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Use of rapid small-scale column tests for simultaneous prediction of phosphorus and nitrogen retention in large-scale filters

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ABSTRACT

Rapid small-scale column tests (RSSCTs) have been previously used to predict the effluent concentration of a single nutrient in large filters with good accuracy. However, in drainage waters originating from heavy textured soils, where there is a need for in-ditch filters to retain both dissolved reactive phosphorus (DRP) and ammonium (NH_4) simultaneously, the suitability of a RSSCT approach to model both parameters must be proved. In this study, a decision support tool was used to identify appropriate media that may be placed in filters for the removal of DRP and NH_4. The selected media for this study were sand and zeolite. Both media were placed in acrylic tubes each with an internal diameter of 0.01 m and with lengths ranging from 0.1 to 0.4 m, and their performance for simultaneous removal of DRP and NH_4 (1 mg DRP and NH_4-N L^{-1}) from water was evaluated. The data generated from the RSSCTs were used to model DRP and NH_4 removals in 0.4 m-long laboratory columns of internal diameter 0.1 m, which had the same media configuration as the small columns and were operated using the same influent concentrations. The developed model successfully predicted the effluent concentration of both the DRP and NH_4-N from the large columns. This indicates using RSSCTs to model the performance of filters will produce substantial savings in operational, financial and labour costs, without affecting the accuracy of model predictions.

1. Introduction

Intensification of agriculture through crop growth strategies and increased animal stocking rates has been enacted in many countries of the European Union (EU) [1]. This may result in unabated diffuse and point-source nutrient (nitrogen (N) and phosphorus (P)) losses to water bodies, causing multiple effects on environmental systems while traveling along biogeochemical pathways and continua from soil to water bodies [2,3]. As surface and subsurface storage components of these mixed nutrients are large, critical and incidental losses which are deleterious for the aquatic system, will occur [4,5]. Therefore, alongside existing best management practices to mitigate surface and groundwater nutrient losses, there is a need for a number of additional measures that can intercept and mitigate nutrients before they leave the farm system. Engineered remediation technologies, often referred to as engineered structures, are amongst these measures and have moved beyond proof of concept in recent years [6]. These are placed at nutrient pollution delivery points in hydrologically active areas [7], where the soil natural attenuation capacity does not exist or has already been exhausted due to accumulation of nutrients [8]. These structures include installation of structures filled with P sorbing materials [9,10] to intercept surface runoff, in-ditch control structures designed to remove both P and N in drainage waters [11], and denitrifying bioreactors connected to tile systems that are filled with carbon-based media that convert nitrate (NO_3) to di-nitrogen gas [11–13]. Efforts are now being made to make the use of engineered structures as a sustainable pollution remediation technique that takes local, environmental and financial conditions of the user into consideration.

Ezzati et al. [14] developed a decision support tool (DST) to assist users in the selection of locally sourced media for use in mitigating

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pollution associated with excess nutrients in drainage waters which incorporates several factors important in choosing filter media such as lifespan, hydraulic conductivity, the potential for pollution swapping, attenuation of non-target contaminants (e.g. pesticides, organic carbon, etc.), local availability, and costs associated with transporting media to site. Within this DST, several water contamination scenarios were identified, such as NO_3 only, dissolved reactive phosphorus (DRP) only, or a mixed discharge of ammonium (NH_4) and DRP.

On heavy textured soils, where land drainage has been installed to extend the grazing season, there is a large body of evidence (e.g. [15]) that identifies NH_4 (not NO_3) and DRP as the main nutrients of concern in both shallow and groundwater drainage systems. The aim of the current study is to design and quantify the effectiveness of small filters containing appropriate media capable of retaining both NH_4 and DRP.

Prior to deployment of filters in field situations, it is advisable to characterise the adsorption capacity of the media using batch experiments. These tests are quick, cheap, and easy-to-perform [16], but fail to replicate in-field conditions, in which there may be additional variables, such as fluctuating water temperatures, flow dynamics and pollutant loads. Consequently, they often fail to accurately estimate lifespan or effectiveness of the media [17]. As the accurate estimation of long-term performance of a medium is only possible under continuous flow conditions in the field [18], the closest simulation to in-field conditions is to allow nutrient-rich water to flow through large-scale adsorption columns which are frequently operated in the laboratory [19,20]. However, these tests are costly and may take a long period to reach steady-state conditions [21].

Rapid small-scale column tests (RSSCTs), which use only a minimum quantity of medium and contaminant solution, have been developed to reproduce the results of large-scale column studies [22]. Callery et al. [23] used RSSCTs to predict the long-term P retention performance of large-scale, single medium adsorption filters. Callery and Healy [24] developed the model further to predict medium saturation, as well as filter-pore and effluent concentration data. This RSSCT and modeling approach has never been attempted to examine a mixed contaminant scenario such as that found in heavy textured soils i.e. the simultaneous treatment of DRP and NH_4. Such a scenario would necessitate the presence of more than one medium in a filter that would retain both nutrients of environmental concern in drainage waters.

Therefore, the objective of the current study is to examine the efficacy of the RSSCT modeling approach in predicting DRP and NH_4 effluent concentration that simultaneously pass through large-scale columns filled with two media. If this methodology proves successful, this approach may provide an accurate and quick method of predicting the performance of filter media that may negate the need for long-term and expensive large-scale column studies.

2. Materials and methods

2.1. Media selection using batch experiments and falling head tests

The DST, developed by Ezzati et al. [14], was used to generate a list of media capable of mitigating DRP and NH_4 in drainage water (Table 1 - Stage 1). Batch and adsorption isotherm experiments were conducted to identify media with the highest adsorption capacities for DRP and NH_4 (Table 1 - Stage 2). The batch experiments were conducted as follows: 2 *g* of locally sourced media, identified in Stage 1, were placed in 50 mL-capacity glass containers. Each medium was overlain with 35 mL of distilled water, which was amended with both KH_2PO_4 and NH_4Cl to produce mixed DRP and NH_4-N solutions with concentrations ranging from 1 mg L^{-1} to 40 mg L^{-1}. The containers were then sealed and placed in an end-over end shaker for 24 h. Following this, the samples were allowed to settle for 1 h and then centrifuged at 3500 rpm for 10 min, before the supernatant was withdrawn and filtered using 0.45-µm filters. All water samples were analysed for DRP and NH_4-N within 24 h using a Thermo Konelab 20 analyser (Technical Lab Services, Ontario, Canada). A multipoint Langmuir isotherm [25] was used to estimate the adsorption capacity of each medium. The specific adsorption (q_e) (the mass of nutrient adsorbed per unit mass of amendment at equilibrium) (g kg^{-1}) was calculated from the following equation [25]:

Table 1
Stages of media selection for dual nutrient mitigation. At the end of each selection stage, media failing the criteria are omitted from the table.

Stage 1 Selection of media using a DST[a]	Stage 2 Batch & Adsorption isotherm tests	Stage 3 K_{sat} tests
Peat soil	Peat soil	
Processed Peat (Puraflo peat)	Processed Peat (Puraflo peat)	
Compost	Compost	
Woodchip	Woodchip	
Dewatered alum-sludge		
Soil (air dried at 40 °C)		
Sand	Eight types of sands[b]	Five types of sand[b]
Turkish (Yildizeli) zeolite (particle size: 1 − 3 and 3 − 5 mm)	Turkish (Yildizeli) zeolite (particle size 1 − 3 and 3 − 5 mm)	Turkish (Yildizeli) zeolite (particle size 1 − 3 and 3 − 5 mm)
Barley straw	Barley straw (cut into 2 mm lengths)	
Maize		
Silage		

[a] Ezzati et al. (2019).
[b] Collected from quarries in the south of Ireland.

$$q_e = (C_0 - C_e)* \frac{V}{M} \tag{1}$$

where C_e is the concentration of nutrient (DRP or NH_4-N) in solution at equilibrium (mg L^{-1}), C_0 is initial concentration, V is the volume of solution (L), and M is the weight of adsorbent medium (g). q_{max}, an estimate of the maximum monolayer adsorption capacity of the media, was calculated by plotting q_e/C_e against C_e and using the slope and intercept from the following equation [25]:

$$\frac{C_e}{q_e} = \frac{1}{b} * q_{max} + C_e/q_{max} \tag{2}$$

where *b* is the coefficient associated with adsorption energy (L mg^{-1}) to form a complete monolayer on the surface.

The average retention efficiency S (%) [26] was calculated as follows:

$$S = \frac{C_e - C_o}{C_o} * 100 \tag{3}$$

where C_e and C_0 are as defined above.

A constant head method [27] was used to measure the saturated hydraulic conductivity (K_{sat}, m d^{-1}) of the media selected in Stage 2 (Table 1 – Stage 3). This parameter helps in avoiding filter clogging and is considered to be one of the factors that ensures effective operation of filters (Segismundo et al., 2017). The elemental composition of selected media was analysed with a Rigaku NEX CG energy dispersive X-ray fluorescence bench-top spectrometer (EDXRF; Rigaku, Austin, USA).

2.2. Preparation of filter columns

In this experiment, two sets of filter columns were constructed: small columns, with lengths ranging from 0.1 to 0.4 m (internal diameter 0.01 m), and large columns with lengths of 0.4 m (internal diameter 0.1 m) (Fig. 1 and Figure S1 in the Supplementary Material). For both scales the selected media for DRP and NH_4 retention was sand and zeolite, respectively. The packing density for sand and zeolite was 1.8 g cm^{-3} and 0.92 g cm^{-3}, respectively.

Each large column was instrumented with an inlet pipe at the base

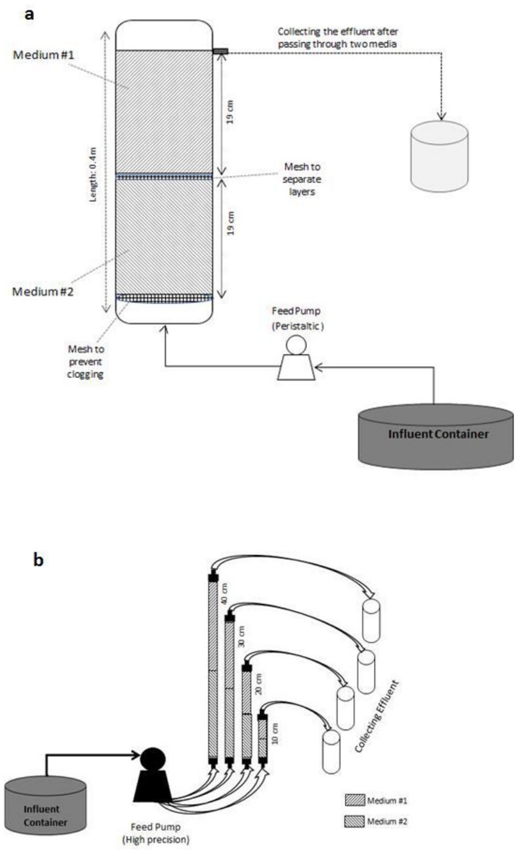


Fig. 1. Schematic diagram of large columns (a) and small columns (b).

and an outlet pipe, which was positioned 0.38 m from the base (after the second media). The media overlay a fine metal mesh, positioned 0.01 m from the base to prevent clogging and to allow for uniform water distribution. The columns were positioned vertically and fixed on a steel frame, with flow entering the bottom of the columns. For the large columns, two media configurations were used to investigate possible differences in nutrient breakthrough. Such an aspect is important in real world filters, where the first medium acts as a bulk removal medium with a large capacity for the contaminant, and the second medium captures the low concentration of the remaining contaminant (e.g. DRP) before discharge. The media configurations were as follows: sand over zeolite or zeolite over sand (each at n = 3) and each layer was 0.19 m deep, giving a total depth of filter media of 0.38 m

For the small columns, polycarbonate tubes with an internal diameter of 0.01 m and lengths of 0.1, 0.2, 0.3, and 0.4 m were used (Fig. 1 (b)). Plastic syringes were connected to either end of the columns, into which acid-washed glass wool (2 g) was placed to retain the media and avoid microbial growth. The columns were positioned vertically and fixed in retort stands, with flow entering the bottom of the columns. As media configuration change made no difference to retention (Section 3.2), a single configuration was chosen i.e. zeolite over sand. To achieve a similar packing density to the large columns for each column length, a mass of 12.4, 24.9, 37.4 and 49.7 g of sand and 6.3, 12.7, 19.1 and 25.5 g of zeolite were used for the 0.1, 0.2, 0.3 and 0.4 m columns, respectively.

2.3. Operation of the filter units

Prior to the start of the experiment, potable water was pumped through the small and large columns to remove background concentrations of DRP and NH_4. When the outlet concentrations were < 0.01 mg L^{-1} and < 0.01 mg NH_4-N L^{-1}, the experiment commenced. KH_2PO_4 and NH_4Cl were used to produce mixed influent water for the large and small columns with concentrations of 1 mg L^{-1} and 1 mg NH_4-N L^{-1}. As the objective of the study was to examine the efficacy of the RSSCT modeling approach in predicting DRP and NH_4 effluent concentration, effects such as competitive adsorption between multiple contaminants were not examined.

Peristaltic pumps were used to pump the influent water to the large columns at a hydraulic loading rate (HLR) of 156 cm d^{-1}, which is similar to the HLR applied in onsite wastewater filtration systems [61]. The large columns were operated for 42 d, with the pumps operational for 5 h per day.

For the small columns, influent water (with a concentration of 1 mg L^{-1} and 1 mg NH_4-N L^{-1}) was pumped into the base of the columns at a HLR 52.8 cm d^{-1} for 6 h per day. The HLR was chosen so as the median empty bed contact time (EBCT) of the small columns was similar to the large columns. The duration of the small column experiment was 11 d, which was the length of time over which both DRP and NH_4-N removals dropped below 100 % to provide enough data for model generation.

2.4. Data collection and analysis

For both column scales, the influent (daily) and effluent (different time points) were sampled in 50 mL tubes and filtered immediately through 0.45 μm filters and analysed for DRP and NH_4-N within 24 h using a Thermo Konelab 20 analyser (Technical Lab Services, Ontario, Canada). During the first 4 days of operation of the large columns, the effluent was sampled after every bed volume. After reaching steady-state conditions (defined as the point at which the effluent concentration began to stabilise), sampling was increased to every 5 bed volumes for another 2 days, and later on increased to every 10 bed volumes. For the small columns, sampling was conducted every two hours. On each sampling occasion, two samples were taken from each column: a sample (5 mL) was taken directly from the effluent (marking the end of the 2-h period and compared with the influent daily concentration) and a sub-sample (50 mL) was taken from the total filtered volume in that 2-h composite period.

In order to model the effluent concentrations of nutrients leaving the large and small columns, the adsorption model of Callery and Healy [24] was used, assuming that pseudo-second order kinetics was occurring for both nutrients ([28] [29–32];):

$$C_t = C_0 - [((A\, V_B^{(\frac{1}{B})} M))/VB]^*[t/(t + K)] \tag{4}$$

where C_t is the filter effluent concentration (mg L^{-1}), C_o is the influent concentration (mg L^{-1}); A, B and K are coefficients representing a constant of proportionality (mg g^{-1}), a constant of system heterogeneity (i.e. existence of multiple types of adsorption sites in the medium) (no units), and a time constant (min), respectively; V_B is the empty bed volumes (the volume of the filter without media) of filtered solution (no units), M is the mass of adsorbent (g), V is the volume of filtered solution (L), and t the empty bed contact time (min) (the average retention time in an empty filter). A coded MS Excel™ file is given in the Supplementary Material.

The coefficients (A, B, and K), determined from the small column study, were fitted using the Levenberg-Marquant algorithm via Solver in Excel to give the least error squared (ERRSQ) of difference between the predicted and the actual effluent concentrations. They were then applied to predict the effluent concentration of the large columns.

As the concentration of NH_4 effluent in the 0.2 to 0.4 m columns was zero during the early bed volumes of the experiment (i.e. 100 % retention was achieved initially), data for the modelling process were taken after 12 bed volumes for all column sizes. From this period onwards, the % retention in the columns dropped below 100 %.

Table 2
Batch experiment and constant head data for maximum adsorption capacity of media (q_{max}; g kg^{-1}), binding energy (k; L mg^{-1}); and selected elemental composition based on XRF analysis of sand and zeolite used in the column experiments.

	q_{max} (g kg^{-1})		k(L mg^{-1})		K_{sat} (m s^{-1})	Na	Mg	Al	Si	Fe	K	Ca	Ti	S	Mn	P
	DRP	NH_4-N	DRP	NH_4-N		% of total composition[a]										
Sand	8.34	0.6	2.87		7.41×10^{-4}	1.3	1.0	11.8	70.9	8.6	4.0	0.1	1.2	0.4	0.2	0.1
Zeolite	6.33	39.52	2.2	9.8	7.39×10^{-4}	–	1.3	12.8	70.0	2.8	7.4	4.3	–	–	0.1	–

P: Phosphorus. Elements presented only for those having > 0.1 % of total composition.
[a] Na: Sodium; Mg: Magnesium; Al: Aluminium; Si: Silicon; Fe: Iron; K: Potassium; Ca: Calcium; Ti: Titanium; S: Sulphur; Ms: Manganese.

2.5. Statistics

To assess if there were any differences in % of nutrient retention capacity based on media configuration in the large columns i.e. sand over zeolite or zeolite over sand, a z-test was conducted. A p value of < 0.05 rejected the null hypotheses i.e. no difference in terms of retention based on the configuration.

3. Results and discussion

3.1. Selection of media

The final selected media for the small and large column experiments were coarse sand (particle size 1 − 2 mm) sourced from the south west of Ireland with a high iron (Fe) content and natural Turkish (Yildizeli) zeolite (particle size 1 − 3 mm). Batch experiment results indicated that both the sand and zeolite had good DRP and NH_4 removals, and had good K_{sat} values for the column experiments (Table 2).

The sand had a q_{max} of 8.34 g DRP kg^{-1} with a binding energy, k, of 2.87 L mg^{-1} (Table 2) This q_{max} was higher than other sands commonly used in filter systems (e.g. Danish sands, which have 0.02 to 0.13 g DRP kg^{-1}; [33]). Zeolite, which is an aluminosilicate mineral, also had good DRP retention, similar to the results of other studies [34–36].

Zeolite, used in the current study to target NH_4 removal, had an aluminium (Al) content of 12.8 % (Table 2), which is within the range of commonly used filter P materials (i.e. 1.3 to over 40 %) [37]. According to Penn et al. [7], high Fe and Al content of a P-sorption material indicates ligand exchange (ion binding to a metal) as the main mechanism for DRP retention rather than precipitation, which would occur in high calcium content materials. Zeolite had a q_{max} of 39.5 g NH_4-N kg^{-1} with a binding energy of 9.8 L mg^{-1} (Table 2). The NH_4-N retention mechanism was either molecular adsorption or ion exchange [38]. Various ranges of q_{max} for zeolite are found in the literature due to variations in country of origin and chemical element [32] e.g. 15.3 − 25 g NH_4-N kg^{-1} ([39,40,41];), 31.9 g NH_4-N kg^{-1} [42], and 40.3 g NH_4-N kg^{-1} [36]. These have resulted in 84 % to complete NH_4-N removal (99 %), depending on operational conditions such as influent concentration, temperature, pH, and adsorbent dosage.

3.2. Retention of DRP and NH4-N in the columns

For the large columns, the DRP retention was initially high at > 95 % for the first two empty bed volumes, V_B, of filtered solution, and decreased gradually to 13 % after > 100 pore volumes (43 V_B) (Fig. 2). One hundred percent NH_4-N retention was achieved for the first 25 pore volumes, but decreased to 80 % after 120 pore volumes (52 V_B) (Fig. 3). Similar trends in NH_4-N retention using zeolite were also documented by other studies ([43] [41,44];). Clinoptilolite zeolite is known to be a very good ion-exchanger [32], and a high adsorption rate has been associated with diffusion of NH_4-N ions [45] through macropores and mesopores to the surface of zeolite [46].

The configuration of the media did not affect DRP or NH_4 retentions ($p > 0.05$). The use of dual media, placed side by side in a filter with each designed to adsorb either P or N from different wastewater types has been previously investigated (e.g. [47]) and, similar to the current study, other studies have found that configuration of the media (N adsorbing media before P adsorbing media, or vice versa) does not affect P or N removal [48].

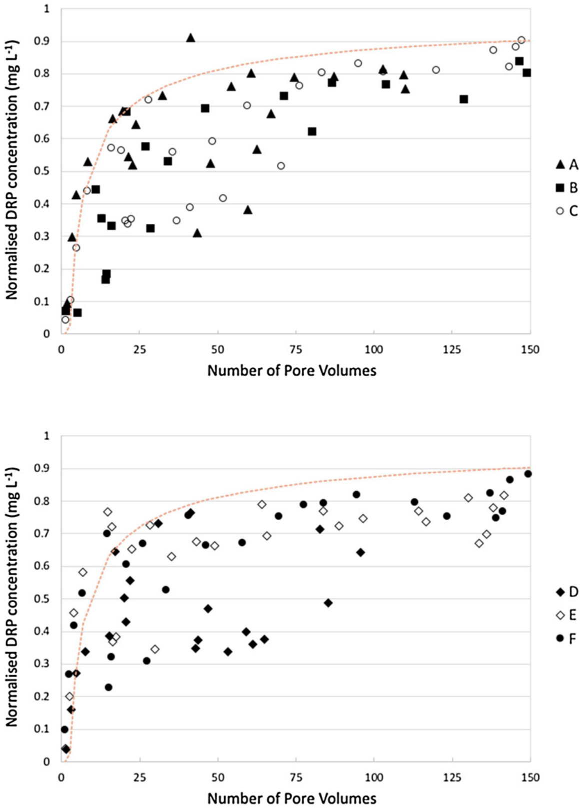


Fig. 2. Normalised DRP concentration (y-axis) vs. pore volume (x-axis) for both configurations of the large columns. The dashed line is the model fit using coefficients from small columns. Top: sand over zeolite (A, B and C). Bottom: zeolite over sand (D, E, F).

The small columns were P-saturated after 1 L of filtered volume (V_B = 50 for the 0.3 m column), whereas the NH_4 saturation of the columns took substantially longer to occur; the 0.1 m column was 80 % saturated after approximately 10 L filter volumes (V_B = 1550) and duration of complete removal was related to the length of the column. Unlike many batch adsorption experiments and large-scale column tests examining the NH_4 removal efficiency of zeolite, RSSCTs operated under continuous loading of a few hours per day has never been investigated. However, the results here are in agreement with other studies, which showed a positive relationship between removal efficiency, mass of adsorbent and contact time [41].

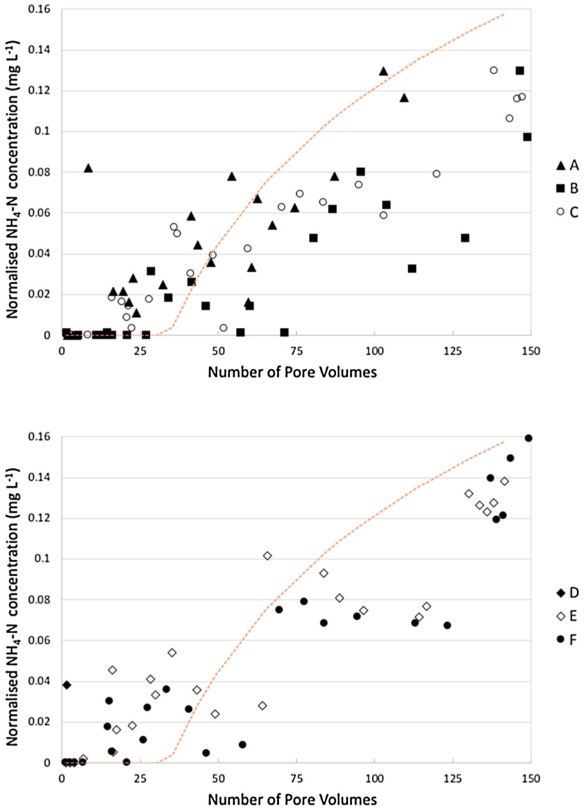


Fig. 3. Normalised NH_4-N concentration (y-axis) vs. pore volume (x-axis) for both configurations of the large columns. The dashed line is the model fit using coefficients from small columns. Top: sand over zeolite (A, B and C). Bottom: zeolite over sand (D, E, F).

3.3. Predicting DRP effluent concentration in large columns using scale column data

Regardless of media configuration, the model developed using the small column data (Table 3, ERRSQ = 5.56) was able to predict the trend of DRP effluent in the large columns. Fig. 2 superimposes the modelled data from the small columns onto the measured data from the large columns and Fig. 4 presents the observed versus modelled data using coefficients from small column tests for each individual column and configuration.

The constant of heterogeneity, B, was a dominant coefficient in predicting effluent concentrations. This is indicative of potentially multiple adsorption mechanisms responsible for nutrient removal which can be explained by the fact that the model is predicting combined removal efficiency of two media with different elemental compositions (Table 2), which are packed into one filter column. According to Callery and Healy [24], the curve produced by Eqn. 4, which is based on second-order kinetics, can indicate the importance of intraparticle diffusion [49] for model prediction within small columns at different lengths. This is shown in Fig. 2, where the tailing of the breakthrough curve has likely been caused by intra-particle diffusion [50]. This may become significant as the surface of the medium/media become saturated or as EBCT increases [24].

3.4. Predicting NH_4-N effluent concentration from large columns using small columns

Complete NH_4-N removal was observed during the initial operational period of the large and small columns, which is consistent with other studies ([51–53,41]). Consequently, the small columns were operated for a longer period of time (11 d in total) to generate enough data for the successful prediction of NH_4-N effluent concentrations leaving the large columns.

Eqn. 4 predicted the behaviour of the filters in retaining NH_4-N (Fig. 3) and Fig. 5 presents observed versus modelled data using coefficients from small column tests for each individual column. The constant of heterogeneity in NH_4-N adsorption, B, was less than DRP (Table 4), which indicates that zeolite, not sand, was the only medium in the columns capable of NH_4-N retention as also observed in the batch experiment. However, the high K values indicate that the adsorption rate did not follow a linear regression with filter depth, as initially proposed by filter bed depth service time (BDST) [54] which has been used by many adsorption studies. The BDST model assumes that intraparticle diffusion is negligible [55], which becomes an important factor as a medium's surface becomes more saturated [24,50]. The proposed model in this study is therefore describing a real-world adsorption system in which several factors control the adsorption (Crini and Badot, 2010), meaning that larger amounts of media and increased contact time may not produce directly proportionally higher adsorption. A similar lack of proportionality between the length of columns (amount of adsorbent) and increase in NH_4-N retention has been reported by Sarioğlu [56]. Although the experiments were carefully designed to provide similar environmental conditions for all columns, there was a small difference between data generated from various large-scale columns. In order to avoid any bias, average effluent data were used to generate model parameters.

3.5. Implications of study for drainage filters

To date, large-scale columns have been mainly used to estimate nutrient saturation and longevity of media to replicate operational conditions ([57,20,58]). However, moving from large-scale columns to RSSCTs would gain financial and labour advantages, whilst not sacrificing the accuracy of model outcomes. This may include considerable

Table 3

Comparison of model parameters, coefficients and ERRSQ values, obtained when (a) fitting Eqn. 4 to DRP concentration data from large columns using model coefficients determined from small columns, (b) parameters at different depths of small columns.

Model Coefficients	(a) Parameters determined using small column data	(b) Parameters at different lengths of small columns			
		Small column depth (m)			
		0.1	0.2	0.3	0.4
A	0.03	280.56	447.05	206.32	669.24
B	2.13	18684.43	18681.93	18687.69	18682.58
K	901	897.99	846.75	972.76	877.25
ERRSQ	5.56	0.04	0.04	0.08	0.052

A: Constant of proportionality.
B: Constant of system heterogeneity.
K: Constant of time.

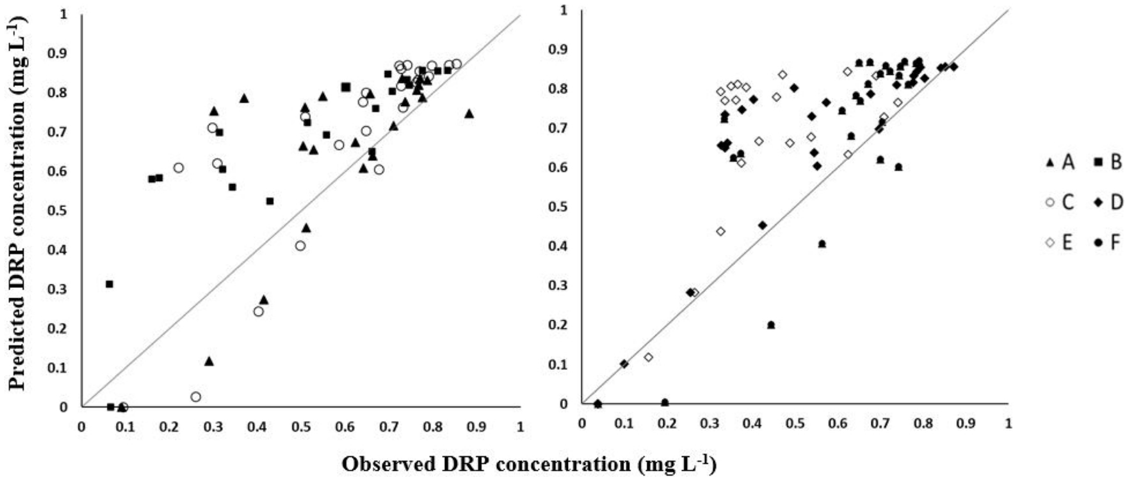


Fig. 4. Observed DRP concentrations versus predicted DRP concentrations using coefficients from small columns. Left: Configuration 1 (zeolite at the bottom, sand at the top) (A, B, C); Right: Configuration 2 (zeolite at the top and sand at the bottom) (D, E, F).

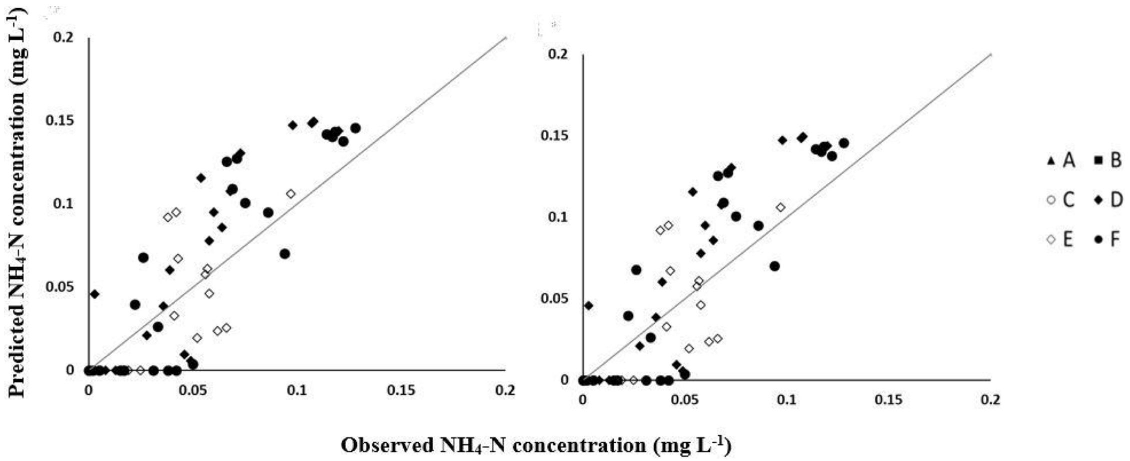


Fig. 5. Observed NH_4-N concentrations of large columns versus predicted NH_4-N concentrations using coefficients from small columns. Left: Configuration 1 (zeolite at the bottom, sand at the top) (A, B, C); Right: Configuration 2 (zeolite at the top and sand at the bottom) (D, E, F).

Table 4

Comparison of model parameters, coefficients and ERRSQ values, obtained when (a) fitting Eqn. 4 to NH_4-N concentration data from large columns using model coefficients determined from small columns, (b) model parameters at different depths of small columns.

Model coefficients	(a) Parameters determined using small column data	(b) Parameters at different lengths of small columns			
		Small column depth (m)			
		0.1	0.2	0.3	0.4
A	0.057	0.051	0.048	0.11	0.11
B	1.13	1.13	1.10	1.04	1.04
K	1961.61	1961.61	1961.61	1961.63	1961.60
ERRSQ	0.13	0.11	0.12	5.23	1.75

A: Constant of proportionality.
B: Constant of system heterogeneity.
K: Constant of time.

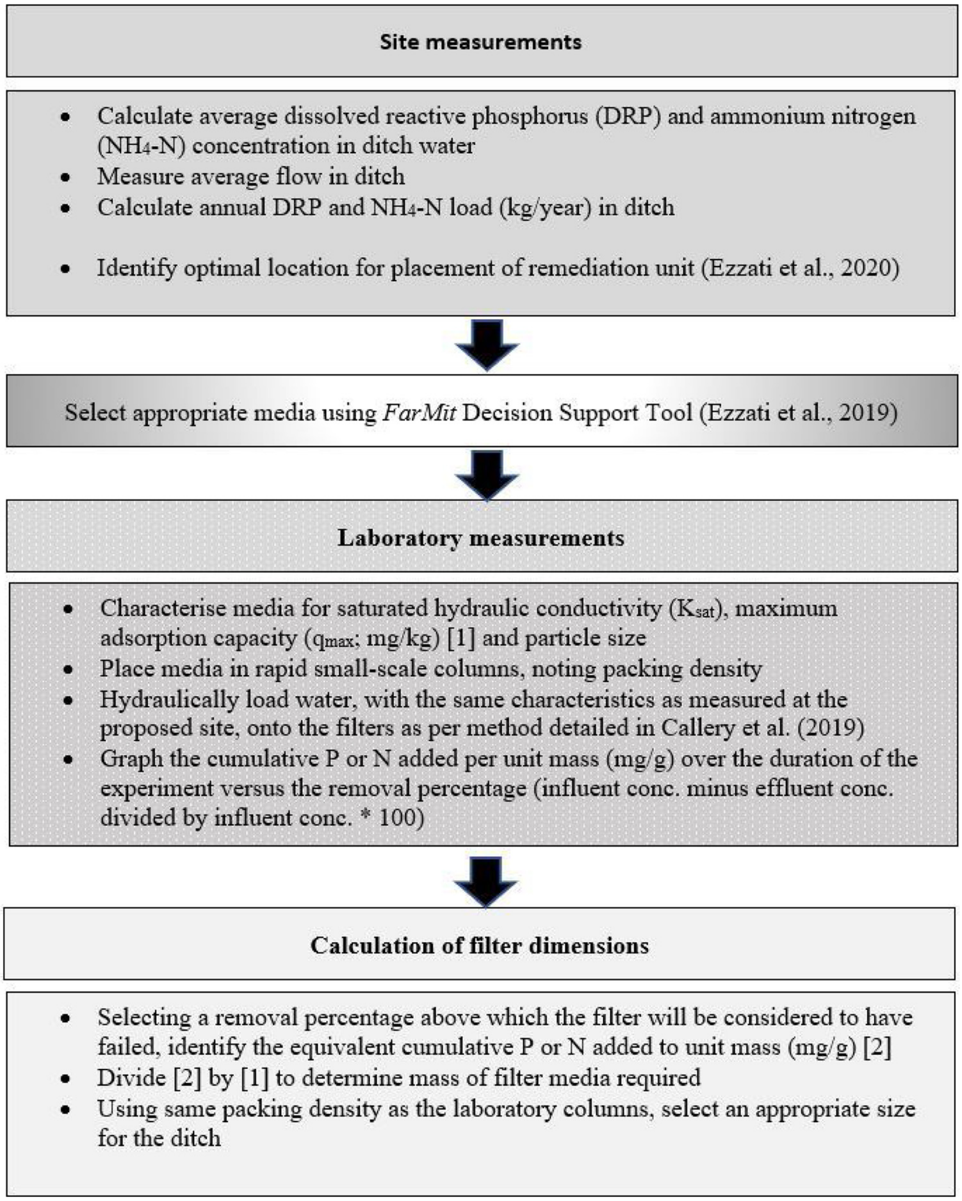
savings on: time required for constructing and operating the columns, labour hours and number of staff required, space required to house the structure and experimental set up, number/capacity of containers, amount of influent (chemical and distilled water), procurement of adsorbent(s) (media) and sampling equipment e.g. tubes, syringes, filter pours; number of pumps, cost of laboratory analysis of water samples; and overhead costs, including electricity and light.

The results of this study validated the model, showing that it could upscale RSSCTs accurately to describe the pattern of large-scale column performance. However, it is important to design the experiment carefully so as the media becomes partially saturated over the duration of the experiment. In the current study, the modelling parameters of Eqn. 4 predicted the NH_4-N effluent concentration in the large columns only after the retention of NH_4-N in the small columns dropped to below 100 %.

Fig. 6 presents a flowchart which shows steps towards the implementation of an efficient field-scale engineered structure filled with adsorptive media, to treat DRP and NH_4-N in drainage water. In general, a successful implementation includes characterisation of nutrient losses in the farm, correct choice of medium/media with a high nutrient retention capacity (and which does not contribute to pollution swapping; [14]), characterisation of the retention capacity, and therefore lifetime, of the selected media, and the identification of an optimal location for installation of structure [8]. This would ultimately provide a sustainable and cost-effective mitigation for the removal of mixed contaminants in agricultural ditches.

4. Conclusions

In this study, rapid small scale column tests were used to predict



Site measurements

- Calculate average dissolved reactive phosphorus (DRP) and ammonium nitrogen (NH_4-N) concentration in ditch water
- Measure average flow in ditch
- Calculate annual DRP and NH_4-N load (kg/year) in ditch
- Identify optimal location for placement of remediation unit (Ezzati et al., 2020)

Select appropriate media using *FarMit* Decision Support Tool (Ezzati et al., 2019)

Laboratory measurements

- Characterise media for saturated hydraulic conductivity (K_{sat}), maximum adsorption capacity (q_{max}; mg/kg) [1] and particle size
- Place media in rapid small-scale columns, noting packing density
- Hydraulically load water, with the same characteristics as measured at the proposed site, onto the filters as per method detailed in Callery et al. (2019)
- Graph the cumulative P or N added per unit mass (mg/g) over the duration of the experiment versus the removal percentage (influent conc. minus effluent conc. divided by influent conc. * 100)

Calculation of filter dimensions

- Selecting a removal percentage above which the filter will be considered to have failed, identify the equivalent cumulative P or N added to unit mass (mg/g) [2]
- Divide [2] by [1] to determine mass of filter media required
- Using same packing density as the laboratory columns, select an appropriate size for the ditch

Fig. 6. Flow chart for the design of an in-ditch field scale engineered structure filled with reactive media for a mixed discharge of NH_4-N and DRP.

effluent DRP and NH_4-N concentrations from much larger columns with good accuracy. As large-scale laboratory filter column tests are time consuming and expensive, but are considered to replicate in-field conditions well, the methodology used in this study will save operational, financial and labour costs, whilst providing good model predictions of DRP and NH_4-N. Future work should consider modelling biological N removal (e.g. nitrate) in filters containing C-rich media (e.g. woodchip), where adsorption is not the dominant removal mechanism. In addition, research should focus on potential uses for saturated filter media.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jwpe.2020.101473.

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