Water Air Soil Pollut (2014) 225:2044
DOI 10.1007/s11270-014-2044-4

Effects of Overland Flow on Critical Soil Test Phosphorus Thresholds in Tillage Soils

John T. Regan · Owen Fenton · Karen Daly · Jim Grant · David P. Wall · Mark G. Healy

Received: 20 February 2014 / Accepted: 18 June 2014

Abstract In Regan et al. (*Journal of Environmental Quality*, *39*, 18–192 2010), a runoff dissolved phosphorus risk indicator (RDPRI), based on rainfall alone, was developed for five Irish tillage soils. Results showed that tilled soils, subjected to simulated rainfall only (3 cm hr^{-1} inclined at 10° slopes), may produce surface runoff phosphorus (P) concentrations in excess of 0.03 mg L^{-1} (the value above which eutrophication of rivers is likely to occur) if their Morgan's phosphorus (P_m), water extractable phosphorus (WEP) and Mehlich-3 phosphorus (M3-P) concentrations exceed 9.5 mg L^{-1}, 4.4 mg kg^{-1} and 67.2 mg kg^{-1}, respectively. The present study developed a modified RDPRI using the same soils, subject to two overflow run-on rates (225 and 450 ml min^{-1}). Results of the 95 % confidence intervals suggested new critical soil test phosphorus (STP) thresholds for P_m, WEP, M3-P, $Pcacl_2$ and $Psat_{ox}$ of 7.83 mg L^{-1}, 4.15 mg kg^{-1}, 61 mg kg^{-1}, 1.2 mg kg^{-1} and 17.1 %, respectively. Whilst these new values for P_m, WEP and M3-P are lower than those determined by Regan et al. (*Journal of Environmental Quality*, *39*, 185–192 2010), the confidence intervals of the two sets of values overlap by more than 25 %, indicating no significant difference. The improved finding for P_m in this study is still in close agreement with the agronomic optimum (P_m=6.1–10 mg L^{-1}) used in Ireland for plant growth and crop yields, and fulfils the statutory requirements of the EU Good Agricultural Practice for the Protection of Waters, which prohibits fertiliser application to tillage soils with a P_m>10 mg L^{-1}.

Keywords Phosphorus · Agriculture · Tillage · Morgan's phosphorus · Mehlich-3 phosphorus

J. T. Regan · M. G. Healy
Civil Engineering, National University of Ireland,
Galway, Co. Galway, Republic of Ireland

O. Fenton (✉) · K. Daly · D. P. Wall
Johnstown Castle, Environment Research Centre, Teagasc,
Wexford, Co. Wexford, Republic of Ireland
e-mail: owen.fenton@teagasc.ie

J. Grant
Kinsealy Research Centre, Teagasc,
Dublin, Co. Dublin, Republic of Ireland

1 Introduction

In tillage soils, excessive organic and inorganic fertiliser application can lead to a build-up of phosphorus (P) in excess of crop requirements. This may result in dissolved reactive phosphorus (DRP) loss in runoff, which is readily available for biological uptake, and poses an immediate threat for accelerated algal growth in rivers and lakes. Phosphorus loss in surface runoff from soils is an important pathway in many agro-environments (Sims et al. 2002). The loss of fertile topsoil due to soil erosion on agricultural land is a growing problem in Western Europe, and has been identified as a threat to soil quality and the ability of soils to provide environmental services (Boardman et al. 2009). Boardman and Poesen (2006) estimated that arable agriculture accounts for approximately 70 % of soil erosion in Europe. It has numerous effects on soil, including thinning by removal

Published online: 06 July 2014

of topsoil, textural coarsening, decline of soil organic matter (SOM) and loss of nutrients (Guerra 1994).

Soil erosion is also associated with P transfer by overland flow, especially from arable land, where particulate phosphorus (PP) is the dominant P fraction exported (Doody et al. 2012). The susceptibility of arable land to P losses by erosion and overland flow is largely a result of soil structural degradation (Palmer and Smith 2013) and land being left bare for periods of the year. An increase in winter cereal cropping has exacerbated this problem, because it combines the period of maximum rainfall with long periods of bare soil (Leinweber et al. 2002). Furthermore, the disturbance of soil structure by tillage operations increases aggregate dispersion and the degree of interaction between soil and runoff water, thereby enabling more dissolved P to be mobilised from soils with high P status (Sharpley et al. 2001). As the area of winter cereals sown in the UK increased dramatically in the 1970s and 1980s, erosion and runoff became widespread, the occurrence of which were documented by several studies (Evans 2005; Watson and Evans 2007).

In Ireland, the main pathway of P loss from soils is via overland flow (Kurz et al. 2005), which is greatest during storm events and is largely inactive at other times (EPA 2008). Saturation excess overland flow (characterised by saturation of the soil over which it is moving) is the dominant type of overland flow generated under Irish conditions (Daly et al. 2000), although research has shown that infiltration excess overland flow also occurs in Ireland (Doody et al. 2010). Infiltration excess overland flow occurs where the infiltration rate for a given soil profile is exceeded. For many soil profiles, saturation excess overland flow is a special case of infiltration excess overland flow whereby infiltration is occurring, albeit at a negligible rate, because of the low hydraulic conductivity of the underlying strata (Nash et al. 2002). Where saturation excess and infiltration excess conditions combine, the result is a complex pattern of P loss (McDowell 2012).

Both saturation and infiltration excess overland flow can occur on tillage soils provided the conditions necessary for it to occur are present. Tillage increases the initial infiltration rate, loosens the topsoil, disrupts soil aggregates and causes compaction of the subsurface soil (Coles and Moore 1998). This can result in a subsurface soil with much lower hydraulic conductivity than the surface soil, and may lead to saturation of the topsoil. The loose topsoil is then susceptible to erosion by saturation excess overland flow. Infiltration excess overland flow is common with cultivated soils, or where surface soil structure has degraded or consolidated to form a ‘seal’, but can also occur on unsealed soil surfaces, especially with high rates or amounts of rainfall (Rose 2004). Factors that increase the volume, velocity and turbulence of overland flow, such as impaired infiltration, high intensity storms, run-on, reduced soil cover, cultivation and high slopes, increase detachment compared with dissolution (Nash et al. 2002). Furthermore, steeper slopes increase the potential for runoff-dominated erosion due to faster flow threads and lower surface area connectivity (Armstrong et al. 2011). Overland flow is, however, just one (e. g. leaching to a surface water contributing groundwater body is another) of the pathways that deliver mixed contaminants, including P, from a myriad of sources (agricultural and non-agricultural from point and diffuse sources) to a catchment outlet (Evans 2011; Huebsch et al. 2013).

The relationship between soil test phosphorus (STP) and DRP loss to water in runoff events needs to be adequately understood and quantified for local soils in order to determine upper critical limits for P in soil that will reduce the risk of diffuse losses from tillage land to surface waters. Laboratory flume studies, as opposed to field studies, are commonly used to study such relationships, as soils in flume studies can be homogenised, which minimises variability in soil physical and chemical characteristics. It is also less expensive and facilitates testing under standardised conditions including surface slope, soil conditions, rainfall intensity and overland flow rate. In a laboratory simulated rainfall study examining nutrient and sediment releases from five Irish tillage soils, Regan et al. (2010) developed a Runoff Dissolved Phosphorus Risk Indicator (RDPRI) to identify the STP level above which there may be a potential threat to surface water quality. Results showed that for the tillage soils tested, runoff DRP concentrations in excess of the European Union Water Framework Directive (EU WFD; Council of the European Union 2000) maximum allowable concentration (MAC) for surface water (0.03 mg L^{-1}) occurred when their Morgan’s P (P_m), Mehlich 3 P (M3-P) and water extractable P (WEP) concentrations exceeded 9.5 mg L^{-1}, 67.2 mg kg^{-1} and 4.4 mg kg^{-1}, respectively. It is hypothesised in the current study that introducing overflow run-on rates into the study design would change such STP thresholds further. This is important, as run-on is a natural phenomenon currently not acknowledged in present STP thresholds. Such a scenario would also replicate intense, episodic summer. This is important as more frequent, intense rainfall events during the summer have been predicted for Ireland by Sweeney et al. (2008).

The present study aimed to produce a modified RDPRI using the relationship between flow-weighted mean concentration (FWMC) of DRP lost in surface runoff generated using simulated rainfall and two overflow run-on rates (225 and 450 ml min^{-1}) on five tillage soils inclined at 10° slopes and P_m, M3-P and WEP. In addition, thresholds were also developed for calcium chloride ($Pcacl_2$) and soil P saturation ($Psat_{ox}$) soil tests.

2 Materials and Methods

2.1 Soils

The soils selected were the same as those used in the Regan et al. (2010) study: (1) Tullow, Co. Carlow; (2) Clonmel, Co. Tipperary; (3) Letterkenny, Co. Donegal; (4) Bunclody, Co. Wexford; and (5) Fermoy Co. Cork. Soils 1 and 2 (from Tullow and Clonmel, respectively) were naturally acidic, sandy loam textured, grey brown podzolic soils. Soils 3 and 4 (from Letterkenny and Bunclody, respectively) were calcareous, fine (Sand, 49/Silt, 39/Clay, 11 %) and coarse (41/38/20 %) loam textured (USDA), brown podzolic soils. Soil 4 (from Fermoy) was sandy loam textured, acid brown earth. The sites selected were in tillage for a minimum of 15 years and represented a full P_m index range from 1 (2.8 mg L^{-1}) to 4 (17.5 mg L^{-1}). Summary data of classification, and chemical and physical properties of all soils used in the rainfall/overflow run-on simulations are presented in Table 1.

2.2 Rain Simulation and Overland Flow Experiment

Two separate experiments were conducted, in which a water overflow run-on rate of either 225 or 450 ml min^{-1} was added at the top of a runoff box (2 m×0.225 m), inclined at a 10° slope (as in Regan et al. 2010), in the presence of rainfall (3 cm hr^{-1}, projected to occur every 5–10 years in the period 2020–2030 (Sweeney et al. (2008)), in order to investigate the effect of increasing overland flow rates on nutrient and sediment release from the study soils. It is acknowledged here that this laboratory set-up only represents high risk overland flow generation conditions in

Table 1 Classification, chemical and physical properties of selected tillage soils (Regan et al. 2010)

Location	Soil type	pH	P_m mg L^{-1}	CEC cmol kg^{-1}	AgSt %	$CaCO_3$ g kg^{-1}	OM	Sand	Silt	Clay	M3-P mg kg^{-1}	$Pcacl_2$	WEP	P_{ox}	Al_{ox}	Fe_{ox}	$Psat_{ox}$ %
Tullow, Co. Carlow	GBP	6.9	17.5	13.4	96.4	5	49	579	267	154	96.3	3.0	11.5	566	1,033	3,482	36.2
Clonmel, Co. Tipperary	GBP	6.7	15.8	11.2	90.0	5	42	528	306	167	89.4	2.1	6.6	457	903	3,867	28.8
Bunclody, Co. Wexford	BP	7.7	7.1	13.9	92.9	26	71	410	387	203	58.7	1.0	3.5	414	2,560	4,755	14.8
Letterkenny, Co. Donegal	BP	6.5	4.8	13.7	98.5	17	55	491	395	114	52.1	1.3	2.8	592	1,700	5,468	23.7
Fermoy, Co. Cork	ABE	6.4	2.8	13.1	97.8	4	51	569	286	145	29.1	1.4	2.3	273	1,227	3,886	15.4

The testing methodology is detailed in Regan et al. (2010)

P_m P determined by Morgan's extraction, *CEC* cation exchange capacity, *AgSt* aggregate stability, *OM* organic matter by loss on ignition, *M3-P* Mehlich-3 extractable P, $Pcacl_2$ calcium chloride extractable P, *WEP* water extractable P, P_{ox} acid ammonium oxalate extractable P, Al_{ox} acid ammonium oxalate extractable Al, Fe_{ox} acid ammonium oxalate extractable Fe, $Psat_{ox}$ soil P saturation as determined by acid ammonium oxalate extraction, *GBP* grey brown podzolic, *BP* brown podzolic, *ABE* acid brown earth

Ireland. The overflow run-on was generated by pumping water into a reservoir at the top of each runoff box using a Cole-Parmer Masterflex® L/S™ peristaltic pump, which was calibrated prior to each experimental run. The water was allowed to flow over a metal plate, which was level with the soil surface. It was envisaged that this approach would best replicate sheet flow arriving at the top of the runoff box. The two run-on rates applied represent possible worst case scenarios in fields, where the soil has become saturated due to high intensity rainfall.

Each experimental run comprised three successive 1-h rainfall/overflow run-on events at time zero, 1 h (this event began 1 h after the first event finished) and 24 h (this event began 24 h after the 2nd event finished) to determine the effect of storm interval on surface runoff. At each time interval, each soil was subjected to either rainfall only, rainfall and run-on flow at 225 ml min^{-1}, or rainfall and run-on flow at 450 ml min^{-1}. Similarly, Hairsine (1988) introduced clear water at the top of a runoff box in the presence of rainfall when investigating erosion of a cohesive soil in a rainfall simulation study. Surface runoff samples were collected when runoff began: once every 2.5 min for the first 20 min and in each subsequent 5-min interval to evaluate changes in runoff volume, and nutrient and sediment concentration over time. Flow-weighted mean concentrations for nutrients and sediment in runoff from each runoff box were determined by dividing the total mass load for the 1-h runoff event by the total flow volume for the same period.

2.3 Statistical Analysis

A linear mixed model (LMM) was fitted to each surface runoff response to test whether the impact of soil type on DRP, total phosphorus (TP), particulate phosphorus (PP) and suspended solids (SS) concentrations in surface runoff was affected by overflow run-on rate and flow event. A random effect with either a compound symmetry or a first-order autoregressive variance-covariance structure was fitted to account for non-independence of successive events (The GLIMMIX and MIXED Procedures, SAS 2004). A log transformation was required for all surface runoff responses to satisfy the assumption of normality of residuals. The analysis was conducted as a factorial combination of overflow run-on and flow event, with soil type as a blocking factor. The general classification by soil type allowed testing of the effects of the overflow run-on rate and flow event, but a number of covariates were recorded as a characterisation of the soil type. A series of models were fitted by removing the soil type category and substituting mostly continuous variables in an attempt to improve understanding of the processes involved. Covariates were fitted initially in a hypothesis-based set of tests, and subsequently best-fit models were obtained using a combination of hypotheses and stepwise selection of regressor variables. All covariate testing was carried out on an analysis model incorporating the experimental factors, so that the full data set could be used without any bias due to the structure of the treatments.

In order to rank the relative importance of the soil parameters, each parameter was assessed individually in its effect on the surface runoff response, averaged across the overflow run-on rates and flow events. The Akaike Information Criterion (AIC) is a statistic that gives a measure of the goodness of fit of a model. As the models were not nested, the extractable soil tests were ranked according to the AICs of their individual models. Each P indicator was added, in turn, to a model with the experimental factors and then assessed to determine which of them produced the best increase in the goodness of fit of the model used for determining the critical value of DRP.

3 Results

3.1 Dissolved and Particulate Phosphorus Loss with Overflow run-on Rate and Flow Event

The range of values of DRP, TP, PP and SS loss for the overflow run-on rates of 225 and 450 ml min^{-1} are presented in Figs. 1 and 2. The FWMC of DRP in surface runoff for the overflow run-on rate of 225 ml min^{-1} from the Tullow and Clonmel soils were the highest and peaked at 0.07 and 0.03 mg L^{-1}, respectively, during the time zero events. These values equated to DRP loads in surface runoff from the Tullow and Clonmel soils of 1.79 (39.8 g ha^{-1}) and 0.73 mg (16.3 g ha^{-1}) during the 1-h flow events. Dissolved reactive phosphorus loads measured in surface runoff from the calcareous Bunclody and Letterkenny soils were 0.51 (11.4 g ha^{-1}) and 0.38 mg (8.5 g ha^{-1}),

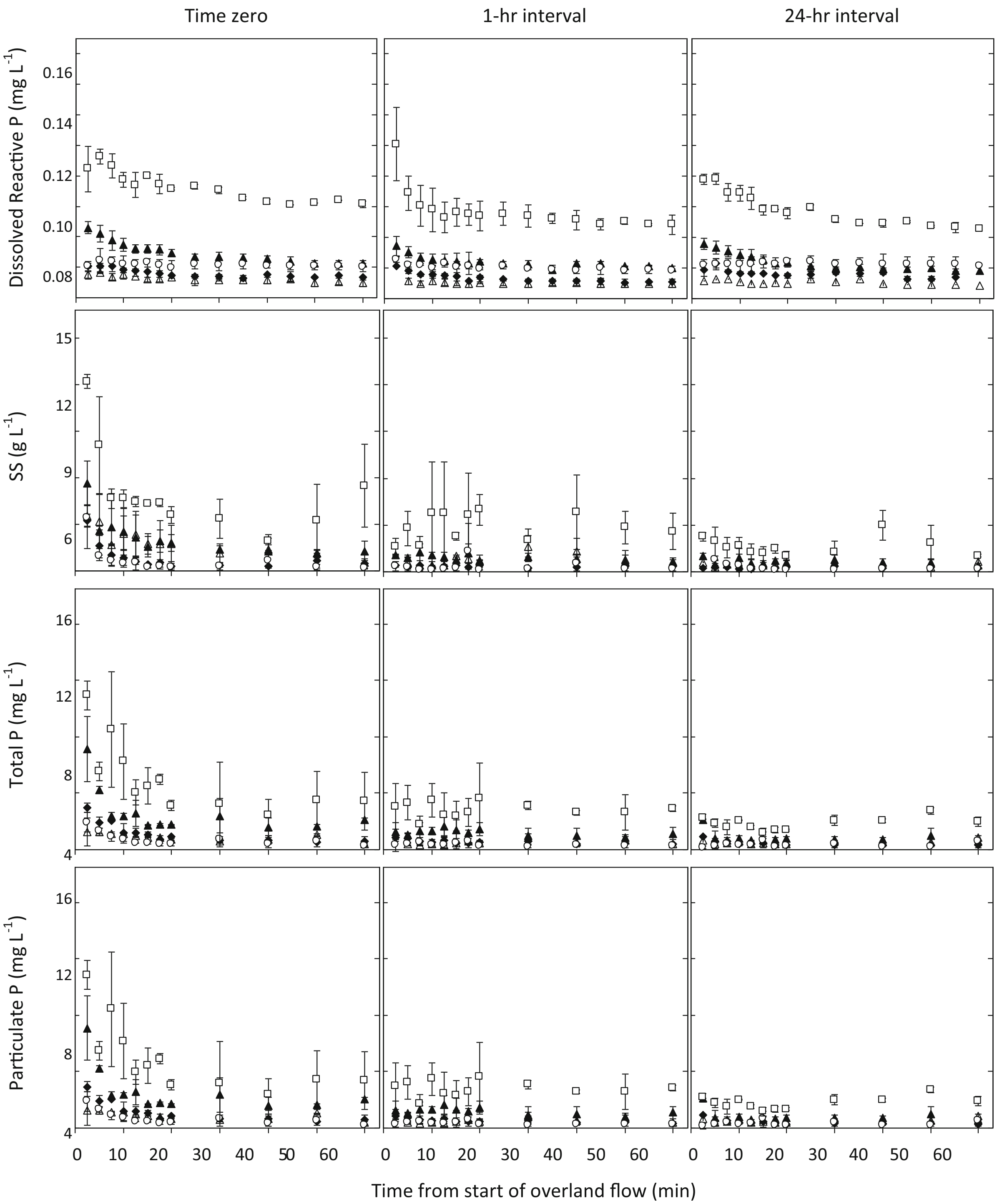

Fig. 1 Phosphorus and sediment concentrations in runoff water from tillage soils subjected to rainfall and overland flow (225 ml min^{-1}) when inclined at a 10° slope. Clonmel (*black triangle*), Tullow (*white square*), Letterkenny (*black diamond*), Bunclody (*white circle*), and Fermoy (*white triangle*)

respectively, for the overflow run-on rate of 225 ml min^{-1}. Surface runoff from the Fermoy soil had the lowest DRP load of 0.3 mg (6.7 g ha^{-1}) when subjected to the same overflow run-on rate.

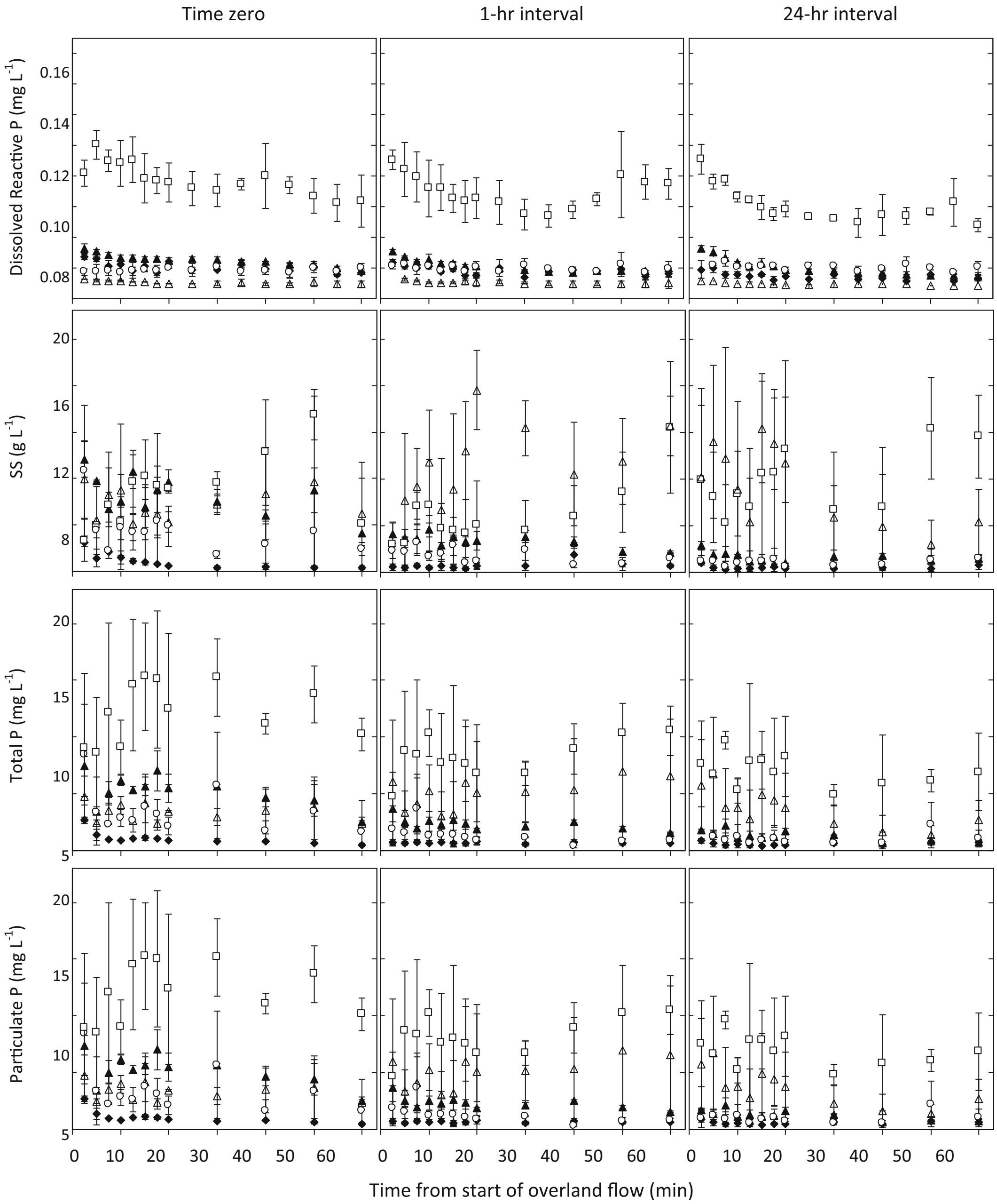

Fig. 2 Phosphorus and sediment concentrations in runoff water from tillage soils subjected to rainfall and overland flow (450 ml min^{-1}) when inclined at a 10° slope. Clonmel (*black triangle*), Tullow (*white square*), Letterkenny (*black diamond*), Bunclody (*white circle*), and Fermoy (*white triangle*)

Steady-state was deemed to have been achieved when consistent volumes in runoff occurred at set time intervals. Generally, the highest SS and P concentrations across the five soils, for an overland rate of 225 ml min^{-1}, occurred within 15 min of the commencement of the zero-hr, 1-h and 24-h events, and reached steady-state no later than 30 min after commencement of runoff, with the exception of the Tullow soil, which did not achieve steady-state for particulate losses.

3.2 Effect of Flow Rate on Phosphorus and Sediment Loss

Introducing overflow run-on rates of 225 and 450 ml min^{-1} at the top of the runoff box had the effect of increasing the runoff rate at the end of the runoff box from approximately 200 ml min^{-1} (for rainfall only) to 425 and 650 ml min^{-1}, respectively, across all the soils. For the higher run-on rate of 450 ml min^{-1}, nutrient and sediment concentrations only achieved steady-state for some soils (Fig. 2). An increase in run-on rate resulted in an increase in concentrations of SS, PP and TP in surface runoff across all soils ($p<0.05$). However, there was no significant difference in DRP in surface runoff between the two run-on rates ($p=0.125$).

The increases in concentrations of SS, TP and PP were generally not proportional to the increase in runoff rate measured at the end of the runoff box. This is to be expected given the vulnerable nature of the soils, after being sieved and then packed into runoff boxes. As might be expected, there was a strong relationship ($r=0.92$, $p=0.0001$) between SS and PP concentrations measured in surface runoff across the five soils. In general, soils that experienced higher SS losses at 450 ml min^{-1} had higher levels of variability in nutrient and SS concentrations between replicate samples.

An increase in extractable soil P resulted in an increase in concentrations of DRP in surface runoff ($p<0.05$) across all soils, with highest losses of DRP coming from soils with highest values of STP (P_m, M3-P, P_{ox}) and $Psat_{ox}$, as presented in Table 1. Based on $Psat_{ox}$ levels measured across the study soils, the Tullow and Clonmel soils had the highest risk of P desorption, with $Psat_{ox}$ levels of 36.2 and 28.8 %. The Tullow soil, which produced the highest values of DRP in surface runoff, at both run-on rates, also had a higher WEP level of 11.5 mg kg^{-1} compared to the Clonmel soil (WEP 6.6 mg kg^{-1}) at somewhat similar P_m values (both high P index 4) and soil pH. The other three soils (3, 4 and 5) had $Psat_{ox}$ levels between 14.8 and 23.7 %, and had lower DRP levels in surface runoff and significantly lower WEP (2.3–3.5 mg kg^{-1}) levels than the Tullow and Clonmel soils.

The potential for particulate losses in surface runoff was very high for the five tillage soils, with the highest losses coming from the Tullow soil (overflow run-on rate=450 ml min^{-1}), where FWMCs for SS and PP of 3.86 g L^{-1} and 4.25 mg L^{-1}, respectively, were measured for the time zero event. Kleinman et al. (2004) and Regan et al. (2010) noted that due to the packed nature of the bare soil (with lower AgSt than soil in the field) used in laboratory runoff box studies, particulate losses from them can represent worst case scenarios when compared with field losses.

3.3 Critical Soil Test P Thresholds for Overland Flow

The LMM analyses (Table 2) used for simulated rainfall/overflow run-on experiments indicated that the effect of soil type (soil distinguished based on physical and

Table 2 Overall ANOVA for responses from LMM analyses (rainfall and overland flow)

Source	DF	*F* value	Pr>F
Dissolved reactive phosphorus			
Soil type	4	639.33	<0.0001
Overland flow	2	17.71	0.0001
Overland flow*soil type	8	29.95	<0.0001
Event	2	32.69	<0.0001
Event*soil type	8	5.24	0.004
Overland flow*event	4	3.89	0.0116
Soil type*overland flow*event	16	2.14	0.0351
Total phosphorus			
Soil type	4	23.17	<0.0001
Overland flow	2	83.87	<0.0001
Overland flow*soil type	8	6.00	0.0015
Event	2	65.05	<0.0001
Event*soil type	8	4.04	0.0011
Overland flow*event	4	1.24	0.3053
Particulate phosphorus			
Soil type	4	21.27	<0.0001
Overland flow	2	83.3	<0.0001
Overland flow*soil type	8	6.16	0.0013
Event	2	80.73	<0.0001
Event*soil type	8	5.23	0.0004
Overland flow*event	4	1.49	0.2310
Soil type*overland flow*event	16	1.75	0.0898
Suspended sediment			
Soil type	4	5.29	0.0073
Overland flow	2	35.13	<0.0001
Overland flow*soil type	8	9.89	<0.0001
Event	2	36.46	<0.0001
Event*soil type	8	1.66	0.1348
Overland flow*event	4	1.91	0.1240

*interaction with

chemical parameters as in Table 1) on the FWMC of DRP interacted with/depended on both run-on rate and time between flow events (p=0.0351). A stepwise regression selection procedure was used to identify the soil extractable P method best suited to predicting DRP loss from Irish tillage soils when subjected to simulated rainfall. Measurement of soil WEP was selected as important when predicting DRP in runoff across all soils, slopes and rainfall events. This is in agreement with other studies where WEP provided the strongest correlation with DRP concentrations in runoff when compared to other STP methods such as M3-P and Pm (Pote et al. 1996), and was able to simulate actual runoff DRP concentrations (Yli-Halla et al. 1995).

The effect of soil type depended only on run-on rate for the FWMCs of SS (p<0.0001), TP (p=0.0015) and PP (p=0.0013) in surface runoff. These results were, as expected, given the small storm intervals being investigated. Larger storm intervals that allow the soil time to dry might be expected to impact on the levels of SS, TP and PP lost in runoff. There was significant interaction of soil type with at least one of the experimental factors for each of the variables examined, indicating the importance of soil type in assessing the potential to release DRP, SS, TP and PP into overland flow (Table 2).

3.4 Critical Soil Test Phosphorus Threshold for Overland Flow

The logarithm of the FWMC of DRP in surface runoff from each soil was linearly related to the P_m of each soil for all overflow run-on rates. The logarithm of the FWMC of DRP in surface runoff from each soil was also linearly related to WEP, M3-P, $Pcacl_2$ and $Psat_{ox}$ concentrations in each soil for all overflow run-on/simulated rainfall events (results not shown). The DRP lost in surface runoff when both simulated rainfall and overflow run-on were applied to the soil increased log-linearly as P_m, WEP, M3-P, $Pcacl_2$ and $Psat_{ox}$ increased. For both overflow run-on rates on all five soils, the time zero event had the highest FWMC of DRP in runoff, whilst the FWMCs of DRP in surface runoff for the 1 and 24-h events were lower than the time zero event, and were generally not significantly different in magnitude from each other.

A critical value was derived for each of the soil extractable P methods above which surface water quality may exceed the EU WFD MAC of 0.03 mg DRP L^{-1} for a surface waterbody. The 95 % confidence limits/intervals (Fig. 3) indicate that provided the P_m does not exceed 7.83 mg L^{-1}, WEP does not exceed 4.15 mg kg^{-1}, M3-P does not exceed 61 mg kg^{-1}, $Pcacl_2$ does not exceed 1.2 mg kg^{-1} and $Psat_{ox}$ does not exceed 17.1 % for tillage soils, the concentration of DRP in surface runoff will be below 0.03 mg L^{-1}. Whilst these new values for P_m, WEP and M3-P are lower than those determined by Regan et al (2010), the confidence intervals of the two sets of values overlap by more than 25 % (Table 3), indicating no significant difference. Furthermore, an all-in approach was adopted in the current study, which allowed testing of any change from one combination of experimental factors to the next. The estimates of noise/error, on which confidence intervals are based, are better when all available data are used (as in the case of an all-in approach) and this may, in part, account for the new lower values and narrower confidence intervals of the new model. The larger data set used in this model also improved its precision. Overall, there was no evidence of a linear relationship between overflow run-on rate and DRP concentration measured in surface runoff (p=0.125). As such, the new lower values for P_m, WEP and M3-P are primarily a result of improvements in the model used to predict DRP in runoff.

4 Discussion

The critical P_m value above which P losses increased sits firmly in the target STP agronomic optimum range (P_m=6.1–10 mg L^{-1}) for plant growth and crop yields. It is also in close agreement with the statutory requirements of the European Union (Good Agricultural Practice for Protection of Waters) Regulations 2014 (Statutory Instrument 31, 2014), which prohibits fertiliser application to tillage soils with a P_m>10 mg L^{-1} and suggests that given the worst case storm scenarios tested, a change in the statutory P_m limit is unwarranted at this time. However, a review of these limits may be needed, should the predicted climate change storms materialise. The threshold M3-P of 61.2 mg kg^{-1}, determined in this study, is in close agreement with the critical M3-P of 65 mg kg^{-1} now being adopted in some states in America. An M3-P value of 45–50 mg kg^{-1} in soil is generally considered to be optimum for plant growth and crop yields (Sims 2000). The findings of this study suggest that keeping the M3-P level in the

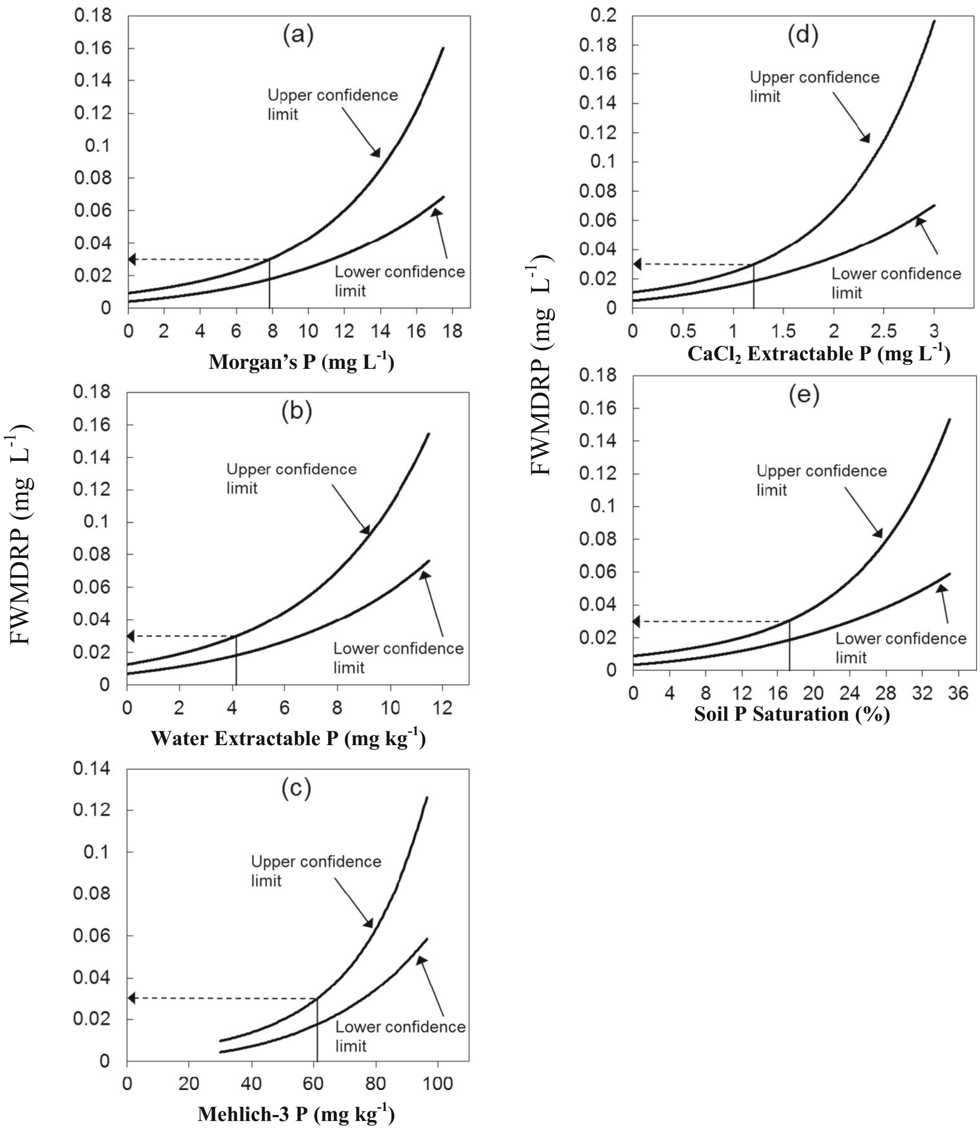

Fig. 3 Runoff Dissolved Phosphorus Risk Indicator using Morgan's P, water extractable P and Mehlich-3 P for selected tillage soils at a 10° slope, under a 30 mm hr^{-1} rainfall and subjected to two distinct overland flow rates (225 and 450 ml min^{-1})

study soils close to this agronomic optimum will ensure that the concentration of DRP in surface runoff will be below 0.03 mg L^{-1}. Caution must be exercised when interpreting STP results in an environmental context, as they comprise only a small percentage of the total soil P reservoir and do not account for potential detachment (Haygarth and Condron 2004) or dissolution from eroded sediments.

Soil P tests developed for environmental purposes, such as WEP and Pcacl$_2$, are less affected by soil type than agronomic soil tests like M3-P and P$_m$ (Self-Davis et al. 2000), and can be valuable for estimating labile forms of P (Simard et al. 1995). Their ability to either better replicate the interaction between soil and runoff or better represent the likelihood of P release from soil to runoff (Vadas et al. 2005), makes them ideal P loss risk indicators. However, these environmental soil P tests have been closely correlated with the standard agronomic soil test (Morgan's P) in Ireland (Daly et al. 2001; Daly and Styles 2005), and the Morgan's P level has been shown to be a good indicator of potential P loss to surface water (Daly and Casey 2003; Kurz et al. 2005) across Irish soils.

Table 3 Comparing Regan et al. (2010) RDPRI outputs with the present study to identify thresholds for each of Morgan's P, P_m; water extractable phosphorus, WEP; Mehlich-3, M3-P; calcium chloride extractable phosphorus, $Pcacl_2$; and soil P saturation, $Psat_{ox}$, above which DRP in surface runoff may exceed 0.03 mg L^{-1} (old limit, SI 258 of 1998) and 0.035 mg L^{-1} (new limit, SI 272 of 2009)

	Upper 95 % CL	Lower 95 % CL	% Overlap of intervals
	Phosphorus<0.03 mg L^{-1} (Old limit, SI 258 of 1998)		
RDPRI P_m (mg L^{-1})	9.5	16	52
New P_m (mg L^{-1})	7.83	11.31	
RDPRI WEP (mg kg^{-1})	4.4	6.83	89
New WEP (mg kg^{-1})	4.15	6.57	
RDPRI M3-P (mg kg^{-1})	67.2	89.3	59
New M3-P (mg kg^{-1})	61.2	76	
$Pcacl_2$ (mg kg^{-1})	1.2	1.79	–
$Psat_{ox}$ (%)	17.1	24.1	–
	Phosphorus<0.035 mg L^{-1} (New limit, SI 272 of 2009)		
P_m (mg L^{-1})	8.78	12.42	–
WEP (mg kg^{-1})	4.87	7.35	–
M3-P (mg kg^{-1})	65.2	80.5	–
$Pcacl_2$ (mg kg^{-1})	1.36	2	–
$Psat_{ox}$ (%)	18.9	26.44	–

CL confidence limit

A $Psat_{ox}$ value of 25 %, or more, has been established on the basis of laboratory data for non-calcareous, sandy soils above the mean high water table from the Netherlands, as a change point above which the potential for P losses through runoff and leaching become unacceptable. The water quality standard used in the Netherlands in determining this critical value is 0.1 mg ortho-P L^{-1} (Breeuwsma et al. 1995). Runoff and leachate P concentrations, measured by Sims et al. (2002) in column leaching studies and rainfall simulations using sandy soils, support the guideline critical value of 25 % for $Psat_{ox}$ that is recommended in the Netherlands. The findings of the current study, which contains a mix of calcareous and non-calcareous soils, suggest that a lower limit of 17.1 % $Psat_{ox}$ would better protect water quality in Ireland by ensuring that DRP losses from Irish tillage soils remain below 0.03 mg P L^{-1}. Soils with $Psat_{ox}$ values that exceed this threshold, such as the Tullow and Clonmel soils, are more heavily saturated with P and are vulnerable to losses to overland flow by P desorption. Values of WEP were highest in these two soils, and this may, in part, be due to their high degree of P saturation. However, these two soils displayed marked differences in their WEP and DRP values in overland flow. The difference in peak values of DRP observed in the Tullow (0.07 mg L^{-1}) and Clonmel soil (0.03 mg L^{-1}) at an overflow run-on rate of 225 ml min^{-1} are reflected in the WEP values of 11.5 and 6.6 mg kg^{-1} for the Tullow and Clonmel soils, respectively. The Tullow soil had a slightly higher STP value than the Clonmel soil (P_m 17.5 mg L^{-1} vs. 15.8 mg L^{-1}) and both had similar pH levels. However, the Tullow soil is a higher risk soil in terms of P desorption to water, and this may be due to higher $Psat_{ox}$ and weakly bound P that readily desorbs into the soil solution when a large volume of water is added. The inability of the Tullow soil to reach steady-state in the current study may also indicate continuous desorption with higher P saturation compared to the other soils (e.g. Fermoy).

This lower $Psat_{ox}$ threshold, as determined for Irish tillage soils subjected to overflow run-on and rainfall in this study, may be a result of the phosphorus sorption capacity (PSC) used in the determination of $Psat_{ox}$ for the study soils. The PSC of soils varies widely depending on clay content, clay mineralogy, organic matter (OM) content, exchangeable aluminium (Al), iron (Fe) and calcium (Ca) concentrations and soil pH (Tisdale et al. 1993). Furthermore, results from Beauchemin and Simard (1999) indicate that the relationship between PSC and $[Fe_{ox}+Al_{ox}]$ contents may vary amongst soil groups. The current study contained calcareous (e.g. Bunclody or Letterkenny) soils that had lower $Psat_{ox}$ when compared to the other non-calcareous soils. The one exception here was the Fermoy soil, which had a very low P content, as indicated by the agronomic and environmental soil tests.

This study's findings show that, for soils subjected to both simulated rainfall and overflow run-on, WEP (AIC=−12.3) and $Pcacl_2$ (AIC=−6.9) performed better than the agronomic soil P tests, P_m (AIC=6.4) and M3-P (AIC=7.1) in predicting DRP in overland flow. Only large differences (here, at least 4) between AIC scores for soil extractable P tests are taken as indicating a difference in the goodness of fit of the model used for determining the critical value of DRP. The addition of WEP to the model produced the best increase in goodness of fit (as is evidenced by WEP receiving the lowest AIC score of −12.3 and the difference between it and the next lowest AIC being>4) and therefore performed better than the other measures of soil P when predicting DRP in runoff. These results are in agreement with Pote et al. (1999), Penn et al. (2006) and Wang et al. (2010), who reported that WEP had consistently stronger relationships with DRP concentrations in surface runoff than other measures of soil P. The authors attributed this to the fact that the extracting solution for WEP (distilled water) is more similar to the simulated rainfall water (tap water) than other extracting solutions.

Soil P saturation (AIC=20.6) ranked lowest, which is probably due to some of the study soils being slightly calcareous in nature and the fact that soil texture ranged from sandy loam to loam. In other studies, the calculation of $Psat_{ox}$ using P_{ox}/ 0.5 (Al_{ox}+Fe_{ox}) has produced strong correlations with soluble P when the range of soils used was homogeneous, but the relationship weakens if a wider range of soil types is considered (Beauchemin and Simard 1999). In a study of published data from 17 studies, Vadas et al. (2005) concluded that for non-calcareous soils, a test for soil P saturation (determined by acid ammonium oxalate extraction) may provide a more universal prediction of dissolved P in runoff than Mehlich-3, Bray-1 or water extractions. Soil P saturation measures the degree to which soil P sorption sites have been filled and has been found to be a good indicator of P availability to runoff (Kleinman and Sharpley 2002).

Due to the limited range in some of the soil parameters measured across the five soils (this was largely due to tillage in Ireland being conducted primarily on sandy loam or loam soils), it was difficult to ascertain which parameters had a significant effect on DRP in overland flow. Higher levels of Fe_{ox} and [Fe_{ox}+Al_{ox}] measured in the study soils were found to have a significant lowering effect (p<0.05) on the concentration DRP measured in surface runoff. This further emphasises the important role these parameters play in determining the PSC of a soil. Overall, there was no evidence of a relationship between overflow run-on rate and DRP concentration measured in surface runoff (p=0.125), implying that rainfall can be used in isolation when developing relationships between soil P level and potential DRP concentrations lost in runoff. This implies that the flow changes (and therefore the mass) but not the concentration. However, a multi-scaled approach (from laboratory to catchment) should be adopted in the future to overcome scale-dependent effects (Regan et al. 2012), as such a relationship has been found at larger scales in Irish soils (Kurz et al. 2005; Kurz et al. 2006; Doody et al. 2006).

5 Conclusions

The main conclusions from this study were:

1. Incorporating overland flow run-on and rainfall simultaneously in tests increased concentrations of DRP, TP, PP and SS in surface runoff across all soils examined. The magnitude of change differed across soils and may be due to inherent differences in soil desorption and binding energies.
2. Increasing overland flow (through the addition of run-on) decreased critical STP thresholds in tillage soils to comply with MAC (0.03 mg DRP L^{-1}) in surface water. A modified RDPRI, distinct from Regan et al. (2010), showed critical STP thresholds for P_m, WEP, M3-P, $Pcacl_2$ and $Psat_{ox}$ of 7.83 mg L^{-1}, 4.15 mg kg^{-1}, 61 mg kg^{-1}, 1.2 mg kg^{-1} and 17.1 %, respectively.
3. The finding for P_m in this study is in close agreement with the agronomic optimum (P_m=6.1–10 mg L^{-1}) used in Ireland for plant growth and crop yield in tillage soils. It is also in close agreement with the statutory requirements of the EU Good Agricultural Practice for the Protection of Waters, which prohibits fertiliser application to tillage soils with a P_m>10 mg L^{-1}.

Acknowledgments The authors would like to thank the funding received for the first author under the Teagasc Walsh Fellowship Scheme. We would also like to thank Michael Walsh, Teagasc, Athenry, for his guidance in classifying soils.

References

Armstrong, A., Quinton, J. N., Francis, B., Heng, B. C. P., & Sander, G. N. (2011). Controls over nutrient dynamics in overland flows on slope representative of agricultural land in North West Europe. *Geoderma, 164*, 2–10.

Beauchemin, S., & Simard, R. R. (1999). Soil phosphorus saturation degree: a review of some indices and their suitability for P management in Québec, Canada. *Canadian Journal of Soil Science, 79*, 615–625.

Boardman, J., & Poesen, J. (2006). *Soil erosion in Europe*. UK: Wiley. 855 pp.

Boardman, J., Shepheard, M. L., Walker, E., & Foster, I. D. L. (2009). Soil erosion and risk-assessment for on- and off-farm impacts: a test case using the Midhurst area, West Sussex, UK. *Journal of Environmental Management, 90*, 2578–2588.

Breeuwsma, A., Reijerink, J. G. A., & Schoumans, O. F. (1995). Impact of manure on accumulation and leaching of phosphate in areas of intensive livestock farming. In K. Steele (Ed.), *Animal waste and the land-water interface* (pp. 239–250). Florida: Lewis Publ. Boca Raton.

Coles N., & Moore, G. (1998). Runoff and water erosion. p. 223-242. In: G. Moore (ed.). Soil guide: a handbook for understanding and managing agricultural soils. Agriculture Western Australia. Bulletin No. 4343.

Council of the European Union, (2000). Water Framework Directive 2000/60/EC establishing a framework for community action in the field of water policy. Available at: www.wfdireland.ie.

Daly, K., Coulter, B., & Mills, P. (2000). *National phosphorus model, In: quantification of phosphorus loss from soil to water. Final report and literature review* (pp. 103–150). Wexford: Environmental Protection Agency.

Daly, K., Jeffrey, D., & Tunney, H. (2001). The effect of soil type on phosphorus sorption capacity and desorption dynamics in Irish grassland soils. *Soil Use Management, 17*, 12–20.

Daly, K. & Casey, A. (2003). Eutrophication from agricultural sources—environmental soil phosphorus test. Final report prepared for the Environmental Protection Agency. ISBN: 1-84095-111-7.

Daly, K. & Styles, D. (2005). Eutrophication from agricultural sources—phosphorus chemistry of mineral and peat soils in Ireland. (2000-LS-2.1.1b-M2) Final Report. Verified May 2014.

Doody, D., Moles, R., & Tunney, H. (2006). Impact of flow path length and flow rate on phosphorus loss in simulated overland flow from a humic gleysol grassland soil. *Science of the Total Environment, 372*, 247–255.

Doody, D. G., Higgins, A., Matthews, D., Foy, R. H., Pilatova, K., Duffy, O., et al. (2010). Overland flow initiation from a drained drumlin grassland hillslope. *Soil Use and Management, 26*, 286–298.

Doody, D. G., Archbold, M., Foy, R. H., & Flynn, R. (2012). Approaches to the implementation of the Water Framework Directive: targeting mitigation measures at critical source areas of diffuse phosphorus in Irish catchments. *Journal of Environmental Management, 93*, 225–234.

Environmental Protection Agency. 2008. Eutrophication from agricultural sources (2000-LS-2-M2) Integrated report. Wexford, Environmental Protection Agency. Available at: http://www.epa.ie/downloads/pubs/research/water/ertdi%20report%2081_web.pdf, verified May 2014.

Evans, R. (2005). Monitoring water erosion in lowland England and Wales—a personal view of its history and outcomes. *Catena, 64*, 142–161.

Evans, R. (2011). Reconnaissance surveys to assess sources of diffuse pollution in rural catchments in East Anglia, eastern England—implications for policy. *Water and Environment Journal, 26*, 200–211.

Guerra, A. (1994). The effect of organic matter content on soil erosion in simulated rainfall experiments in W. Sussex, UK. *Soil Use and Management, 10*, 60–64.

Haygarth, P. M., & Condron, L. M. (2004). Background and elevated phosphorus release from terrestrial environments. In E. Valsami-Jones (Ed.), *Phosphorus in environmental technology principles and applications*. London: IWA Publishing.

Hairsine, P.B. (1988). A physically based model of the erosion of cohesive soils. PhD thesis dissertation. Griffith University, Brisbane, Australia.

Huebsch, M., Horan, B., Blum, P., Richards, K. G., Grant, J., & Fenton, O. (2013). Impact of local weather conditions and agronomic practices on groundwater nitrogen content in a karst aquifer on an intensive dairy farm in Southern Ireland. *Agriculture, Ecosystems and Environment, 179*, 187–199.

Kleinman, P. J. A., & Sharpley, A. N. (2002). Estimating soil phosphorus sorption saturation from Mehlich-3 data. *Communications in Soil Science and Plant Analysis, 33*, 1825–1839.

Kleinman, P. J. A., Sharpley, A. N., Veith, T. L., Maguire, R. O., & Vadas, P. A. (2004). Evaluation of phosphorus transport in surface runoff from packed soil boxes. *Journal of Environmental Quality, 33*, 1413–1423.

Kurz, I., Coxon, C., Tunney, H., & Ryan, D. (2005). Effects of grassland management and environmental conditions on nutrient concentrations in overland flow. *Journal of Hydrology, 304*, 35–50.

Kurz, I., Reilly, C. D., & Tunney, H. (2006). Impact of cattle on soil physical properties and nutrient concentrations in overland flow from pasture in Ireland. *Agriculture, Ecosystems and Environment, 113*, 378–390.

Leinweber, B. L., Turner, B. L., & Meissner, R. (2002). Phosphorus. In P. M. Haygarth & S. C. Jarvis (Eds.), *Agriculture, hydrology and water quality* (pp. 29–56). Wallingford: CAB International.

McDowell, R. W. (2012). Minimising phosphorus losses from the soil matrix. *Current Opinion in Biotechnology, 23*, 1–6.

Nash, D., Halliwell, D., & Cox, J. (2002). Hydrological mobilization of pollutants at the field/slope scale. In P. M. Haygarth & S. C. Jarvis (Eds.), *Agriculture, hydrology and water quality* (pp. 225–242). Wallingford: CAB International.

Palmer, R. C., & Smith, R. P. (2013). Soil structural degradation in SW England and its impact on surface-water runoff generation. *Soil Use and Management, 29*, 567–575.

Penn, C. J., Mullins, G. L., Zelazny, L. W., & Sharpley, A. N. (2006). Estimating dissolved phosphorus concentrations in runoff from three physiographic regions of Virginia. *Soil Science Society of America Journal, 70*, 1967–1974.

Pote, D. H., Daniel, T. C., Sharpley, A. N., Moore Jr P. A., Edwards, D. R., & Nichols, D. H. (1996). Relating extractable soil phosphorus to phosphorus losses in runoff. *Soil Science Society of America Journal, 60*, 855–859.

Pote, D. H., Daniel, T. C., Nichols, D. J., Sharpley, A. N., Moore, P. A., Jr., Miller, D. M., et al. (1999). Relationship between phosphorus levels in three ultisols and phosphorus concentrations in runoff. *Journal of Environmental Quality, 28*, 170–175.

Regan, J. T., Rodgers, M., Healy, M. G., Kirwan, L., & Fenton, O. (2010). Determining phosphorus and sediment release rates from five Irish tillage soils. *Journal of Environmental Quality, 39*, 185–192.

Regan, J., Fenton, O., & Healy, M. G. (2012). A review of phosphorus and sediment release in tillage soils, the methods used to quantify losses and the current state of mitigation practice. *Biology & Environment: Proceedings of the Royal Irish Academy, 112*, 157–183.

Rose, C. W. (2004). *An introduction to the environmental physics of soil, water and watersheds* (8th ed.). Cambridge: Cambridge University Press. 261 pp.

SAS Institute. (2004). *SAS online. Version 9.1*. Cary: SAS Inst.

Self-Davis, M. L., Moore, P. A., Jr., & Joern, B. C. (2000). Water- or dilute salt-extractable phosphorus in soil. p. 22-24. In G. M. Pierzynski (Ed.), *Methods of phosphorus analysis for soils, sediments, residuals, and waters. Bull. 396. Southern Ext./Res. Activity-Info. Exchange Group (SERA-IEG-17)*. Manhattan: Kansas State Univ.

Simard, R. R., Cluis, D., Gangbazo, G., & Beauchemin, S. (1995). Phosphorus status of forest and agricultural soils from a watershed of high animal density. *Journal of Environmental Quality, 24*, 1010–1017.

Sims, J.T. (2000). Soil test phosphorus: Principals and methods. p. 9-19. In: G.M. Pierzynski (ed.). Methods of phosphorus analysis for soils, sediments, residuals, and waters. Bull. 396. Southern Ext./Res. Activity-Info. Exchange Group (SERA-IEG-17), Kansas State Univ.

Sims, J. T., Maguire, R. O., Leytem, A. B., Gartley, K. L., & Pautler, M. C. (2002). Evaluation of Mehlich 3 as an agri-environmental soil phosphorus test for the Mid-Atlantic United States of America. *Soil Science Society of America Journal, 66*, 2016–2032.

Sharpley, A. N., McDowell, R. W., & Kleinman, P. J. A. (2001). Phosphorus loss from land to water: integrating agricultural and environmental management. *Plant and Soil, 237*, 287–307.

Statutory Instrument 31. European Union (Good agricultural practice for protection of waters) Regulations (2014). Statutory Instruments. SI No. 31 of 2014. Department of Environment, Heritage and Local Government, The Stationary Office, Dublin, 54 p.

Sweeney, J. F., Albanito, F., Brereton, A., Caffarra, A., Charlton, R., Donnelly, A., et al. (2008). *Climate change—refining the impacts for Ireland*. Johnstown Castle: Environmental Protection Agency.

Tisdale, S. L., Nelson, W. H., Beaton, J. D., & Havlin, J. L. (1993). *Soil fertility and fertilizers* (16). New York: MacMillan Publishing Company.

Vadas, P. A., Kleinman, P. J. A., Sharpley, A. N., & Turner, B. L. (2005). Relating soil phosphorus to dissolved phosphorus in runoff: a single extraction coefficient for water quality modelling. *Journal of Environmental Quality, 34*, 572–580.

Wang, Y. T., Zhang, T. Q., Hu, Q. C., Tan, C. S., O'Halloran, I. P., Drury, C. F., et al. (2010). Estimating dissolved reactive phosphorus concentration in surface runoff water from major Ontario soils. *Journal of Environmental Quality, 39*, 1771–1781.

Watson, A., & Evans, R. (2007). Water erosion of arable fields in north-east Scotland, 1985–2007. *Scottish Geographical Journal, 123*, 107–121.

Yli-Halla, M., Hartikainen, H., Ekholm, P., Turtola, E., Puustinen, M., & Kallio, K. (1995). Assessment of soluble phosphorus load in surface runoff by soil analyses. *Agriculture, Ecosystems and Environment, 56*, 53–62.