

<b>Project title</b>	Review and evaluation of two phosphate stripping materials for reducing phosphorus concentrations in watercress discharge outflows.
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We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

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# **GROWER SUMMARY**

## **Headlines**

- Current application practice for phosphate fertilisers on watercress farms, shown as necessary for economic, high quality production, may lead to some discharges to watercourses which could potentially conflict with new limits being introduced by regulators under the Water Framework Directive, although further interpretation of the regulations is required.
- Suitable phosphate stripping technologies, when applied in pilot experiments to water discharge outflows on watercress farms, were technically capable of removing a substantial proportion of the soluble phosphate. The practicality of using the equipment on the scale required (given typical water volumes on watercress farms) and their associated capital investment and running costs, appear economically infeasible at present.

## **Background and expected deliverables**

Commercially grown watercress requires significant quantities of added phosphate (P) fertiliser to produce high quality, commercially acceptable crops, as required by the market. These applications can result in high concentrations of P in bed discharge waters, especially when more soluble forms of fertiliser are employed.

Regulators, in response to the Water Framework Directive, have proposed new target levels for total reactive phosphate (TRP) of 40-60 µg TRP/litre for whole farm discharges to watercourses, calculated on an annualised average basis. This project formed part of a series through which the watercress industry is seeking information on limiting significant environmental impacts. A previous study (HDC Project FV 338) looked at the effect of differing P fertiliser applications on P concentrations in discharge levels from beds, but discharges from the whole farm will be taken into account in determining compliance with the new target. Whole farm discharge concentrations will be affected by the proportion of beds fertilised at any one time, retention of P in settlement ponds and the dilution effects of waters from other sources, including groundwater.

An alternative or complementary approach to amending fertiliser application is to remove the phosphate from the discharge waters before it enters the watercourse. This 'stripping' technology has gained acceptance in various fields, including use in sewage treatment works.

As well as the technical challenge presented by applying this technology to watercress farms, the materials and/or techniques involved must also have a benign environmental profile, to avoid replacing one problem with another.

The objectives of this HDC-funded project were:

- a) Through means of a literature review of phosphate stripping, identify two commercially available products / technologies potentially suitable for use on watercress farms.
- b) To determine the pattern of P discharging from watercress farms following P fertilisation.
- c) Undertake an evaluation of the identified products on a commercial watercress farm to assess their potential to reduce phosphate levels in discharges to watercourses.

## **Summary of the project and main conclusions**

The literature review undertaken included a wide range of material including peer-reviewed publications, 'grey' literature and commercial information. In addition, a conference on 'Nutrient recovery from Wastewater Streams', held in Vancouver during 10 -13 May 2009, was attended. The conference brought together over 200 delegates and focussed on phosphate and nitrate recovery to build recycling strategies and hence sustainability.

The materials and their associated equipment, and their suitability for use on watercress farms, were evaluated according to the following criteria:

- Ability to strip out P in high water flow situations
- Cost of product per tonne
- Running costs
- Cost of installation equipment to hold product
- Duration of P stripping ability and decline curve
- Disposal costs of materials
- Product safety data
- Environmental safety

The Literature Review is available as a separate report from the HDC.

An analysis of the findings initially identified 3 commercially-available products for potential trialling: Baraclear™, Phoslock™ and Virofilter™, with Phoslock™ and Virofilter™ being the preferred materials/technologies for evaluation by the project. The two systems were evaluated at separate watercress sites in Hants.

Phoslock™ is a bentonite clay (95%), with a coating of the rare earth element lanthanum. In the trial it was applied by adding the product directly to the discharge water upstream of the first settlement pond. Virofilter™ consists of treated residues derived from bauxite mining, stabilised within cement granules. This material was packed within an upright metal cylinder in the trial, with the bed discharge water diverted through the filter material to assess its efficacy. Residence time within the cylinder could be adjusted to try and regulate the amount of phosphate removed.

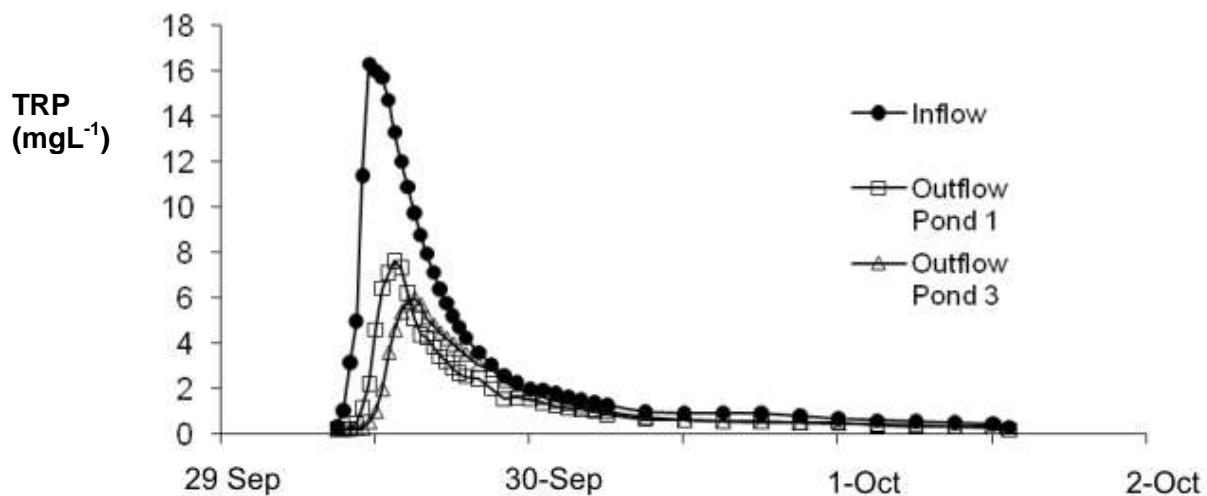
Preliminary monitoring of water flows was undertaken at 3 potential trial sites in July and August 2009 to determine the volumes of water that would needed to be 'P-stripped'. Areas of watercress beds were fertilised with either slow-release or more soluble compound fertiliser and subsequently analysed for P to determine discharge patterns. Two of the sites were selected for trials work, on the basis of more readily measurable water flow rates. This initial work also enabled dosage calculation for the stripping materials based on the anticipated phosphate loading.

In this initial monitoring work, when either a soluble compound fertiliser (19:14:14, supplying 45kg/ha P<sub>2</sub>O<sub>5</sub>) or an organic slow-release fertiliser (7.5:12:7.5, supplying 72kg/ha P<sub>2</sub>O<sub>5</sub>, 79% of which was water-soluble) was applied, peak P concentration in the discharge water appeared shortly (1-9 hours) afterwards and subsequently declined. This was consistent with the findings of Project FV 338. Total reactive phosphate (TRP) concentrations are apt to vary significantly through the growing season, being dependent on fertiliser application practice, bed cleaning operations and other factors, including interaction with bottom sediments. As in the preceding project, TRP concentrations in discharge waters were higher following the use of soluble fertiliser compared with slow-release fertiliser. Sampling at both inlet and outlet of the settlement ponds showed that they had some effect in reducing the amount of total reactive phosphate (TRP), but the amount depended on residence time within the ponds, which could be quite short. Use of soluble fertiliser also led to increases in soluble N and K in the discharge water, which, particularly as regards ammonium-N could potentially also have some environmental impact.

For the main experiments, fertiliser was again applied to the beds as for the preliminary monitoring.

### *Phoslock<sup>TM</sup>*

Following application of fertiliser, as undertaken in the preliminary monitoring, 2 tonnes of Phoslock<sup>TM</sup> was applied to discharge waters on 29/30 September 2009 over a 20 hour period draining 2.94 ha of watercress beds at the Drayton Farm site by adding it to the discharge channel upstream of the first settlement pond. The application rate was varied over time to match the anticipated pattern of phosphate discharge.



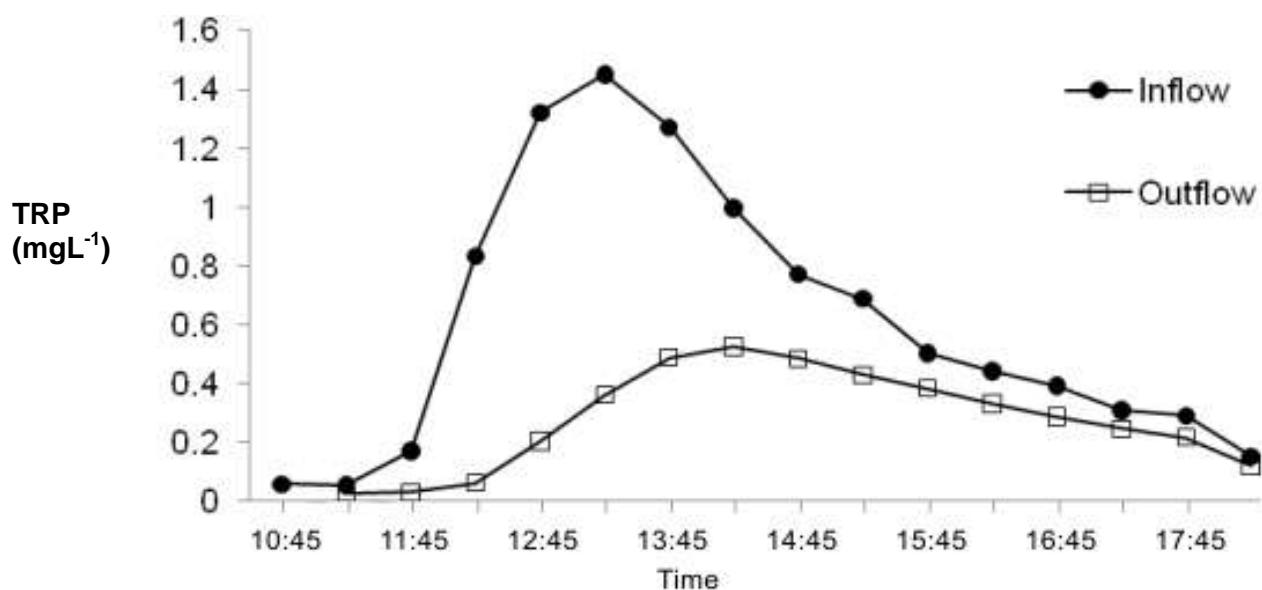
### **TRP concentration profiles at each discharge monitoring point at Drayton farm after phosphate fertilization and application of Phoslock<sup>TM</sup>**

Taking into account the reduction in TRP achieved by the settlement ponds alone, the Phoslock<sup>TM</sup> reduced average phosphate concentration by 50% on a time-weighted basis (to take account of uneven sampling periods). Some of the water analyses taken from settlement pond outlets during the course of the experiment also showed elevated levels of nitrate, which reflected the highly soluble nature of the fertiliser used at this site. This confirmed a recommendation from HDC Project FV 338, that use of highly soluble fertilisers should be restricted where possible, consistent with the crop requirements of the commercial production systems utilised.

Water flows from the final settlement pond were clear, though levels of lanthanum, the constituent of Phoslock<sup>TM</sup> which binds the phosphate, increased from 'not detected' (prior to the addition of Phoslock<sup>TM</sup>) to a maximum of 1.7 mg/L. However, this is not considered a risk to the environment or to human health.

### Virofilter<sup>TM</sup>

For this experiment approximately 2 tonnes of the Virotec<sup>TM</sup> filter material was contained within an upright cylinder and discharge water draining 0.17ha of watercress beds was routed through it. Fertiliser was applied to the relevant beds, as for the preliminary monitoring, on 6 October 2009, with the water being held within the Virotec<sup>TM</sup> filter material for 25 minutes. Sampling was undertaken for phosphate before and after treatment and analysis was undertaken for a range of other elements. A pump failure at this stage brought the trial to a premature end, but it was repeated on 16/17 December 2009, increasing the bed discharge water residence time within the cylinder firstly to 64 and then 100 minutes. TRP concentrations were reduced following treatment by 52% (using the farm's slow-release fertiliser), and 63% and 75% (using the soluble 19:14:14 fertiliser) for the 25, 64 and 100 minutes residence times respectively. On a time-related basis, this equated to reductions in TRP of 39%, 50% and 92% respectively.



**TRP concentration profiles at the inflow and outflow of the pond at Pinglestone farm after phosphate fertilization and filtering through Virotec filter media. Residence time was 64 minutes.**

TRP concentrations were quicker to peak with the highly soluble fertiliser and the highest levels at the inflow to the equipment were approximately double those resulting from the application of the slow-release fertiliser. There were marked increases in the sulphate and sodium levels recorded for all residence times, but other changes were either modest or of short duration. A very small rise in pH was recorded. The organic slow release fertiliser did not lead to any increase in nitrate levels at the settlement pond outlet, but a marked elevation in ammonium-N followed the 19:14:14 fertiliser application. This was less notable than at the other experimental site, but still undesirable.

Pumping the discharge water through the Virotec filter media did reduce peak ammonium-N concentrations from 1.45 mg/L to 0.66 mg/L and from 1.33 mg/L to 0.38 mg/L for 1 and 1.5 h residence times respectively, although this was based on a limited number of samples.

## **Financial benefits**

These pilot trials successfully demonstrated that substantial reductions in phosphate levels in waters discharged from watercress beds can be achieved technically. The exact regulatory requirements for discharge levels have however to be confirmed and hence the extent to which changes to current practice may be required on say a single day, or over the whole season, remains unclear. As plant and equipment would have to be designed individually for each watercress farm, it is not possible to quote specific costs for the materials and equipment used. Additionally the project was not designed to test the duration over which the Virofilter material would function successfully, before it became saturated, which could have a significant effect on running costs. However, based on the size of equipment trialled/quantity of materials used, on a limited proportion of the water outflows of single farms, it is evident that the sizing of the equipment and the quantities of consumables required would be very substantial; it would be premature to consider this technology as economically sound at this stage, especially given the very competitive market conditions in which watercress is produced.

## **Action points for growers**

- Keep a watching brief on phosphate stripping technologies to identify any techniques or materials likely to offer effective phosphate removal combined with limited residence time (given the high water volumes used on watercress farms) and which could offer cost-effective capital investment and running costs
- Review the outputs of all recent work on watercress P nutrition, including HDC projects FV 302 and FV 338, to enable the industry to contribute effectively to the proposed development of the Environmental Code of Practice for Watercress with the EA.
- The area of bed fertilised at any one time has a very large influence on the peak concentrations measured in the discharge and that one method of reducing the P loss from waterbeds is to spread out fertilisation as much as possible.

## **SCIENCE SECTION**

### **Introduction**

A previous HDC Project (FV 338 Watercress: evaluation of fertiliser regimes for the efficient and sustainable use of phosphate fertilisers by watercress growers), concluded that current commercial rates of applied phosphate fertiliser (e.g. 2,200 kg/ha P<sub>2</sub>O<sub>5</sub> per year for Maxwells Farm) are justified to maintain acceptable commercial standards of watercress production in terms of quality and economic yield. In a comparison of different rates of fertiliser application, watercress crops responded to the higher applications of P to produce commercial, high quality crops. In the trial, lower rates of applied P fertiliser resulted in sub-standard quality (namely stem purpling), which would lead to crop rejection.

The use of higher commercial rates of applied phosphate (P) was associated with higher P concentrations in the outflow from watercress beds. Bed discharge P concentrations were also higher when the more soluble 19:14:14 fertiliser was used compared to a less soluble Fibrophos fertiliser (0:22:12). There are however occasions in the growing season when applications of more soluble P are required to maintain crop quality and yield. Consequently, while adherence to a best practice policy (as outlined in HDC report FV 338) of minimising the use of high solubility sources of P is desirable, in practice this cannot always be sustained throughout the year.

Although project FV 338 indicated that commercial rates of fertiliser should not be reduced, new phosphate target levels have been proposed by the water regulators as part of the implementation of the EU Water Framework Directive (WFD). The target levels appropriate for streams/rivers draining chalk landscapes (relevant to watercress production) are an annualised average of 40-60 µg TRP/litre, where TRP is the total reactive form of P routinely measured by the Environment Agency. While every effort has been made by the watercress industry to reduce discharge concentrations through optimum flow, sediment and crop management, namely by the use of settlement ponds and rotational fertilizing and harvesting on farms, discharge P concentrations may remain at unacceptably high levels, especially after application of water-soluble fertilisers. At the time of writing, it is unclear whether these levels will in fact be problematic under the new regulations.

The proposed target concentrations, which apply to the discharge from the whole farm (and not just from individual beds) to the watercourse, may therefore not be met. Project FV 338 did not include an assessment of the pattern of discharge P concentrations from the watercress farm, only the pattern of P discharge from individual beds.

The two may differ at any one time due to (a) dilution from non-fertilised beds on the farm, (b) retention of P within the settlement ponds and (c) contributions of clean water flow from non-bed sources, including the underlying groundwater. Clearly the range in P concentrations discharged from the farm needs to be quantified to provide a framework for implementation of potential solutions.

One potential solution for lowering the range and average P concentrations discharging from watercress farms is to remove the phosphate from the discharge water before it enters the watercourse using chemical and physical precipitation, known as phosphate (P)-stripping. A demonstration of one P-stripping material (Virotec<sup>TM</sup> filter media) held in November 2008 at The Watercress Company farm suggested that the technique has considerable potential when utilised *in-situ* to remove phosphate from flowing discharge water. There are a number of other alternative stripping materials that could be used effectively to reduce P in discharge waters after the sediment has been removed by the settlement ponds, but a review of these materials is required to evaluate both their potential where high volumes of water need to be filtered and to consider their environmental safety when the discharge water is being released back into a watercourse.

A review of all available stripping materials would provide some insight into their potential effectiveness for P removal within the watercress industry but would also ensure that the materials would not pose a risk to wildlife habitats from environmental contamination further downstream of the watercress farm. The Environment Agency stressed at the Annual Review of FV338 in December 2008, when phosphate stripping techniques were discussed as a possible way forward, the importance of fully considering, at the initial product review stage, the environmental safety of any materials to be used in the discharge water, before any trial should commence. A number of stripping materials are available but for application reasons many will not be applicable to the watercress industry or may pose an environmental risk.

The objective of this follow-on project was to determine the pattern of P discharging from watercress farms and whether phosphate can be removed from the discharge waters to an acceptable level on a commercial farm before it is returned to the watercourse. This would allow the industry to continue to supply sufficient phosphate to meet the demands of the watercress crop but without exceeding the target TRP concentrations set by the Environment Agency. Following a review of the phosphate stripping products available, two of the most promising products were evaluated in a commercial situation.

This scoping study provided an opportunity to investigate the practicalities of these P-stripping materials before the considerable financial investment likely to be involved in installing the equipment on farms was evaluated by the industry. This practical investigation would not only ensure that the materials removed phosphate effectively in the farm situation, but also provided information on how the materials should be most effectively utilised and their capabilities.

The project objectives were:

Objective 1. To undertake a review of phosphate stripping materials for [potential] use in watercress production.

Objective 2. Evaluation of two materials for their effectiveness at removing phosphate from watercress discharge waters.

## **Materials and methods**

### **Review**

A review of available literature on phosphate stripping materials and technologies was undertaken, including attendance at a conference on ‘Nutrient recovery from Wastewater Streams’ during 10-13 May 2009. The conference brought together various waste stream industries, regulators, researchers, process engineers and commercial managers to develop a broad-based, interdisciplinary understanding of processes and techniques for phosphorus (and nitrogen) recovery from wastewater streams, as well as reuse.

The literature review included peer-reviewed publications, grey literature and commercial information. The materials and their associated equipment, and their suitability for use on watercress farms, were evaluated on the following criteria:

- Ability to strip out P in high water flow situations
- Cost of product per tonne
- Running costs
- Cost of installation equipment to hold product
- Duration of P stripping ability and decline curve
- Disposal costs of materials
- Product safety data
- Environmental safety

A subsequent SWOT analysis was undertaken, to determine a shortlist of products with potential for more detailed evaluation. Further consideration reduced this list to two commercially-available products for evaluation in the on-farm trials (see separate FV 338a Literature Review report).

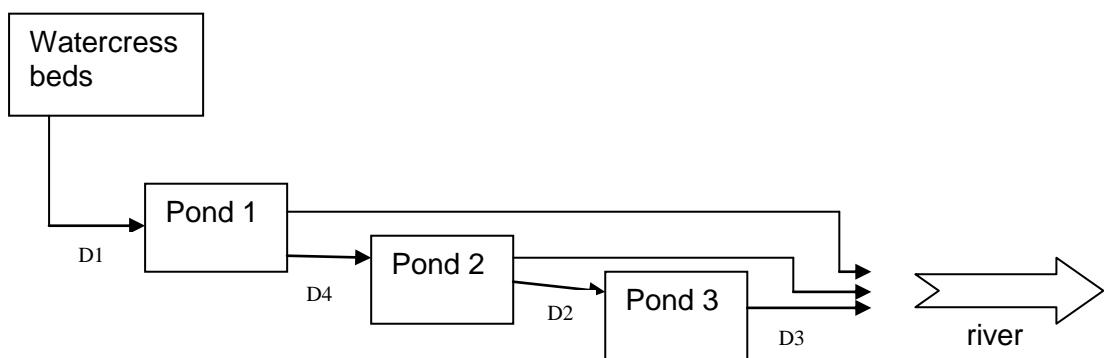
### Comparison of two P-stripping materials

Following the recommendations from the review, two potential P-binding materials (Phoslock™ and Virofilter™) for reducing the discharge concentrations of TRP from watercress farms to acceptable levels were investigated at two farm sites (Drayton and Pinglestone, Hants) to assess their cost-effectiveness and practicality. Preliminary information was obtained on the background water chemistry, range in TRP concentrations and flow rates discharged to the watercourse from three potential trial sites (Drayton, Fobdown and Pinglestone, Hants) to enable the required quantities of the two materials to be calculated and appropriately positioned.

### Preliminary monitoring

Discharge flow rates at three potential trial sites (Drayton, Fobdown and Pinglestone) were monitored using a Valeport (Model 801) electromagnetic flow meter on six occasions during July and August 2009 to determine the volumes of water that needed to be P-stripped. At Drayton, the discharge from the watercress beds passes through a series of settlement ponds to remove sediment and P, schematically drawn in Figure 1a. Discharge flow rates were monitored at the inlet to pond 1 (D1), the inlet to pond 3 (D2) and at the outlet of pond 3 (D3), which then discharges to a stream. At Fobdown and Pinglestone, where bed discharge flows through a single settlement pond only, flow rates were monitored at the inflows (F1 and P1) and outflows (F2 and P2).

(a)



(b)



**Figure 1.** The Drayton site showing (a) schematic diagram of the three pond system and (b) stream channel into which the beds discharge upstream of pond 1.

On each occasion, the water at each flow monitoring point was sampled for determination of a range of element (anion and cation) concentrations in order to characterise the background chemistry of the discharge water. Analysis was undertaken by the Environment Agency. To establish the pattern of P concentrations in the discharge following fertiliser application, the discharge was also automatically sampled for a period of 24 h following an application of P fertiliser at each flow monitoring point on 29 July 2009 and TRP determined on each sample. Samples were taken every 30 minutes for 3 hours, every hour for the subsequent 3 hours and every 3 hours thereafter. Automatic sampling was carried out at Drayton (representing a three pond system) and at Fobdown (representing a single pond system).

At Drayton, the beds A-D (total fertilised area of 1.58 ha) were fertilised with water-soluble compound (blended) NPK fertiliser (19:14:14) supplying 45 kg/ha of phosphate ( $P_2O_5$ ) on the 29 July. Beds E-G (total fertilised area 1.36 ha) were fertilised on the 30 July. This is the same fertiliser as used in the previous project, FV 338. At Fobdown and Pinglestone, the beds (total fertilised areas of 0.4 and 0.17 ha, respectively) were fertilised with the farm's own-brand organic slow-release blended fertiliser (7.5:12:7.5) supplying 72 kg  $P_2O_5$ /ha of which the contained phosphate was 79% water-soluble. Products were as used for commercial practice.

## **Field comparison of two P-stripping materials**

The review concluded that the two most appropriate P-stripping materials to test on a commercial holding were Phoslock™ and Virotec™ filter media (Virofilter™). Phoslock™ is bentonite clay coated with the rare earth lanthanum (La). The combination of the high exchange capacity of the clay and high specificity for P by lanthanum has been shown to be highly effective at removing various forms of P (polyphosphates as well as orthophosphate) from water over a wide pH range 6-10 (Douglas *et al.*, 2004). Bentonite constitutes 95% of the product. Virofilter™ is composed of granules (10-25 mm) of a Bauxite mining residue which had been neutralised with sea-water and homogenised within a cement-based medium. The residue contains iron (Fe), aluminium (Al) and calcium (Ca) as the principal P-binding elements and has been shown to be very effective at reducing P concentrations in wastewater streams – see review section.

These materials/systems were approved by the Environment Agency for use in this project.

### *Phoslock™*

Phoslock™ was trialled at Drayton Farm where the discharge entering the settlement ponds drains a watercress area of 2.94 ha. The Phoslock™ was applied to the inlet channel upstream of pond 1 (Figure 1a, 2) on 29 September 2009 over a 20 hour period, at doses designed to match the expected pattern of TRP concentrations based on the preliminary monitoring. A total of 2 tonnes of Phoslock™ was applied to bind the 8.6 kg of orthophosphate that needed to be removed from the water based on the results of the preliminary monitoring. The water flow at the Phoslock™ dosage point was increased to create the turbulence needed for optimum mixing of the Phoslock™ (Figure 2) in the inlet channel. The entry point of the watercress bed discharge with the river is ca. 700 m upstream of pond 1.

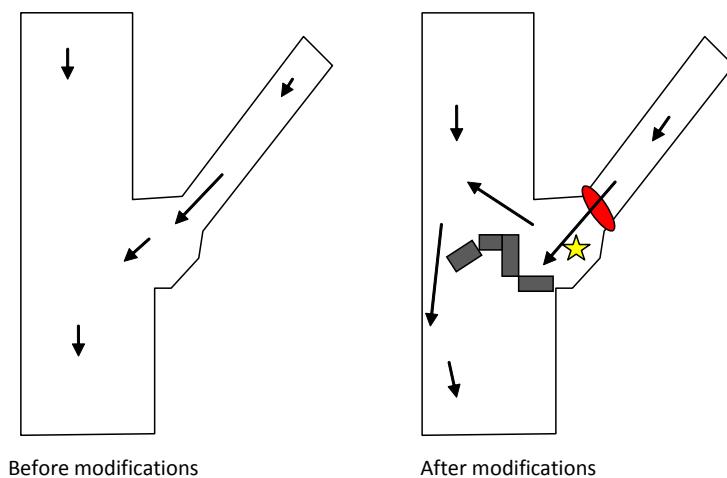
Fertiliser was applied to the watercress beds by hand at the same rate (45 kg P<sub>2</sub>O<sub>5</sub>/ha) as used in the preliminary monitoring. The TRP concentrations in the inlet channel (D1), the discharge from pond 1 (D4) and from pond 3 (D3) were continuously monitored for a total of 52 hours. Samples were taken every 30 minutes for the first 10 hours, every hour for the subsequent 11 hours and every 3 hours thereafter for determination of TRP. Every fourth sample was also sub-sampled for determination of a range of elements to determine any changes in background chemistry and any increase in contaminant elements applied in the Phoslock™ (i.e. lanthanum). Three spot flow measurements were also taken at each monitoring point during the trial to compare with the preliminary monitoring data.

## Virofilter™

The Virotec™ filter media was trialled at Pinglestone Farm where the discharge water drains a watercress area of 0.17 ha (four beds) and enters a single settlement pond before discharging to the stream. Approximately 2 tonnes of the filter media were packed into a tall metal cylinder ( $2\text{ m}^3$ ) with inflow and outflow entry points (Figure 3).

The farm's own-brand slow-release phosphate fertiliser was applied to the beds on the 6 October 2009 at the same rate (72 kg/ha) as previously used in the preliminary monitoring campaign. The discharge water from the outlet of the settlement pond was pumped through the cylinder from bottom to top to maximise the filtering effect of the media, before being returned to the stream channel. The residence time through the cylinder was controlled by the flow rate through the pump and was 25 minutes (a flow rate of  $4.8\text{ m}^3/\text{hr}$ ). The water entering and leaving the cylinder was automatically sampled for a total period of 15-18 hours for determination of TRP. This time period was smaller than at Drayton because of pump failure. Every fourth sample was also sub-sampled for determination of a range of elements to determine any changes in background chemistry and any increase in contaminant elements applied in the Virotec™ (Fe, Al, Na, Ca).

In view of the pump failure, the Virotec™ was re-trialled on 16-17 December 2009 using exactly the same procedure except that the residence time was increased to 64 minutes (day 1, corresponding to a flow rate of  $1.8\text{ m}^3/\text{hr}$ ) and 100 minutes (day 2, corresponding to a flow rate of  $1.2\text{ m}^3/\text{hr}$ ).



**Figure 2.** Diagram showing the junction of the two streams (Drayton Farm) before and after modifications. The arrows indicate flow direction. The length of the arrow is an indication of flow velocity. The circle indicates a blockage created to increase waterfall depth. Grey blocks indicate the location of concrete blocks placed in the river to obstruct normal flow. The star indicates the Phoslock injection point, which is also the location of the highest turbulence.



**Figure 3.** Position of the tank containing the Virotec filter media in relation to the settlement pond (Pinglestone Farm).

### **Analytical details**

All analyses were undertaken by the Environment Agency according to their standard analytical methods and protocols. In addition to TRP, the range of determinands measured included: pH, conductivity (Cf), suspended solids (SS), ammonium-N ( $\text{NH}_4\text{N}$ ), nitrate-N ( $\text{NO}_3\text{N}$ ), nitrite-N ( $\text{NO}_2\text{N}$ ), total oxidised N (TON), sulphate-S ( $\text{SO}_4\text{S}$ ), sodium (Na), potassium (K), calcium (Ca), manganese (Mn), iron (Fe), boron (B), barium (Ba), strontium (St), lanthanum (La) and aluminium (Al). Not all determinands were measured on all samples and not all samples submitted to the Environment Agency were analysed.

## **Results**

### **Review of P-stripping materials**

Examination of the literature and the range of processes used to remove P in sewage treatment works and wastewater applications such as constructed wetlands showed that the

methods used commercially to remove P most efficiently often employed materials combining adsorption and precipitation processes.

Two distinct approaches to P-stripping were being widely used; chemical dosing appeared very effective both to remove P and cap P release from bottom sediments in standing waters, whilst a wide range in P-binding filter materials showed variable effectiveness according to residence times and environmental conditions. Chemical dosing may also require strict health and safety control, with bunded areas for hazardous or dangerous goods. Filter materials had the advantage of longevity and potential re-use as slow-release fertiliser materials. The high water flow rates through watercress beds would pose a challenge for both approaches.

The final scope of the project was limited by the amount of EA funding available, which restricted the number of options that could be trialled. Adapting existing methods and technologies for P removal which operate successfully in managed or cultivated wetlands, waste water treatment/purification works or by remedial dosing to reduce eutrophication in lakes, appear to offer growers the most promising options - but successful management and economic viability are also requirements for their use on watercress farms. While high levels of P in waste water from sewage treatment works may require multiple treatments to ensure adequate reductions in P loading, discharges on watercress farms should only require a single application or only one treatment method to reduce phosphate levels adequately.

Further details are provided in the Project Literature Review.

### **Preliminary monitoring**

The flow rates measured at each monitoring point are shown in Table 1. Flow rates varied considerably between the sites, between monitoring points and indeed between sampling occasions. At Drayton, flows averaged over the six sampling occasions were 0.164, 0.087 and 0.065 m<sup>3</sup>/sec at D1, D2 and D3, respectively. At the inlet to pond 1 (D1), this average flow rate is equivalent to 14 million litres/day, with a range of 11-17 million litres/day. These are substantial amounts of water when considering the practicalities of P-stripping. At the outlet to pond 3 (D3), the average flow rate was equivalent to 5.6 million litres/day (range 3-7 million litres/day). There was a large drop in flow rate equivalent to ca. 5 million litres/day between the inlet to pond 1 (D1) and the inlet to pond 3 (D2) and further reductions between the inlet and outlet of pond 3 (D2-D3). This flow rate reduction is due to the regulated diversion of pond water from the first two ponds to the adjacent stream to maintain a satisfactory level of water in the pond system (Figure 1a). However, for the duration of the main trial, these diversions were not operated to improve consistency. Some drop in flow

may also be expected due to groundwater seepage and evapotranspiration during normal operation.

At Fobdown and Pinglestone, the average flow rates at the pond inlets were 0.053 and 0.090 m<sup>3</sup>/sec, respectively, which is equivalent to 4.6 and 7.8 million litres/day. At Pinglestone, the average flow rate at the pond outlet was almost identical to the inlet flow rate (7.6 million litres/day), but at Fobdown the flow rates at the pond outlet were very variable and considerably increased (Table 1). The latter is thought to be due to the difficulty in measuring flow rates at the discharge pipe at Fobdown, which was often below the water level in the stream it was discharging to. The Fobdown site was therefore considered unsuitable for further trial work.

**Table 1.** Flow rates (m<sup>3</sup>/sec) at each discharge monitoring point at Drayton, Fobdown and Pinglestone (Hants) over six sampling occasions during July and August 2009.

Date	Drayton			Fobdown		Pinglestone	
	D1	D2	D3	F1	F2	P1	P2
22/7/09	0.184	0.107	0.080	0.064	2.67	0.093	0.091
27/7/09	0.164	0.090	0.072	0.065	2.91	0.091	0.097
29/7/09	0.162	0.080	0.069	n.d.	n.d.	n.d.	n.d.
04/8/09	0.192	0.106	0.080	0.052	0.201	0.129	0.097
10/8/09	0.157	0.065	0.044	0.048	2.60	0.069	0.079
17/8/09	0.127	0.072	0.044	0.038	0.096	0.068	0.079
Mean	0.164	0.087	0.065	0.053	1.696	0.090	0.088
S.D.	0.023	0.017	0.017	0.011	1.417	0.025	0.009

Drayton: D1 – inlet to pond 1; D2 – inlet to pond 3; D3 – outlet to pond 3;  
 Fobdown: F1 – inlet to pond; F2 – outlet to pond; Pinglestone: P1 – inlet to pond; P2 – outlet to pond.

S.D. – standard deviation      n.d. – no data

The background chemistry of the discharge water was similar at all the sites, which were in relatively close proximity to one another (<5 miles) and typical of chalk groundwater (Table 2). Only one background chemistry sample analysis was carried out by the Environment Agency at the outlet to pond 3 at the Drayton site (D3), compared with five or six analyses at the other sample points. Most determinands were present at low concentrations, but with notably high Ca levels (89-121 mg/L), which can influence the effectiveness of P-stripping

materials (see Literature Review), and high nitrate N ( $\text{NO}_3\text{N}$ ) concentrations (5-6 mg/L) which represent contamination from nitrogen fertilisers (and possibly manures) in the wider catchment area. Ammonium-N concentrations were low (<0.3 mg/L). Concentrations of suspended solids (SS) were quite variable but usually <20 mg/L, and often <10 mg/L.

Continuous monitoring of the discharge water after fertilisation showed a consistent pattern of TRP concentrations increasing to a peak and declining thereafter on day 1, 29 July (Figure 4). On day 2, TRP started to increase again after fertilisation of the remaining beds. At Drayton, peak TRP concentrations of 3.8, 2.5 and 2.4 mg/L were measured 6, 6 and 9 hours after the start of sampling at D1, D2 and D3, respectively. This suggests that the residence time of ca. 3 h through the pond system reduced peak inlet TRP concentrations by 37%. Time-weighted average TRP concentrations were also calculated for the monitoring period due to the uneven sampling periods. These calculations assume that flow rates over the monitoring period were constant at each monitoring point. The time-weighted average TRP concentrations at D1, D2 and D3 over day 1 (excluding the rise in TRP on the second day) were 0.89, 0.81 and 0.78 mg/L, respectively. This represents a real reduction in average TRP concentrations of only 12% as bed discharge water goes through the pond system.

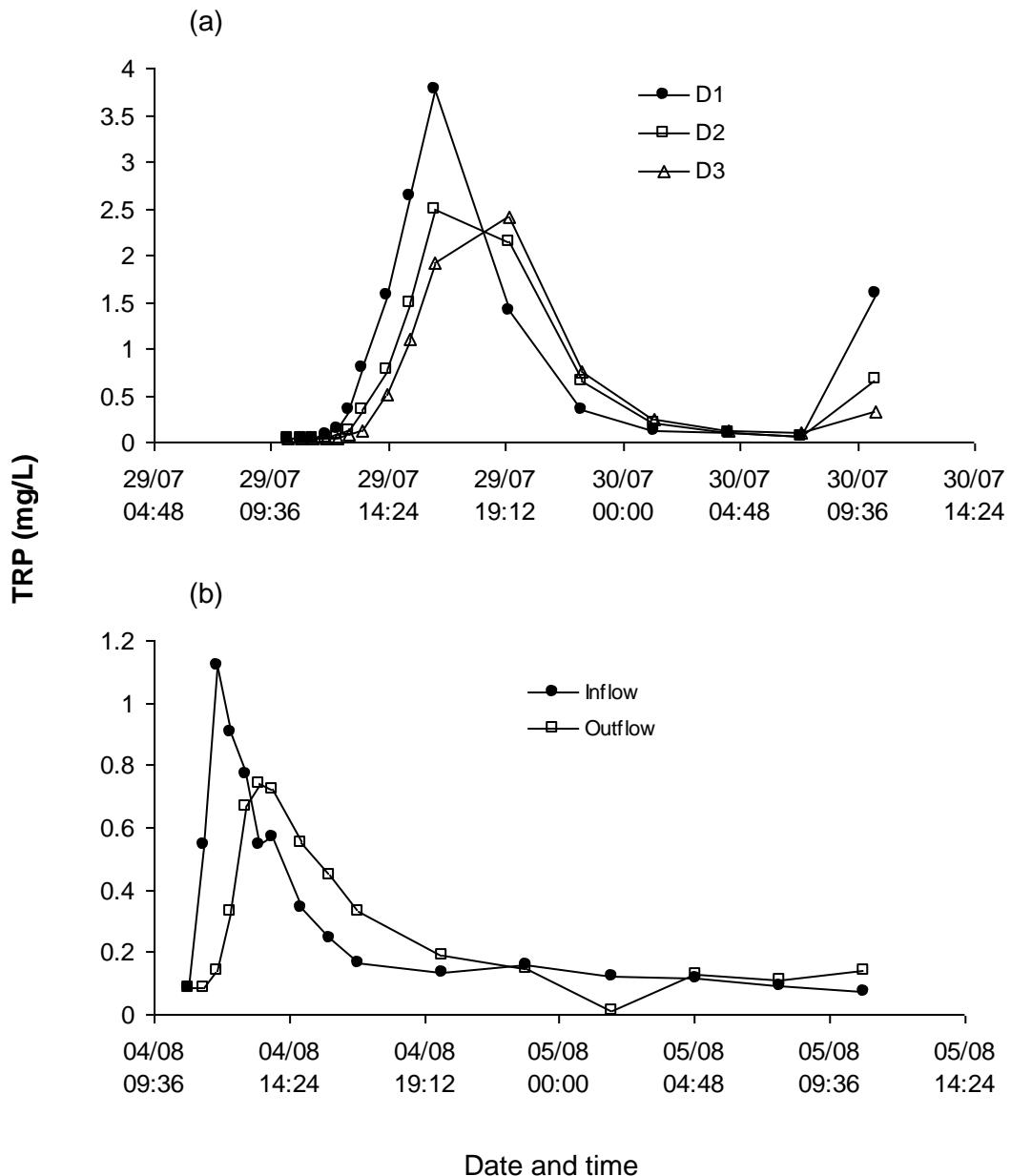
At Fobdown, peak TRP concentrations of 1.12 and 0.74 mg/L were measured 1 and 2.5 hours after the start of sampling at the inlet and outlet, respectively. The residence time is therefore very short (1.5 hours) reducing the TRP concentration by 34%. However, the time-weighted average TRP concentrations at the inflow and outflow over the full monitoring period were both 0.22 mg/L. The time-weighted average TRP concentrations measured at Drayton were therefore noticeably greater than those measured at Fobdown despite a higher background TRP concentration at Fobdown. Spot TRP concentrations at the inlets to ponds before any fertiliser was applied were 0.088 mg/L at Fobdown and 0.037 mg/L at Drayton.

It should be borne in mind that these experiments were in effect pilots, designed to examine the candidate material's potential for P removal and practicality of use. Thus, although measured levels of TRP following P-stripping exceeded the new regulatory level of 40-60 ug/L (0.04 – 0.06 mg/L), further calculation and trialling would be required to more closely align discharge water flows and P content with equipment capacity and design, to determine physical requirements and costs on an individual farm basis. In addition, the interpretation of what constitutes an 'average annualised figure', as described by the regulators, is an important consideration in concluding what additional steps, if any, are necessary to lower current P discharge levels.

**Table 2.** Average background concentrations of selected determinands at monitoring points at Drayton, Fobdown and Pinglestone (Hants) during July and August 2009.

Site	n	TRP	NH <sub>4</sub> N	NO <sub>3</sub> N	NO <sub>2</sub> N	SS	SO <sub>4</sub> S	Na	K	Mg	Ca	Mn	Fe	Ba	St
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
<b>Drayton</b>															
D1	6	0.133	0.17	5.7	0.06	7	10	7.8	1.8	1.9	120	10	55	16.6	211
D2	6	0.053	0.14	5.5	0.05	12	10	7.6	1.5	1.9	120	10	47	16.4	211
D3	1	0.030	0.11	6.0	0.08	9	10	8.7	1.9	1.9	121	10	30	15.5	211
<b>Fobdown</b>															
Inflow	5	0.078	0.04	5.0	0.05	3	10	6.3	1.0	1.8	104	10	31	13.8	216
Outflow	5	0.143	0.10	4.5	0.06	5	10	6.3	1.0	1.9	107	14	81	15.3	223
<b>Pinglestone</b>															
Inflow	5	0.252	0.10	5.6	0.03	5	11	6.8	1.6	2.9	89	10	43	14.2	215
Outflow	5	0.254	0.15	5.6	0.03	3	10	6.8	1.5	1.9	114	25	169	16.1	221

TRP – Total Reactive Phosphate NH<sub>4</sub>N – ammonium N; NO<sub>3</sub>N – nitrate-N; NO<sub>2</sub>N – nitrite-N; SS – suspended solids; SO<sub>4</sub>S – sulphate-S; Na – sodium; K – potassium; Mg – magnesium; Ca – calcium; Mn – manganese; Fe – iron; Ba – barium; St – strontium.



**Figure 4.** Temporal variation in TRP concentrations at each discharge monitoring point at (a) Drayton and (b) Fobdown after phosphate fertilization.

#### Field comparison of two P-stripping materials

##### *Phoslock™* (Drayton Farm)

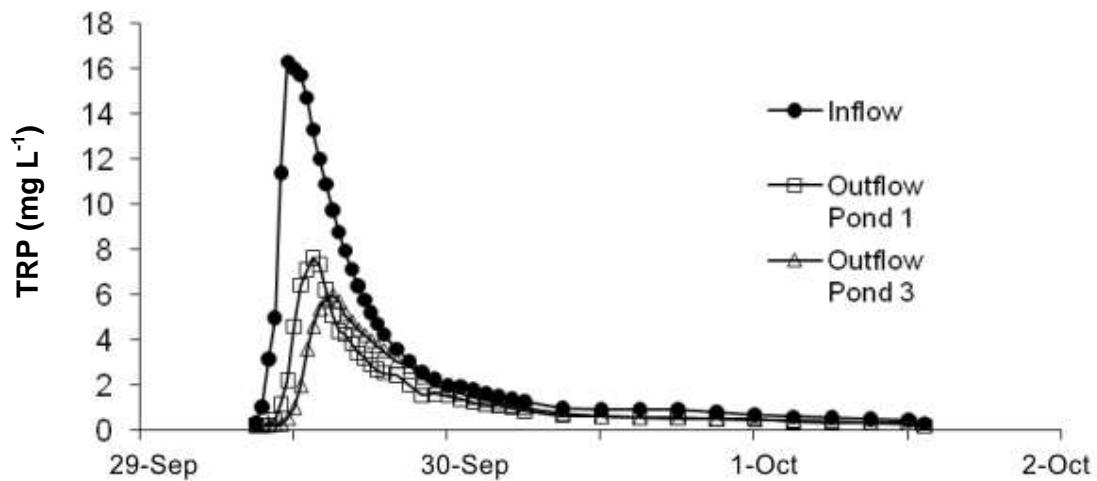
The amounts of *Phoslock™* applied to the inlet channel to pond 1 totalled 2 tonnes. The rate of application varied from 15-500 kg per hour depending on the anticipated range in TRP concentrations from the preliminary monitoring. Directly after *Phoslock™* application, the bentonite particles (containing the La and P) formed a thick suspension in the inlet channel, stimulated by the turbulence of the water in the channel (Figure 5). On some occasions, the

suspension had to be broken up by hand to allow representative sampling at the inlet to pond 1. However, the bentonite particles settled out during passage through the pond system and the water discharging out of pond 3 was clear.



**Figure 5.** Suspension of bentonite particles containing La and P in the stream channel upstream of pond 1 after application of Phoslock<sup>TM</sup>.

The effect of the Phoslock<sup>TM</sup> on the pattern of TRP concentrations measured after fertilization with 19:14:14 is shown in Figure 6. A peak concentration of 16.3 mg/L was measured at the inflow monitoring point (D1) 2.5 hours after the start of fertilization. Peak concentrations at the outlet to pond 1 (D4) and the outlet to pond 3 (D3) were 7.6 mg/L after 4 hours and 6.0 mg/L after 6 hours, respectively. Much of the P retention therefore occurred in ponds 1 and 2. The reduction in peak TRP concentrations at the outlet of pond 3 (and discharging to the stream) relative to the inlet concentration was 63%. Time-weighted average TRP concentrations at D1, D4 and D3 were 2.63, 1.34 and 1.33 mg/L, respectively. Phoslock<sup>TM</sup> therefore reduced average TRP concentrations by 50%.



**Figure 6.** Temporal variation in TRP concentrations at each discharge monitoring point at Drayton after phosphate fertilization and application of Phoslock™.

Spot flow rates measured during the trial averaged 0.099, 0.118 and 0.028 m<sup>3</sup>/sec at D1, D4 and D3, respectively. Whilst flow rates were maintained through ponds 1 and 2, the flow decreased substantially at the outlet to pond 3. The reason for this is not clear and only one measurement was taken. Flows at D4 were comparable to those measured at D1 and D2 during the preliminary monitoring (Table 1).

The more extensive analytical determinations undertaken on selected samples taken during the automated sampling period showed significant increases in the concentrations of NH<sub>4</sub>N, NO<sub>3</sub>N, NO<sub>2</sub>N and K at the inlet channel resulting from the application of the 19:14:14 fertiliser (Table 3). Conductivity was also consequently increased. These increased concentrations persisted through the pond system, with peak values of 17 and 18 mg/L for NH<sub>4</sub>N and NO<sub>3</sub>N, respectively measured at the outlet of pond 3 (D3). These very high N concentrations are of environmental concern, both in terms of potential harm to aquatic biota (from NH<sub>4</sub>N, NO<sub>2</sub>N) and human health (from NO<sub>3</sub>N). Levels of nitrite-N were also increased and although concentrations are very low relative to the other forms of N, they maybe of environmental concern. Concentrations of K also remained elevated at D3 but are not of environmental concern.

Some elevated concentrations of suspended solids (SS) were measured in the inlet channel before application of Phoslock™ (Table 3). This is likely to be a result of natural local perturbations upstream of the channel rather than an effect of the fertilization. Manganese (Mn) and iron (Fe) concentrations showed similar small increases associated with this SS transport.

The concentrations of SS at the outlet to pond 3 were no greater than those in the inlet channel before the Phoslock<sup>TM</sup> was applied, as evidenced by the very clear water discharging from pond 3. Other background elemental concentrations remained relatively constant throughout the monitoring period (Table 3).

Phoslock<sup>TM</sup> contains La as its main P binding agent and La concentrations show marked increases after application which persist through the pond system. At the outlet to pond 3, La concentrations had increased from below detection level (<0.006 mg/L) to a peak concentration of 1.7 mg/L. These increased La concentrations are not considered to pose a risk to aquatic biota or human health since the La is likely to be in colloidal (i.e. bound) form rather than a free state. Although the samples were filtered through a 0.45 µm filter to remove any particulates, small white particles were still observed in the samples. It is well known that very fine colloidal material will pass 0.45 µm and it is also highly likely that some precipitation of LaP will continue to occur during storage prior to analysis. Hence the high binding affinity of free La to P (and other anions) in the natural environment would soon render the La unavailable to biota. Phoslock<sup>TM</sup> has been approved for use by the Environment Agency.

#### *Virofilter<sup>TM</sup>* (Pinglestone Farm)

At Pinglestone, three residence times were tested with the Virotec filter media; 25 minutes, 64 minutes and 100 minutes (Figure 7). With a 25 minute residence time using the farm's slow-release fertiliser, peak TRP concentrations were reduced from 0.64 mg/L to 0.31 mg/L, a reduction of 52%. With a 64 minute residence time using the much more water-soluble 19:14:14 fertiliser, TRP concentrations were reduced from 1.45 mg/L to 0.53 mg/L, a reduction of 63%. When using a 100 minute residence time with a 19:14:14 fertiliser, the concentrations were reduced from 1.20 mg/L to 0.30 mg/L, a reduction of 75%.

Corresponding time-weighted average TRP concentrations for inflow and outflow were 0.322 and 0.195 mg/L for the 25 minute residence time, 0.507 and 0.253 mg/L for the 64 minute residence time and 1.02 and 0.081 mg/L for the 100 minute residence time. These represent reductions of 39%, 50% and 92%, for the three residence times, respectively.

Background concentrations in selected samples during the automated sampling period at Pinglestone are given in Table 4.

**Table 3.** Average background concentrations of selected determinands during automated sampling at Drayton: inlet channel and inlet to pond 3.

Site	Date	Time	pH	Cf	NH <sub>4</sub> N	NO <sub>3</sub> N	NO <sub>2</sub> N	SS	SO <sub>4</sub> S	Na	K	Mg	Ca	Mn	Fe	Ba	St	La
				µS cm <sup>-3</sup>	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	µg/L	µg/L	µg/L	µg/L	µg/L
<b>D1</b>	29/09	1035	7.97	668	12.5	14.6	0.029	10	12	8.3	12.8	2.0	119	10	30	15.3	211	<0.006
	29/09	1235	7.85	906	37.9	30.4	0.176	206	21	9.8	41.7	2.4	118	48	131	19.1	212	0.007
	29/09	1435	7.82	817	26.4	23.9	0.329	25	21	9.9	35.2	2.6	118	12	70	15.7	211	<0.006
	29/09	1635	7.93	678	17.7	18.2	0.570	42	18	10.2	26.7	2.6	117	10	65	13.9	205	0.007
	29/09	1835	7.87	607	10.6	12.4	0.662	8	14	9.1	18.0	2.4	119	10	38	12.0	207	<0.006
	29/09	2205	7.90	544	5.0	7.7	0.525	3	12	8.7	9.8	2.3	120	10	30	11.3	208	<0.006
	29/09	0205	7.86	514	2.7	6.6	0.280	6	10	8.3	6.1	2.2	117	10	30	12.7	207	<0.006
	30/09	0605	7.82	502	1.8	6.1	0.184	3	10	9	4.1	2.1	120	10	30	11.0	207	<0.006
	30/09	1805	8.03	508	0.67	5.6	0.151	3	10	7.9	3.0	2.1	119	10	30	12.6	207	<0.006
	01/10	0605	7.90	492	0.30	5.6	0.051	3	10	7.6	1.8	2.0	120	10	30	12.1	209	<0.006
<b>D4</b>	05/10	1320	7.75	490	0.03	4.6	0.025	7	10	6.7	1.2	1.8	108	10	36	13.6	193	n.d.
	29/09	1035	7.88	533	0.87	6.0	0.021	4	10	7.8	2.6	1.9	119	10	30	15.6	210	0.037
	29/09	1235	7.79	680	18.8	19.4	0.036	10	14	9.2	18.8	2.1	118	10	43	22.9	218	0.497
	29/09	1435	7.76	750	20.2	19.7	0.114	15	17	11.6	24.1	2.5	114	10	69	29.4	224	0.642
	29/09	1635	7.86	641	14.7	16.9	0.249	21	16	12.3	19.6	2.7	115	10	89	35.3	223	0.457
	29/09	1835	7.87	596	9.8	12.8	0.355	20	14	11.4	16.0	2.5	117	10	198	38.1	219	1.269
	29/09	2205	7.82	541	5.0	8.7	0.371	22	12	9.4	9.4	2.3	119	10	113	31.4	213	0.888
	29/09	0205	7.76	513	2.4	6.8	0.237	9	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.025
	30/09	0605	7.84	505	1.6	6.5	0.156	7	10	8.0	3.9	2.0	122	10	36	20.1	210	0.016
	30/09	1805	8.00	503	0.52	6.1	0.109	3	10	7.7	2.7	2.0	121	10	30	18.1	214	<0.006
<b>D1</b>	01/10	0605	7.88	497	0.24	6.0	0.043	3		7.9	1.9	1.9	121	10	30	15.4	211	0.006
	05/10	1330	7.63	499	0.04	5.3	0.023	3	10	7.4	1.6	1.8	114	10	30	14.8	199	n.d.

Drayton: D1 – inlet to pond 1; D4 – outlet from pond 1; n.d. – no data.

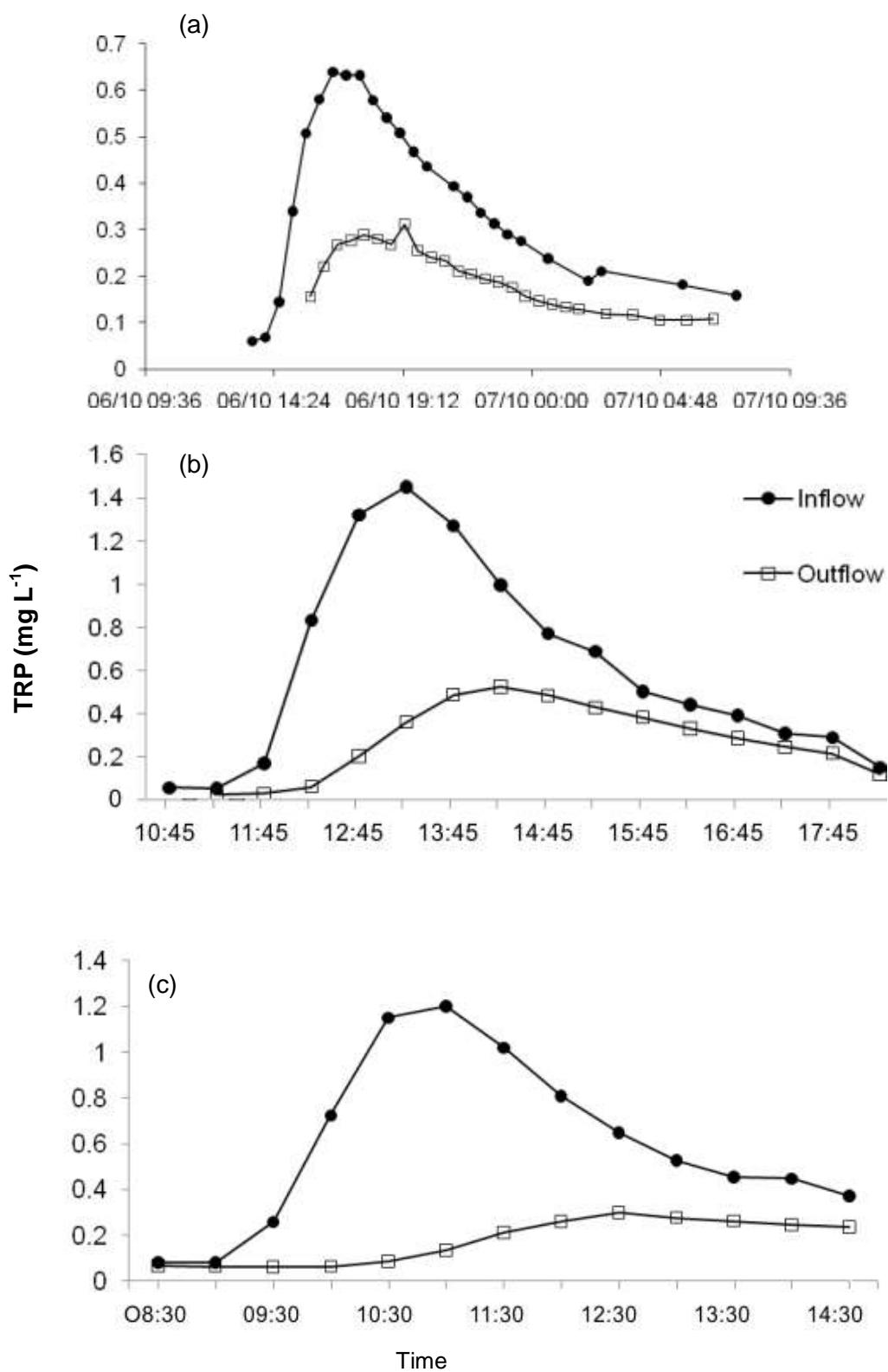
Cf - conductivity; NH<sub>4</sub>N – ammonium N; NO<sub>3</sub>N – nitrate-N; NO<sub>2</sub>N, nitrite-N; SS – suspended solids; SO<sub>4</sub>S – sulphate-S; Na – sodium; K – potassium; Mg – magnesium; Ca – calcium; Mn – manganese; Fe – iron; Ba – barium; La – Lanthanum.

**Table 3 (contd).** Average background concentrations of selected determinands during automated sampling at Drayton: outlet from pond 3.

Site	Date	Time	pH	Cf	NH <sub>4</sub> N	NO <sub>3</sub> N	NO <sub>2</sub> N	SS	SO <sub>4</sub> S	Na	K	Mg	Ca	Mn	Fe	Ba	St	La
			unit	µS cm <sup>-3</sup>	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	µg/L	µg/L	µg/L	µg/L	µg/L
D3	29/09	1035	7.92	527	0.03	5.5	0.022	6	10	7.9	1.8	2.0	122	10	67	16.3	217	<0.006
	29/09	1235	7.9	587	5.5	9.6	0.025	5	11	7.8	6.6	2.0	117	10	51	17.1	212	0.423
	29/09	1435	7.84	653	17.2	17.8	0.059	10	15	9.5	18.9	2.2	118	10	56	23.8	219	0.627
	29/09	1635	7.89	688	16.9	18.3	0.149	8	16	11.9	21.4	2.5	114	10	43	26.4	222	1.572
	29/09	1835	7.84	644	13.3	15.8	0.254	4	16	11.8	19.3	2.6	112	10	30	27.2	215	1.743
	29/09	2205	7.83	587	7.7	10.6	0.366	4	13	9.5	12.9	2.3	118	10	30	23.4	211	0.733
	29/09	0205	7.82	550	3.6	7.7	0.300	3	11	8.7	7.4	2.2	121	10	30	20.5	212	0.105
	30/09	0605	7.86	525	2.0	6.8	0.190	3	11	8.6	5.0	2.1	118	10	30	18.9	207	0.021
	30/09	1805	8.02	518	0.57	6.1	0.112	3	10	8.0	2.8	2.0	122	10	30	18.5	212	0.008
	01/10	0605	7.87	490	0.30	6.2	0.051	3	10	7.6	2.0	1.9	122	10	30	16.4	212	0.007
	05/10	1325	7.62	492	0.04	5.6	0.024	3	10	7.3	1.5	1.8	111	10	30	14.3	194	n.d.

Drayton: D3 – outlet from pond 3; n.d. – no data.

Cf - conductivity; NH<sub>4</sub>N – ammonium N; NO<sub>3</sub>N – nitrate-N; NO<sub>2</sub>N, nitrite-N; SS – suspended solids; SO<sub>4</sub>S – sulphate-S; Na – sodium; K – potassium; Mg – magnesium; Ca – calcium; Mn – manganese; Fe – iron; Ba – barium; St – Strontium; La – Lanthanum.



**Figure 7.** Temporal variation in TRP concentrations at the inflow and outflow of the pond at Pinglestone after phosphate fertilization and filtering through Virotec filter media. Residence time was (a) 25 minutes, (b) 64 minutes and (c) 100 minutes.

**Table 4.** Average background concentrations of selected determinands at Pinglestone during filtering of pond discharge through the Virotec filter media.

Site	Date	Time	pH	Cf	NH <sub>4</sub> N	NO <sub>3</sub> N	NO <sub>2</sub> N	SS	SO <sub>4</sub> S	Na	K	Mg	Ca	Mn	Fe	Ba	St	Al
				µS cm <sup>-3</sup>	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	µg/L	µg/L	µg/L	µg/L	µg/L
<b>Residence time: 25 mins</b>																		
<b>Inflow</b>	6/10	1505	7.96	492	0.38	7.1	0.043	3	10	6.6	2.4	1.80	107	10	30	15	217	n.d.
	6/10	1705	7.96	490	0.49	7.6	0.049	3	10	6.8	2.8	1.87	111	10	30	14.6	222	n.d.
	6/10	1905	7.92	491	0.36	7.3	0.054	3	10	6.8	2.3	1.86	110	10	30	14.9	220	n.d.
	6/10	2105	7.88	488	0.28	6.9	0.060	3	10	7.3	1.9	1.87	112	10	30	14.5	221	n.d.
	6/10	2305	7.89	480	0.21	6.5	0.062	3	10	7	1.6	1.86	112	10	30	14.7	220	n.d.
	7/10	0235	7.87	478	0.16	6.2	0.058	3	10	6.7	1.4	1.84	111	10	30	14.5	217	n.d.
<b>Outflow</b>	6/10	1715	8.02	98	0.30	7.0	0.043	3	32	62.5	5.4	14.3	167	10	84	10	272	n.d.
	6/10	1915	8.05	714	0.27	6.9	0.048	3	25	41.9	3.6	9.1	125	10	52	10	217	n.d.
	6/10	2115	8.07	622	0.22	6.5	0.054	3	22	32.5	2.9	7.6	111	10	57	10	196	n.d.
	6/10	2315	8.06	583	0.18	6.5	0.059	3	21	28.3	2.4	6.8	105	10	52	10	191	n.d.
	6/10	0115	8.09	595	0.17	6.3	0.057	3	25	33.2	2.5	7.8	101	10	73	10	183	n.d.
	7/10	0445	8.13	561	0.15	6.0	0.056	3	28	31.4	2.2	7.5	93	10	80	10	170	n.d.

Cf - conductivity; NH<sub>4</sub>N – ammonium N; NO<sub>3</sub>N – nitrate-N; NO<sub>2</sub>N, nitrite-N; SS – suspended solids; SO<sub>4</sub>S – sulphate-S; Na – sodium; K – potassium; Mg – magnesium; Ca – calcium; Mn – manganese; Fe – iron; Ba – barium; St – strontium; Al - aluminium.

n.d. – not determined. Aluminium was not determined by the Environment Agency.

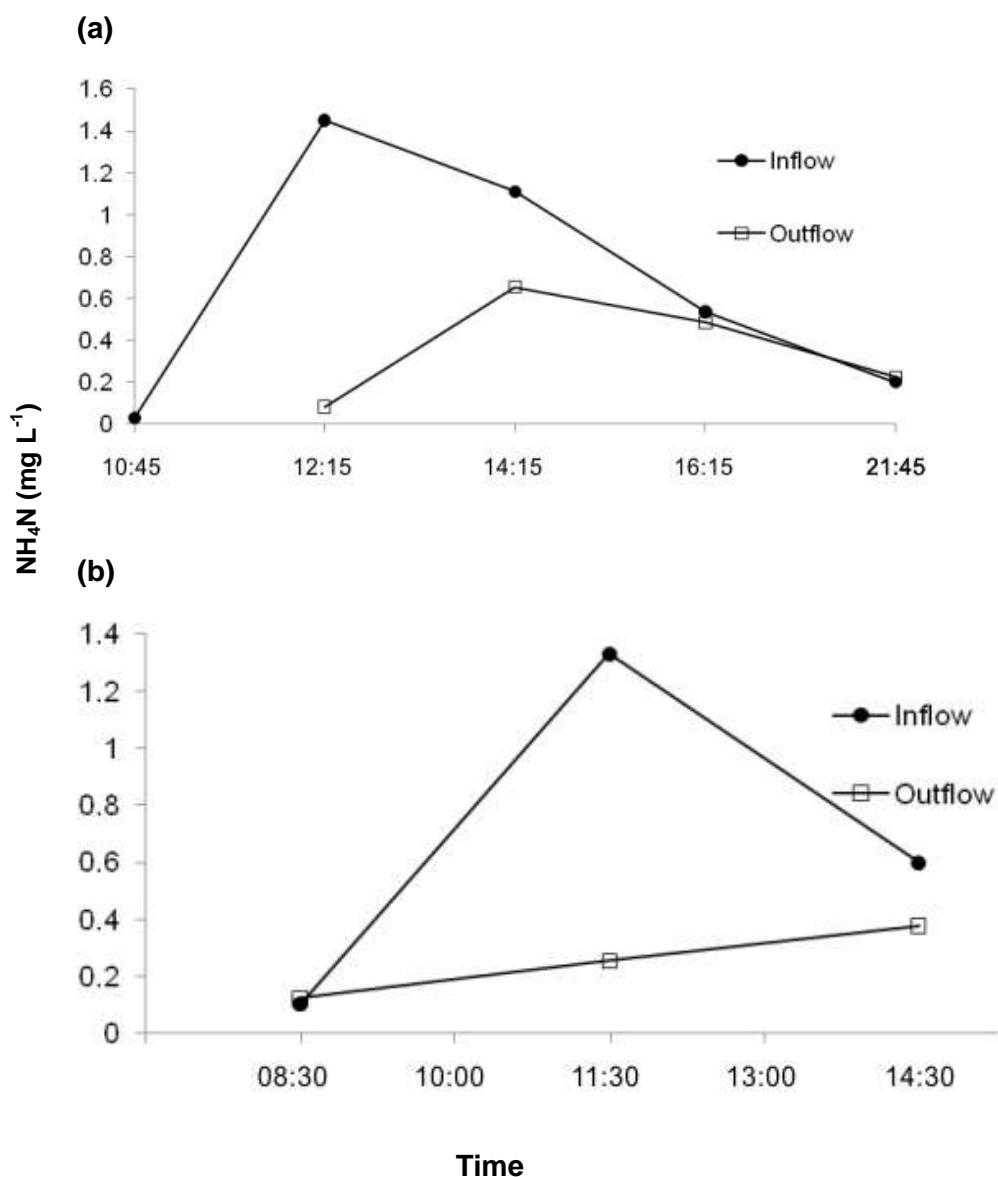
**Table 4 (contd).** Average background concentrations of selected determinands at Pinglestone during filtering of pond discharge through the Virotec filter media.

Site	Date	Time	pH	Cf	NH <sub>4</sub> N	NO <sub>3</sub> N	NO <sub>2</sub> N	SS	SO <sub>4</sub> S	Na	K	Mg	Ca	Mn	Fe	Ba	St	Al
			unit	µS/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	µg/L	µg/L	µg/L	µg/L	µg/L
<b>Residence time: 64 mins</b>																		
Inflow	16/12	1045	7.95	n.d.	0.03	6.2	0.007	3	10	7.1	1.2	1.8	116	10	30	14	222	11
	16/12	1215	7.96	n.d.	1.45	7.1	0.008	3	10	7.3	3.4	1.8	116	10	30	15	222	18
	16/12	1415	7.93	n.d.	1.11	6.7	0.009	3	10	7.1	2.7	1.8	115	10	30	15	221	10
	16/12	1615	7.84	n.d.	0.54	6.4	0.009	3	10	6.7	1.9	1.8	111	10	30	14	212	14
	16/12	2145	7.81	n.d.	0.20	6.0	0.012	3	10	6.7	1.5	1.8	112	10	30	15	216	12
Outflow	16/12	1215	8.28	n.d.	0.08	6.2	0.060	3	80	47.6	3.2	5.8	108	10	62	10	172	55
	16/12	1415	8.16	n.d.	0.66	7.0	0.030	3	53	37.3	3.4	4.6	99	10	30	10	161	29
	16/12	1615	8.16	n.d.	0.48	6.3	0.023	3	39	28.7	2.7	3.9	92	10	30	10	157	26
	16/12	2145	8.07	n.d.	0.23	6.3	0.017	3	25	22.3	1.9	3.5	91	10	30	10	160	23
<b>Residence time: 100 mins</b>																		
Inflow	17/12	0830	7.84	n.d.	0.10	6.2	0.011	3	10	6.7	1.3	1.8	112	10	30	15	213	20
	17/12	1130	7.95	n.d.	1.33	6.6	0.010	3	10	6.9	2.8	1.8	112	10	30	14	214	12
	17/12	1430	7.99	n.d.	0.60	6.4	0.011	4	10	6.8	1.9	1.8	114	10	30	14	216	13
Outflow	17/12	0830	8.03	n.d.	0.12	6.8	0.015	3	17	17.6	1.4	3.4	91	10	30	10	164	22
	17/12	1130	8.04	n.d.	0.25	6.5	0.016	3	20	20.6	1.7	3.8	90	10	30	10	155	22
	17/12	1430	8.10	n.d.	0.38	6.6	0.016	3	21	21.3	1.9	3.8	84	10	30	10	154	24

Cf - conductivity; NH<sub>4</sub>N – ammonium N; NO<sub>3</sub>N – nitrate-N; NO<sub>2</sub>N, nitrite-N; SS – suspended solids; SO<sub>4</sub>S – sulphate-S; Na – sodium; K – potassium; Mg – magnesium; Ca – calcium; Mn – manganese; Fe – iron; Ba – barium; St – strontium; Al - aluminium

For all residence times, there was a large increase in the concentrations of SO<sub>4</sub>S and Na and smaller or variable increases in pH, K, Mg, Ca, Fe and Al. The rise in pH was very small, increases in Fe were large when the tank was first used but, for 64 minute and 100 minute residence times, there was very little effect from the filter media. Aluminium was not analysed by the Environment Agency in the first trial (25 minute residence time), but in the subsequent trials there was an initial rise when the pond discharge was first pumped through the filter media, but concentrations then returned to background levels on the second day (longer residence time). Strontium concentrations were actually reduced by the Virotec filter media (Table 4).

When using the slow-release fertiliser there was no apparent increase in the concentrations of any of the forms of N at the pond outlet. However, when the more water-soluble 19:14:14 fertiliser was used, NH<sub>4</sub>N concentrations were notably increased. Whilst these increases were much lower than those observed at Drayton, these elevated concentrations are still a cause of environmental concern. Pumping the discharge water through the Virotec filter media reduced peak NH<sub>4</sub>N concentrations from 1.45 mg/L to 0.66 mg/L on 16 December and from 1.33 mg/L to 0.38 mg/L on the 17 December, but the number of samples measured were lower than those taken for TRP (Figure 8).



**Figure 8.** Virotec filter media reduced ammonium N ( $\text{NH}_4\text{N}$ ) concentrations at Pinglestone on (a) 16 December – 1 h residence time and (b) 17 December – 1.5 h residence time.

## **Discussion – Experimental results**

### **Comparison of two P-stripping materials**

#### **Preliminary monitoring**

The preliminary monitoring showed a number of key points in relation to the feasibility and suitability of deploying P binding materials to remove orthophosphate P from the discharge waters from watercress farms. These are summarised as follows:

1. The volumes of water discharged from watercress farms are very large and very variable. Water flow through individual beds is regulated during the growing season to allow transplanted crops to take root and for frost protection. In addition, groundwater levels can fluctuate during periods of stable weather whilst discharge from farms can be diluted by inputs from other stream sources. For example at Drayton, TRP concentrations entering the ponds can be quite low due to the merging of the watercress bed channel and the stream. This variability makes it difficult to calculate the amounts of P-binding materials required to remove a given amount of P, particularly for those that require dosing such as Phoslock™.
2. The background chemistry of the discharge water on the trial farms is typical of chalk groundwaters having a high pH and calcium content. These conditions generally favour precipitation of phosphorus naturally from the watercolumn, but can also reduce the reaction time of P-binding materials that use the process of precipitation to remove P, such as Phoslock™.
3. Spot measurements of discharge suggested that TRP concentrations during the growing season are highly variable, largely depending on when fertilisers are applied, or when beds are cleaned out, but also on a range of other factors that influence watercolumn concentrations through interaction with bottom sediments (Palmer-Felgate, Jarvie, Withers *et al.*, 2009). For example inlet concentrations at Drayton during the preliminary monitoring period varied from only 0.02 to 0.047 mg/L, except for one sample which contained 0.64 mg/L. During the trial at Drayton, the TRP concentration of the inlet water before any fertiliser was applied was 0.35 mg/L. Similarly, TRP concentrations at the inlets to settlement ponds at Fobdown and Pinglestone varied from 0.05 – 0.12 mg/L and from 0.05-0.59 mg/L, respectively, over quite short timescales. Again this variability makes dosing of P-binding materials difficult.

4. Application of the highly water-soluble 19:14:14 fertiliser caused a large increase in all the forms of N and in K concentrations in the discharge water. The largest increases were obtained at Drayton and will be due to the release of soluble N and K from the fertiliser. The magnitude of the increases is of environmental concern. In particular, the loss of ammonium-N is likely to be much more damaging to aquatic ecosystems than the loss of phosphorus.

The variable and often high P levels and water flows noted on watercress farms pose substantial challenges for the design and use of P stripping materials and equipment, though some of these factors are also encountered in other uses to which this technology is applied.

### **Field comparison of two P-stripping materials**

Peak TRP concentrations rose as high as 16 mg/L when all the beds at Drayton (2.94 ha) were fertilised within a short space of time. These peak values were short-lived and average time-weighted concentrations over the day of fertilization were no greater than 3 mg/L at Drayton. Interestingly, when only 1.58 ha of bed area at Drayton was fertilised during the preliminary monitoring period, peak concentrations rose to only 4 mg/L with a time-weighted average of 0.89 mg/L.

At Pinglestone, which had a much smaller bed area (0.17 ha) to fertilise, peak TRP concentrations rose to only 0.7 mg/L (average time-weighted TRP concentrations were 0.32 mg/L) when slow-release fertiliser was used, even though the rate of application (72 kg P<sub>2</sub>O<sub>5</sub>/ha) was greater than that used at Drayton (45 kg P<sub>2</sub>O<sub>5</sub>/ha). When 19:14:14 fertiliser was used instead of the slow-release fertiliser but at the same rate and over the same bed area, peak concentrations rose up to 1.2-1.45 mg/L. At Fobdown (the trial site not used), the use of the same slow release fertiliser as used at Pinglestone to a bed area of 0.4 ha increased peak TRP concentrations to only 1.1 mg/L, whilst the time weighted daily average was only 0.22 mg/L. These results clearly show the increased risk of P loss associated with the use of water-soluble compound fertilisers. As pointed out in the previous report of the bed trials, careful consideration should be given to the use of such highly water-soluble fertilisers on watercress.

### *Phoslock™*

Although the residence times of the ponds were quite low, the three pond system was sufficient for the bentonite particles to settle, provided the flow escape channels from the pond outlets to the river were kept closed during the application period. There was no increase in the amounts of suspended sediment discharged from pond 3 as a result of

Phoslock™ application. To what extent this holds true for single pond systems with shorter residence times is not clear and was not tested in this trial.

The inlet TRP concentrations after fertiliser application were a lot higher in the actual trial compared to those measured in the preliminary monitoring programme. Although the same amounts of fertiliser were applied, the area of the bed that received the fertiliser was greater in the actual trial (2.94 v 1.58 ha), which caused a sharp rise in the peak concentration measured.

As the rates of Phoslock™ application were matched to an anticipated peak of ca. 4 mg/L, its effectiveness in reducing TRP peak concentrations was not as great as was anticipated. However, a reduction in peak concentrations of 63% and of average (time-weighted) concentrations of 50% was still achieved. Whilst some reduction in TRP concentrations can be expected to occur naturally through the pond system, Phoslock™ application is clearly an effective means of reducing TRP concentrations without any significant environmental impacts. There was no major alteration of stream chemistry other than a small increase in La concentrations which previous work has suggested is not a hazard.

With adequate information on the amounts of P that are required to be removed from the water, the results obtained here suggest that Phoslock™ dosages could be matched to reach the target concentrations of 0.04-0.06 mg/L in the discharge water. Dosage equipment would need to be developed to deliver the material without blocking and further work is required for this option to be viable. The main problem with dosing is the large variability in flow and TRP concentration and a system of continuous *in-situ monitoring* would probably be needed in order to calculate the dosage rates required. Commercially available probes to analyze 'real-time' P concentrations in the inlet water are available and these could be deployed to ensure appropriate Phoslock™ dosing rates. This project did not assess whether pond sediment containing LaP can be applied to agricultural land without making soil P unavailable. Experiments undertaken at Nijmegen University (Netherlands) with Phoslock™ applied directly to soil indicate that plants did not experience any serious limitations to P supply in dry soil (unpublished data by Jeroen Geurts, submitted to *Ecological Engineering*). Organic acids produced naturally by plant roots have the potential capability to solubilise precipitated phosphate in soils, although bentonite-La-P particles should not be considered as a slow-release P fertiliser until further work can substantiate any P release by these natural mechanisms.

The amounts of Phoslock™ material required, however, are large and the cost of dosage would be high, probably prohibitively so. (Our supplier requested that current prices charged, which may or may not reflect those available for commercial producers, remain confidential).

### *Virofilter<sup>TM</sup>*

The Virofilter<sup>TM</sup> technology also proved an effective means of reducing TRP concentrations in the discharge water. Project budget restrictions prohibited a full evaluation of the filter media in terms of volume of material used and length of monitoring period. However, with a single filter bed (tank) and a residence time of 100 minutes, peak TRP concentrations fell to 0.3 mg/L, a reduction of 75% (92% on a time-related basis), when a highly soluble fertiliser was applied.

As with Phoslock<sup>TM</sup> system, design could be improved to achieve the desired TRP concentrations of 0.04-0.06 mg/L, for example by having a series of filter beds/tanks through which the discharge passed. In many cases, however, there is too little distance between the sedimentation pond and the river to provide the necessary space for large filter systems.

The main advantage of the Virofilter<sup>TM</sup> technology over the Phoslock<sup>TM</sup> dosing system is that it does not need to be continually added at varying rates; the filter media will cope with a range in P concentrations. The lower the concentrations to be treated the greater the period (years) over which the filter media will be effective. Once P saturated, the filter media can still be used as a de-odouriser by water companies and/or re-applied to agricultural land where the contained P is slowly released to the soil solution. One further advantage of Virofilter<sup>TM</sup> noted during the trial, is the beneficial effect the media has in reducing ammonium N concentrations.

The trial did show that the media cause an increase in the concentrations of SS and in Fe/Al/Na when first used. Other trials undertaken by Virotec suggest that such increases may last up to 2 weeks, but that after this initial settling down period, no further increases in anion/cation concentrations, or indeed pH, occur. Further development of the media structure and content is underway to minimise these issues.

Costs of the Virotec material quoted by the suppliers were of the order of £400/tonne. A 'commercial supply' price was not available from the suppliers of Phoslock, but indications are that treatment costs will be higher, taking into account the loss of the material during treatment

## **Conclusions**

Although neither Phoslock™ nor Virofilter™ application achieved the desired target concentrations in the discharge water of 0.04-0.06 mg/L, this was largely due to the limitations of the trial design imposed by budget restrictions. Both P-stripping materials were effective in reducing TRP concentrations without large increases in contaminant elements that might cause a hazard either to human health, or to aquatic habitats. Further work would however be necessary for both materials, to treatment design before it could be concluded whether that target P concentrations could be achieved through these systems of P-stripping.

The costs of treatment are very high due the large volumes of water that need to be treated. The range in P concentrations to be treated are also variable and appear to depend on both the area of bed being treated at any one time and the type of fertiliser used. Indications are that costs are greater with Phoslock™ than with Virofilter™. It is unclear whether the extra sediment generated by using Phoslock can be re-applied to land without influencing soil P availability in either the short or longer term. The Virotec filter media is therefore potentially a more sustainable method of P removal, with the option of disposing of the media via other outlets, possibly providing a revenue return.

## **Recommendations**

Increased monitoring of the discharge outlets from watercress farms would provide more information on the frequency with which (or if) TRP (and other nutrient) concentration targets are breached through the year. As the target is an annual average, it may well be that (a) no breach is actually occurring, even though concentrations may exceed the stated target level for short periods on individual days, and (b) it is feasible, at least in some circumstances, to adopt more sustainable practices (such as reducing the bed area fertilised at any one time and/or greater use of slow-release fertilisers) to reduce peak concentrations and/or achieve target TRP concentrations.

## **Technology transfer**

Industry representatives are intending to discuss the findings of this project with the Environment Agency in the near future. It is recommended that any consideration of technology transfer activity should await the outcome of this meeting.

## Glossary

### Phosphate forms:

**Particulate Phosphate (PP)** – the phosphate attached to suspended solids. Calculated as the difference between TP and TDP.

**Soluble Reactive Phosphate (SRP)** - a measure of orthophosphate, the filterable (<0.45 µm), soluble, inorganic fraction of phosphorus, the form directly taken up by plant cells (µg/litre).

**Soluble Un-reactive Phosphate (SUP)** – dissolved (<0.45 µm) phosphate that is not inorganic. This fraction contains dissolved P in organic and polyphosphate forms.

**Total Dissolved Phosphate (TDP)** – the sum of SRP and SUP.

**Total Reactive Phosphate (TRP)** – the inorganic phosphate that is present in an unfiltered sample without preliminary hydrolysis or digestion (µg/litre). It represents the sum of SRP and that portion of PP which is easily extracted and hence bio-available to aquatic organisms. The principal method used by the EA.

**Total Phosphate (TP)** - a measure of all the forms of phosphorus, dissolved and particulate, that are found in a sample (mg/kg). It represents the sum of SRP, SUP and PP.

**Suspension Solids (SS)** - solids held in suspension of a liquid (SS mg/litre).

## References

Douglas, G.B., Rob, M.S., Coad, D.N., and Ford, P.W. (2004) A Review of solid phase adsorbents for the removal of phosphorus from natural and wastewaters. *Phosphorus in Environmental Technology: Principles and Applications*. Editor: Valsam-Jones, E. pp. 291-320.

MacDonald, N (2010) Watercress: Evaluation of fertiliser regimes for the efficient and sustainable use of phosphate fertilisers by watercress growers. HDC report FV 338.

MacDonald, N (2007) An industry survey of watercress growers to establish best practice in phosphate fertiliser use. HDC report FV 302.

Palmer-Felgate, E.J., Jarvie, H.P., Withers, P.J.A., Mortimer, R.J.G., Krom, M.D. 2009. Stream-bed phosphorus in paired catchments with different agricultural land use intensity. *Agriculture Ecosystems & Environment*, 134, 53 – 66.

Other references are listed in the Literature Review section.

**Note:** The Literature Review which formed part of this project is available as a separate document from HDC.

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