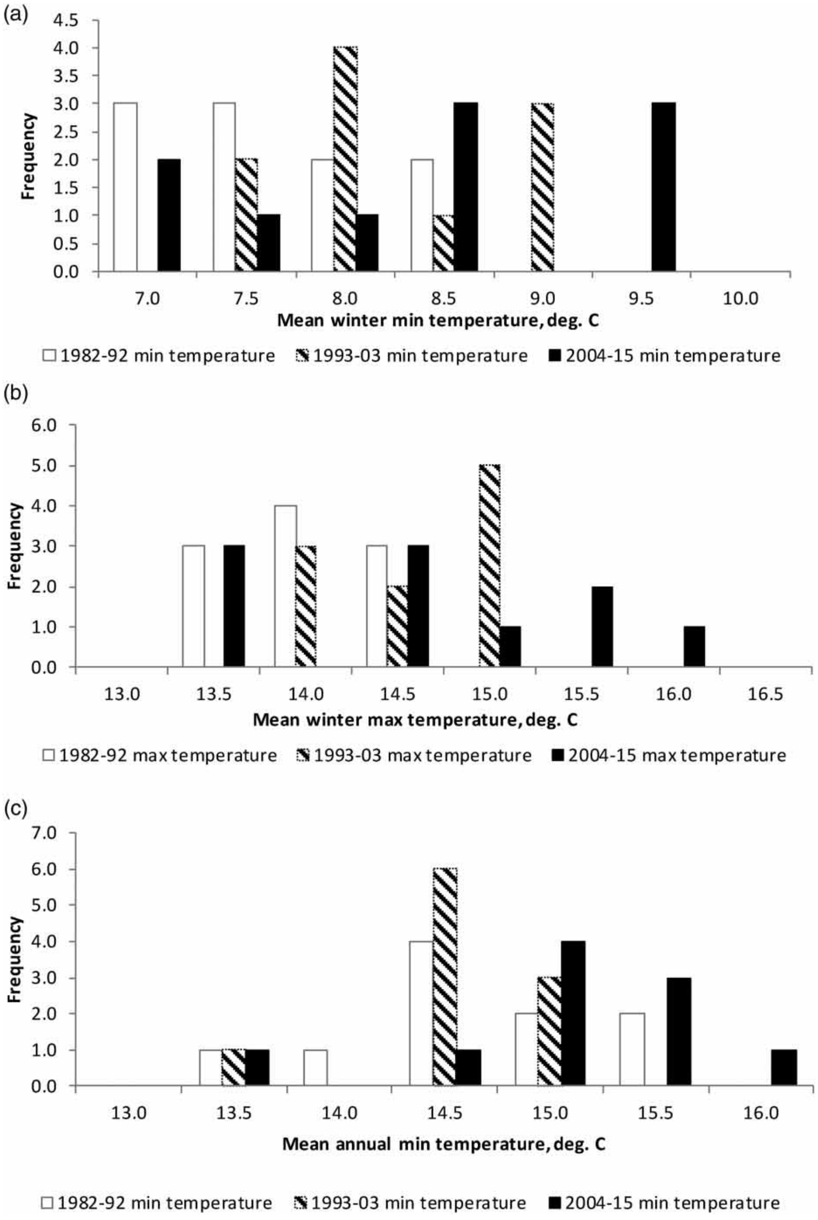

Figure 3 | Frequency distribution of (a) mean autumn minimum and (b) mean autumn maximum temperature (degrees C) and (c) mean annual minimum temperature for 1982–1992, 1993–2003 and 2004–2015 periods showing shift in temperature distribution over these periods towards higher temperatures.

North Wyke is located in the south-west of the UK with strong prevailing westerly winds, well placed to receive Atlantic winter storms, and the above figures show the NAO to be a strong influence on its climate.

Sensitivity and calibration of runoff curve

Before the validation for the whole model, the sensitivity of the runoff module was assessed using a separate earlier short-term dataset of Longlands South for 1960. Longlands South curve number adjusts with soil moisture between 74 (at permanent wilting point) and 99 (at field capacity) representative for heavy clay loam on grassland. Figure 5(a) depicts the sensitivity of the runoff curve number module, showing the large variation in the amount of precipitation necessary to create runoff at permanent wilting point (curve number 74) and at field capacity (curve number 99). At permanent wilting point it would take a

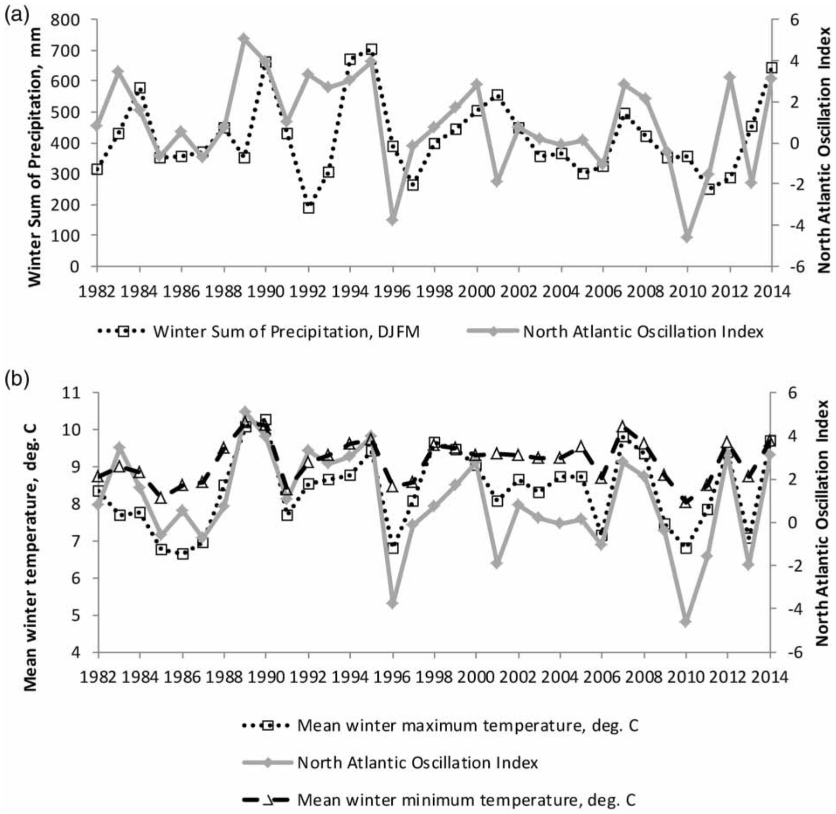

Figure 4 | (a) The winter sum of precipitation (in mm for months DJFM) and (b) the winter mean minimum and maximum temperature (degrees C for months DJFM) for North Wyke compared against the NAO Index.

precipitation of over 20 mm to start runoff. For a soil at field capacity, using the runoff curve number at 99, almost all the precipitation should run off. Figure 5(b) shows the calibration of precipitation and runoff with the curve number at 99, with a high correlation of 0.99 and mean squared prediction error of 1.4%. The sensitivity and calibration of the runoff module was tested to satisfy that it is working correctly for inclusion in the model and gives no indication otherwise.

Model validation for soil moisture

At North Wyke, 2012 was a relatively wet year (1,129 mm precipitation) and 2013 was a relatively dry year (969 mm precipitation). A dry year with more variation in soil moisture involving evaporation and recharge is more of a rigorous test of a soil moisture simulation than a wet year. Observed 2012 and 2013 soil moisture datasets from the farm platform field sensors in Longlands South and Wyke Moor were used to validate the soil water model.

Simulations from both fields and from both years gave satisfactory results (Table 2) confirming that simulations follow the same pattern as measured values and describe the trend better than the mean of the observations.

The RMSEs for simulations from both fields from 2012 fall close to a 95% CI and within a 90% CI for 2013 data. Deviations were associated with rapid short-term drying and re-wetting periods. At this point other processes might have come into play that the simulation does not contain, such as capillary action and upwards flow of water. An improvement would probably be to include the Richards equation for non-uniform water flow and re-distribution between soil layers (as in Mirus 2015). A more complex, agricultural system model commonly applied to the NWFP, such as SPACSYS (Wu *et al.* 2007, 2015), includes the Richards equation for water potential to simulate water and fluxes. Fine analysis of fluxes is more important at a

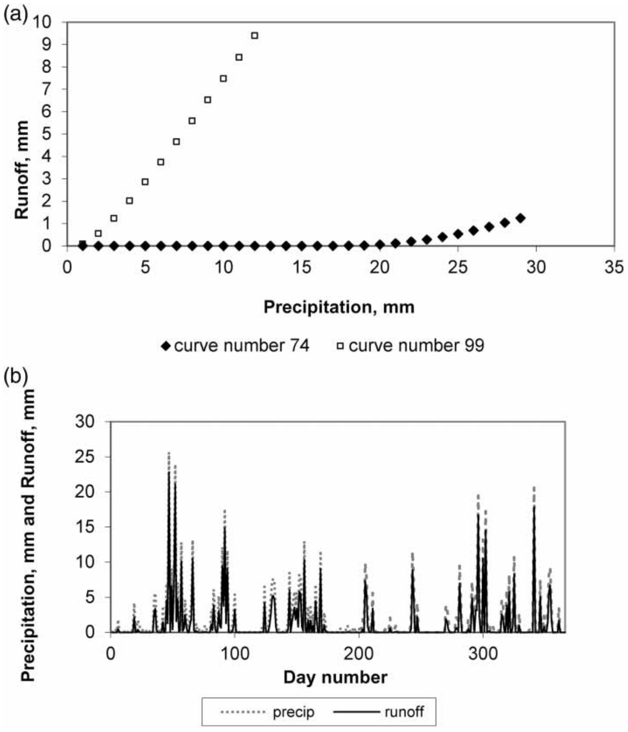

Figure 5 | (a) Runoff against increasing precipitation at permanent wilting point for Halstow series soil, curve no. = 74; at field capacity, curve no. = 99. (b) Precipitation and runoff (in mm) for Halstow series soil at field capacity (using a separate climate dataset for model calibration).

small scale, since a particular focus of SPACSYS is the root architecture where more detail is required than the historic trend of climate and associated soil water.

The SH_2O-NW model uses average soil water retention parameters based on one single horizon because the soil that the water percolates through is not deep to the impermeable layer, but this could be modified. Mirus (2015) found that identifying a dominant hydropedological unit proved an acceptable simplification of subsurface layering, and that steeper soil water retention curves mitigated the over-predicted runoff that pedo-transfer functions can produce.

Some observed data were above the calculated field capacity, this could be an error in estimating soil properties, and in the model's assumptions of a single soil layer, but it can also be that the soil properties vary around the field and that the site relies on a single sensor to give a representative value of a field. Figure 6 gives an indication of the variability of soil moisture measurements taken manually from different locations on the same day within Longlands South. Six randomly located soil core samples to 10 cm were extracted on four separate dates and moisture calculated by oven drying soil and weighing. Unfortunately, the soil moisture automated sensor was out of operation, so there are no sensor data for comparison. Spatial soil moisture variability at field scale has been commented on in other studies (for example, Qu *et al.* (2014) investigating the relationship of soil water content to soil hydraulic properties by inverse modelling). The SH_2O-NW model simulates a water balance using soil and climate algorithms with average field parameters, yet sometimes the field location may behave unexpectedly. Considering the portion of the Longlands South graph in Figure 7(a) (labelled A) and the Wyke Moor graph in Figure 7(b) (labelled B), the

Table 2 | Statistical analysis of model performance for observed and simulated soil moisture

	Longlands South		**Wyke Moor**		**DayCent model Longland South**	
Year	**2012**	**2013**	**2012**	**2013**	**2012**	**2013**
R	1.00	0.97	0.98	0.96	0.97	0.94
RMSE	3.00%	9.50%	5.33%	9.59%	7.53%	13.0%
EF	0.99	0.94	0.96	0.93	0.92	0.88
CD	0.97	1.02	1.00	0.94	0.92	0.95
RE	−1.34	−2.54	−1.46	0.05	2.54	−2.16
MD	−0.004	−0.007	−0.005	0.0001	0.008	−0.006
ME	0.04	0.09	0.07	0.10	0.11	0.14
N	365	300	365	259	365	300

R = correlation coefficient; RMSE = root mean square error; EF = modelling efficiency; CD = coefficient of determination; RE = relative error; MD = mean deviation; ME = maximum error.

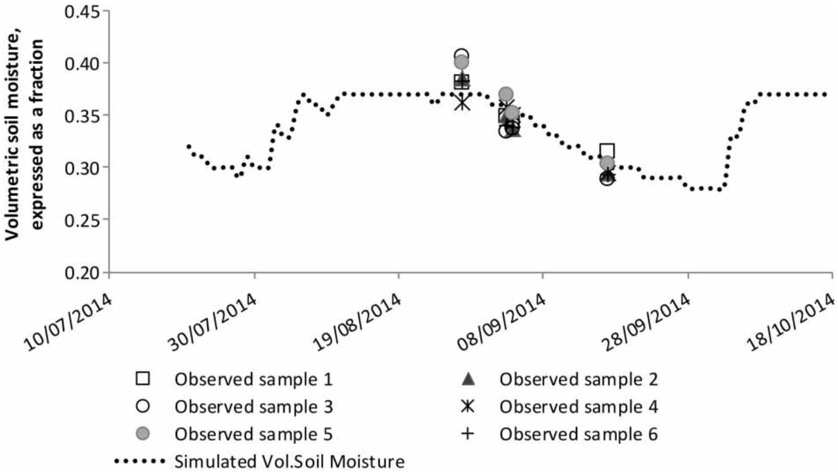

Figure 6 | Comparison of manual volumetric soil moisture measurements taken on the same dates at random locations within Longlands South indicating the degree of variation which can occur within the field.

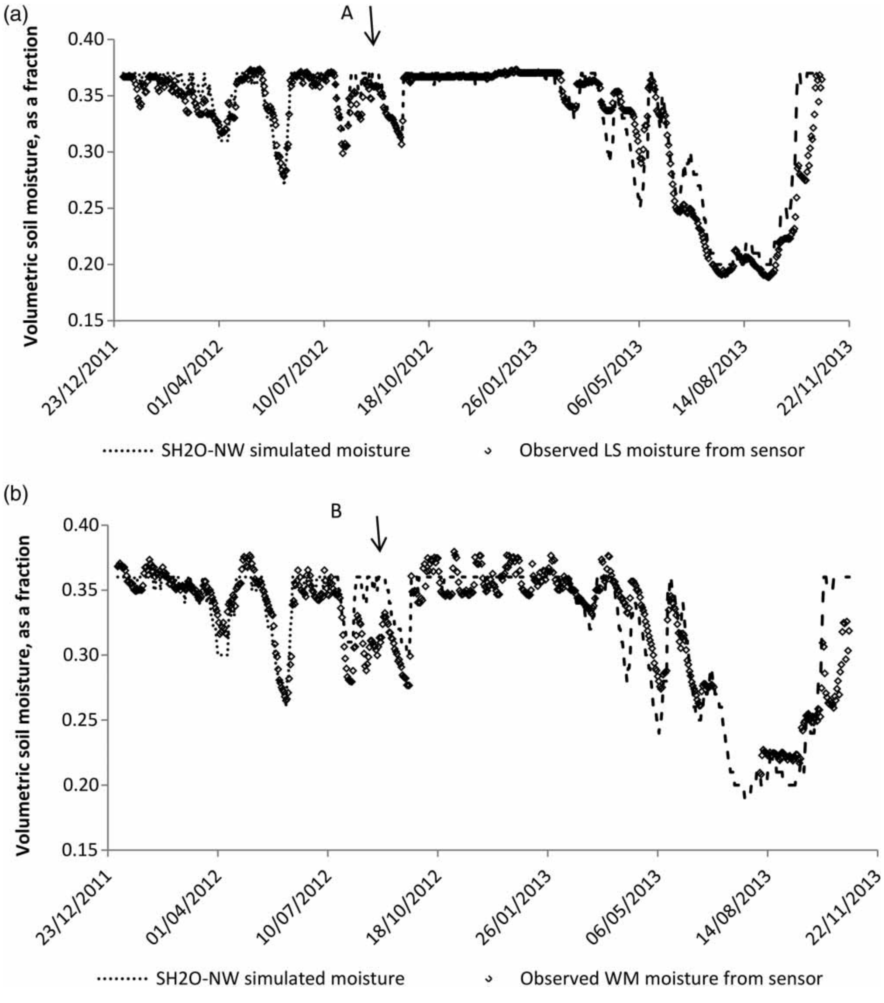

Figure 7 | SH_2O-NW simulated and observed volumetric soil moisture (expressed as a fraction), also noting the portion of the graph (A and B) where observed sensor response varies between fields to multiple days of rainfall for (a) Longlands South and (b) Wyke Moor.

SH_2O-NW soil moisture simulation for both fields has a plateau at field capacity. This is due to there being a total of 59 mm rainfall between 4th and 24th August with 15 out of 21 days having a rainfall event. Longlands South observed data (A) reflects this with an increase back to field capacity, but Wyke Moor observations (B) increase then decrease in the middle of the period.

Depending on soil moisture data from one centrally located sensor is over-simplifying the system and making assumptions because the soil moisture data will vary across the field, and neither the process model, nor the moisture sensors, account for spatial variability. A denser network of point location sensors may be desirable, but in reality on a farm, one sensor per field requiring protection from trampling by cattle is a practical option. Soil moisture and runoff data for this project are taken from the sensor data downloaded from the data portal of the NWFP (https://nwfp.rothamsted.ac.uk/), not from fieldwork. Therefore it would be advisable to have a statistical measure of confidence for the sensor data, but in this study parameters were not yet available to calculate this.

Finally, to put the relative performance of the soil moisture simulation into perspective, the SH_2O-NW model was compared with the globally known DayCent (Parton *et al.* 1998) model for soil moisture simulation against sensor values (Table 2). DayCent employs the Root Zone Water Quality Model (RZWQM, Ahuja *et al.* 1999; Del Grosso *et al.* 2011) which is a more sophisticated soil water simulation than SH_2O-NW. RZWQM is a known model alone or incorporated into DayCent, which uses the Green–Ampt (Green & Ampt 1911) equation for infiltration and runoff and water flux re-distribution through multiple soil layers. Table 2 shows a favourable comparison of the SH_2O-NW model and DayCent for 2012 and 2013. Holistic agricultural system models such as DayCent are complex models with feedbacks that are not expected to achieve the accuracy on every parameter, and their focus is on nutrient cycling, there is a slightly larger RMSE, but other statistical indicators of performance are similar.

Model validation for runoff

To compare simulated against observed runoff for Longlands South and Wyke Moor, values were standardized to runoff in m^3/ha/day for 2012. Most statistical analyses showed increased error for the Wyke Moor runoff simulation than for Longlands South. Results are shown in Table 3 for the simulated–observed runoff comparisons for 2012, since runoff data were scarce in the drier year of 2013.

Runoff is more variable and less easy to simulate than moisture. The simulation under-predicts, which may be due to under-prediction of the runoff curve in the model, or the assumption of a tipping bucket mechanism for a field layer, i.e., when a soil layer is at full water carrying capacity, it allows excess water to drain, in these cases laterally to the drainage channels. The model has limitations in that it assumes a homogeneous vertical soil layer, which covers up heterogeneity of the soil. There is also an unknown element to how leak-proof the field system is, especially after a prolonged dry period on clays in which cracks have developed.

Rainfall-observed runoff (Figure 8) shows a non-uniform relationship below 6 mm of rainfall which makes the linear nature of the SH_2O-NW model's processes more applicable to runoff from precipitation over 6 mm.

The runoff output from a DayCent simulation was also compared against observed data (Table 3). The high correlation coefficient but also relatively high errors reflect the high association between simulation and observation but

Table 3 | Statistical analysis of model performance for observed and simulated runoff

Year	Longlands South 2012	Wyke Moor 2012	DayCent model Longlands South 2012
Field area (ha)	1.75	7.02	1.75
R	0.58	0.57	0.99
RMSE	175%	163%	176%
EF	0.31	0.31	0.52
CD	1.85	2.57	0.37
RE	6.59	27.8	−70.6
MD	2.94	64.5	−144
ME	433	1976	1138
N	92	92	92

R = correlation coefficient; RMSE = root mean square error; EF = modelling efficiency; CD = coefficient of determination; RE = relative error; MD = mean deviation; ME = maximum error.

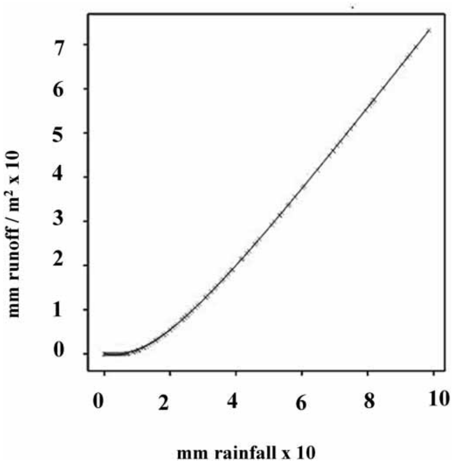

Figure 8 | Rainfall plotted against Longlands South runoff showing non-linear relationship below 6 mm.

also that the simulation under-predicted. The performance of this more sophisticated holistic system model compared favourably with our SH$_2$O-NW model, which requires fewer input parameters, supporting the hypothesis that you can use a simple model to obtain a satisfactory soil water runoff at field-scale.

Long-term datasets of soil moisture and runoff, with runoff risk analysis

The SH$_2$O-NW simulation for Longlands South and Wyke Moor was backdated to the 34-year historic time series of climate, resulting in a 34-year record for soil moisture (Figure 9(a) and 9(b), Longlands South and Wyke Moor, respectively) and field runoff (Figure 9(c) and 9(d), Longlands South and Wyke Moor, respectively). (Figures produced using the HydroTSM package in R (Zambrano-Bigiarini 2014; R Core Team 2014).) Assuming management is stable for the long-term pasture, the historic patterns can be viewed as the agri-system's response to the climate. When viewed over the whole historic period, the temporal patterns shown by illustrations in Figure 9 display longer consecutive years of temporary summer moisture deficits and correspondingly, consecutive years with relatively long duration of little or no runoff during the 1980s and 1990s, and mixed conditions over consecutive years after 2000. 2015 has the longest extended period for low field runoff with a relatively dry year of 933 mm of precipitation.

Relationships have been found using an index for summer NAO (SNAO) with climate (Follard *et al.* 2009). We tested the relationship between a SNAO Index for June, July and August and corresponding average soil moisture but found no significant relationship. We have found the NAO Index to be particularly related to winter storms for our site data. At this time of year (December to March for the winter index) the soil moisture for this high precipitation site is constantly at field capacity, and so there would be no relationship.

Although Hallsworth series soil is a less drained soil than the Halstow series, the Hallsworth soil in Wyke Moor displays a slightly drier soil moisture time series than the Halstow soil in Longlands South. When 2012 and 2013 simulated and observed runoff was compared for Table 3, runoff per hectare was determined and compared for the two fields (not shown) and gave very similar runoff amounts, except that the Hallsworth soil had continuous runoff during the wet year of 2012 with no reduction as expected, but ceased runoff during the dry summer of 2013 earlier than the Halstow soil. This was the opposite of expectations but supported by the observed flow. This could be due to the sloped character and hence increased drainage of Wyke Moor compared to the more level terrain of Longlands South. The heaviest runoff is shown occurring in December 1999, and the most recent in February 2014. The full amount of runoff is illustrated from each field to show the difference that can result from a change in field area and a slower draining soil type for Wyke Moor at 7.02 ha compared to Longlands South at 1.75 ha. Results show a similar pattern in both separately calibrated field simulations, but they are located not far from one another and share the same climate data. Winter runoff for Longlands South gives reasonable agreement with the NAO Index, with a correlation coefficient of 0.52, significant at 95% confidence level. Figure 10 shows the NAO Index for December–March 1982–1983 to 2014–2015 plotted against winter runoff (December to March totals to match the NAO Index). Although winter 2016 was stormy (Met Office 2016), this paper was written before March and so unable to compare against the high NAO of 3.56.

In the south-west of England, risk assessment in terms of field runoff can be linked to flooding. A risk assessment for

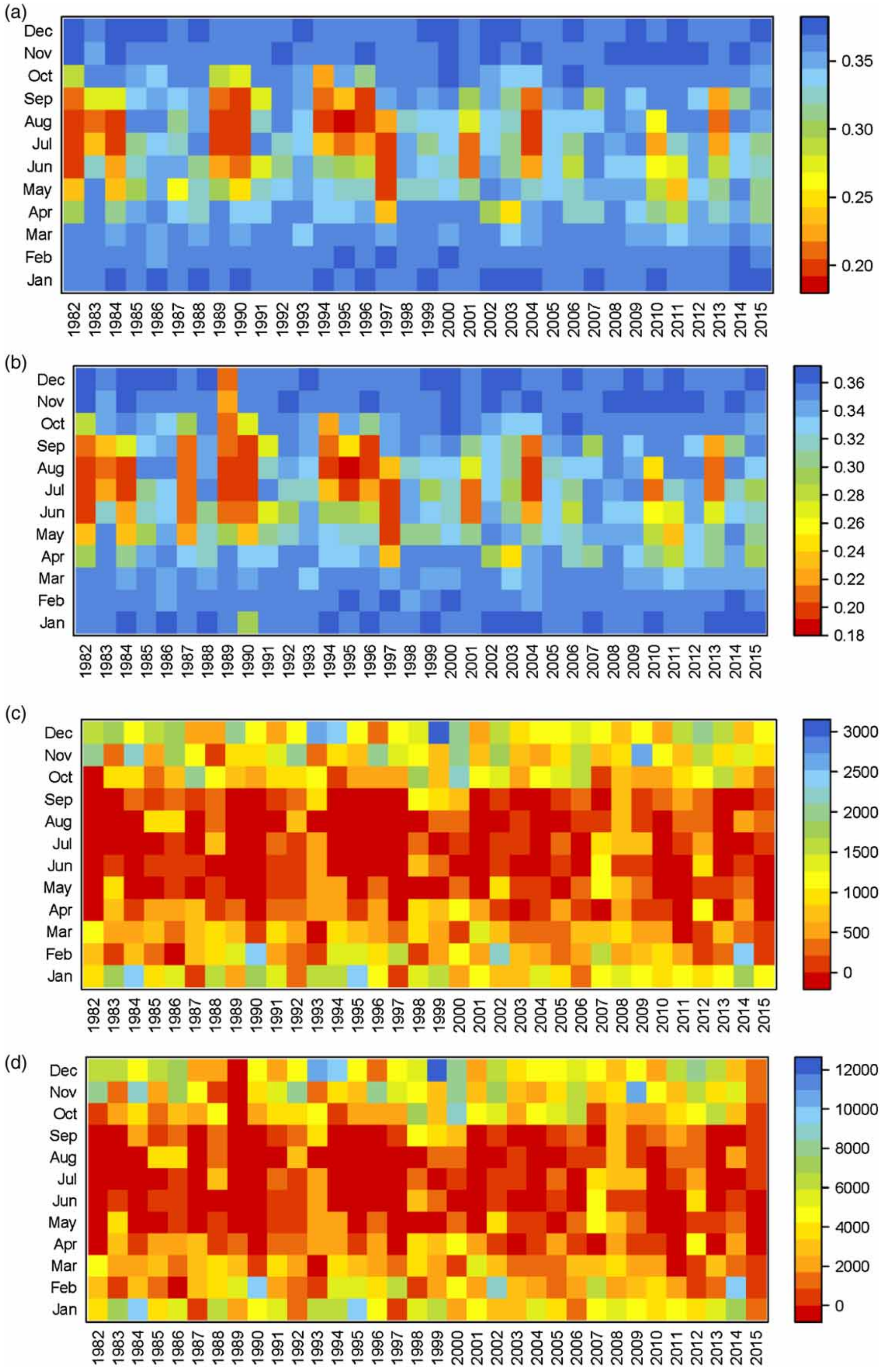

Figure 9 | Simulated volume moisture fraction 1982–2015 for (a) Longlands South and (b) Wyke Moor. Simulated runoff 1982–2015, m^3/day for (c) Longlands South and (d) Wyke Moor.

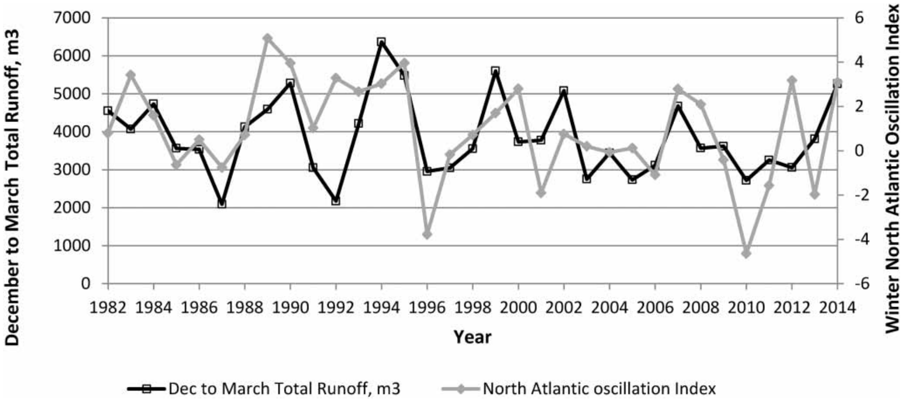

Figure 10 | The NAO Index for 1982–1983 to 2014–2015 plotted against winter runoff (December to March totals to match the NAO Index).

field runoff was undertaken focusing on Longlands South data to determine the likelihood of occurrence with increasing severity.

A frequency analysis adds probability to the simulated runoff (Figure 11(a)). From this the return period (Figure 11(b)) for different thresholds has been calculated based on the data of Longlands South from 1982 to 2015. The runoff frequency is based on data which include periods of intense short-term flooding, so the higher range refers to reasonably severe runoff thresholds with long return

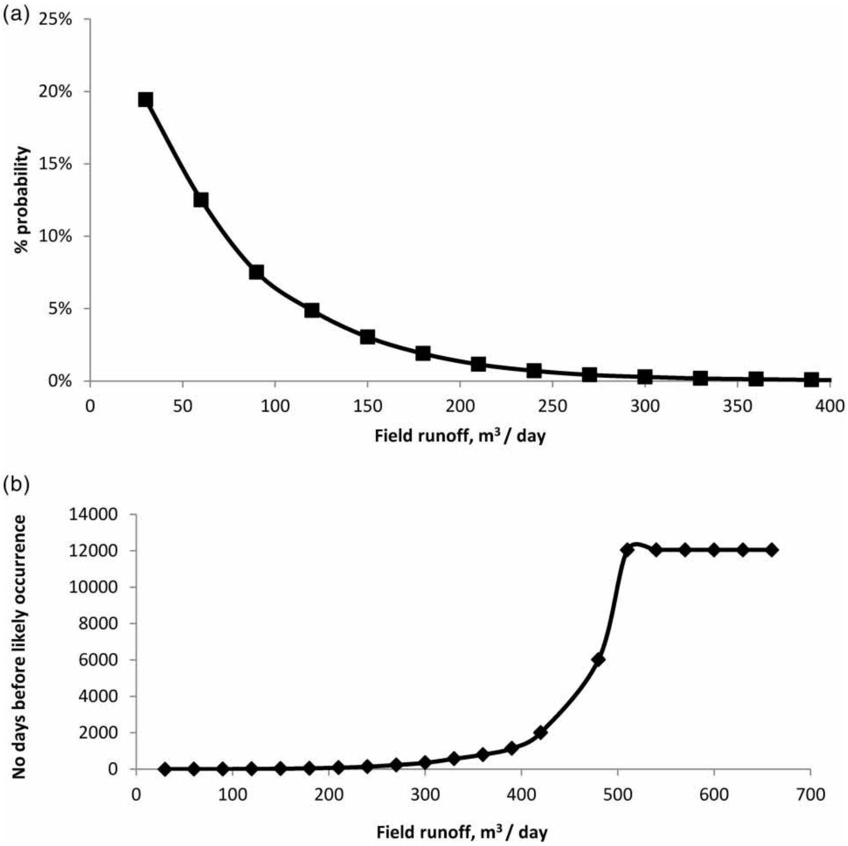

Figure 11 | Risk analysis using data from Longlands South: (a) probability of field runoff exceedance and (b) return period of runoff threshold exceedance.

periods. A very heavy runoff of 400 m^3/day from a 1.75 ha field has a 0.07% probability, which gives a return period of 1 in 1,339 days or just less than 4 years on average during the 34-year period. An extreme runoff of 600 m^3/day has a probability of occurrence 1 in 12,000 days or 32 years.

A Mann–Kendall trend analysis on the model output from these fields determined with 95% confidence that between 1982 and 2015 the number of days per year with soil moisture below a third of its water carrying capacity (encompassing a short-term summer deficit) had decreased, however the runoff from these soils had a stable trend, corresponding to the stable trend in precipitation.

CONCLUSION

The aim of this research was to determine the extent to which a simple model, requiring little in the way of input, could simulate our field moisture and field drainage. The model itself, SH_2O-NW, has been previously published, but was applied to a new site. The goal was not to apply the most eloquent model, but rather to see if we could obtain a historical record of the water balance of our fields in a relatively simple way to look for patterns and trends resulting from the historical climate record we had collated. The aim was also to determine that the climate and winter runoff were associated with the NAO.

Our statistics show there are some discrepancies in model results, and we accept there are more sophisticated models which may reduce those, however this model did perform satisfactorily compared against a more sophisticated model, and there were limitations in the observed data.

On both the naturally better drained Halstow soils of Longlands South, and Wyke Moor where wetter Hallsworth soil are found, the SH_2O-NW model can account for wetter periods of soil moisture and for the main summer soil moisture deficit and autumn re-wetting but has limitations involving short-term, rapid extreme changes in drying and re-wetting.

Observed data had limitations by dependence on one field sensor observation of soil moisture per field which gives non-replicated data. Sensors have been shown to give unexpected anomalies, and cannot reflect the variability in moisture around the field that has been obtained by soil sampling measurements. Using more than one field in a study allows an assessment of whether anomalies are due to sensor or model. It is recommended that CL are provided for the soil moisture sensor data, to compare modelled data against.

The total field drainage was measured at the flume, so it does not encounter the problems of spatial variability seen with sensing soil moisture, thus deviation in simulation compared to observed runoff would most likely be due to the model. Runoff validation is satisfactory above 6 mm rainfall, but below that there is a non-uniform relationship, so overall the model is more appropriate to wetter conditions or years. On Wyke Moor, while model performance for soil moisture slightly improved compared to Longlands South, model performance for runoff slightly reduced.

In comparing our model against DayCent for its soil moisture simulation, we have used a globally known model many agricultural scientists will be familiar with employing a more sophisticated water balance involving multiple soil layers, sub-daily timesteps and using a version of Darcian unsaturated water flow. This model compared favourably with our model. On the whole, the results support the hypothesis that you can use a simple model to obtain a satisfactory water balance at field-scale to assess annual and seasonal patterns and trends, and also that the climate and winter runoff are influenced by the NAO. A useful addition would be to implement a Darcian unsaturated water flow by either the Richards equation or the Green–Ampt equation to account for upward water flow.

The model was applied to the 34-year historic time series of climate to produce a simulated soil moisture and field runoff history of Longlands South pasture. The historic climate influencing the soils of North Wyke and the soil runoff has been shown to track the NAO. The pattern for the whole 34-year period shows longer consecutive years of temporary summer deficits and no or little summer runoff during the 1980s and 1990s, and mixed wetter and drier summers over consecutive years since. This is supported by the literature (Marsh 2004); there are reports that southern England had increased soil moisture deficits from 1988 to 1992 and from 1995 to 1997, but that above average rainfall since mid-1997 has counterbalanced any higher evaporative demands.

A Mann–Kendall trend analysis shows that the occurrence in the number of soil deficits per year below a third of water carrying capacity has decreased over 34 years but shows a stable trend for runoff consistent with the stable trend in precipitation. There are indications of a progressive historical rise in minimum temperature.

The model was used in a risk assessment to assess the likelihood of varying degrees of soil water runoff. A very heavy runoff which we would expect to cause localized flooding of 400 m^3/day from one field has a 0.07% probability, which makes its return period 1 in 1,339 days or just less than 4 years during the 34-year period.

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