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Identifying Critical Source Areas for Phosphorus Loss in Ireland Using Field and Catchment Scale Ranking Schemes

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Phosphorus (P) in agricultural runoff is a major pollutant in many of Ireland's surface waters. Identification of areas that are at a high risk for P loss to surface waters is a critical component of river basin management. Two P ranking schemes (PRS's) were developed for Ireland, based on multi-criteria analysis approaches proposed in both the U.S. and Europe, to predict the relative likelihood of P loss at both the field and catchment scales. The Field PRS was evaluated by comparing predicted rankings of potential P loss and transport against measured edge-of-field Dissolved Reactive P (DRP) loss for three fields with varying soil P levels. Qualitatively, results indicated that the Field PRS rankings corresponded to the magnitudes of measured P loss for the field sites, as well as to a reasoned evaluation of the relative likelihood that the fields would lose P that would subsequently make its way to surface water. The Catchment PRS was evaluated on a total of thirty-one catchments and sub-catchments by comparing predicted rankings of potential P loss and transport against measured in-stream median Molybdate Reactive P (MRP). Rankings of the relative likelihood of P loss and transport predicted by the Catchment PRS were positively correlated with median in-stream MRP ($r = 0.51$, $P<0.05$). Although the data available for these evaluations were limited, especially at field scale, and further research may identify the opportunity for modifications, both field and catchment scale P ranking schemes demonstrated a potential for identifying critical P source areas within catchments dominated by grass-based agricultural production systems, such as those in Ireland.

Keywords: Diffuse pollution management, multi-criteria analysis, catchment management

Introduction

In a survey on water quality in Ireland, Bowman *et al*. (1996) concluded that diffuse phosphorus (P) pollution from agriculture is 'of major significance in the upward trend in the spread of eutrophication of rivers and lakes', and that this trend will continue in the absence of corrective action. Agriculture was targeted as the pollution source for almost half of the 'slight-to-moderately-polluted', and a quarter of the 'seriously-polluted' streams. For example, McGarrigle and Donnelley (2003) reported that 59% of total P losses in a rural Irish catchment were attributable to diffuse pollution from agriculture. Eutrophication can occur in surface waters having relatively low concentrations of Molybdate Reactive P (MRP), which often include fresh (*i.e.*, non-saline) waters used for recreation, salmon habitat and drinking water; these are of great importance in Ireland and elsewhere. Phosphorus is of particular concern in freshwater systems because it is thought to be the limiting nutrient for eutrophication, thus relatively small MRP additions can result in algal blooms (Gibson, 1997).

The problem of P transfer from agricultural areas to surface waters is not unique to Ireland, and is a pressing environmental concern in many regions of the world (Sharpley and Rekolainen, 1997). Moss *et al.* (1996) concluded that nutrient pollution from agricultural P sources has become an increasingly dominant factor affecting British water quality. In the Netherlands, agricultural sources have also caused surface water eutrophication (Steenvoorden and Oosterom, 1979). From 1974 to 1991, Foy *et al.* (1995) noted an increasing trend in the Dissolved Reactive P (DRP) load of six rivers in Northern Ireland. Similar trends have also been reported for South West England (Heathwaite *et al.*, 1996).

Identification of areas in the landscape that pose the greatest risk for P loss to surface waters is a critical component of P management. In general, a large proportion (up to 90%) of the P exported from catchments on an annual basis can occur from a relatively small portion of a catchment and during only one or two storm events (Sharpley and Rekolainen, 1997; Pionke *et al.*, 1997). Sharpley *et al.* (1993) emphasized that 'Strategies to remediate water quality problems associated with P movement in the landscape will be most efficient if sensitive or source areas within a watershed are identified, rather than implementing general strategies over a broad area'. Cleneghan *et al.* (2001) observed that 'the cornerstone of European and national policy to tackle eutrophication is the adoption of a catchment based approach to water quality management'. McGarrigle (1998) stated 'There is an urgent need for effective catchment management strategies which can reduce the P load to rivers and in particular that from agricultural sources where long-term trends are giving cause for concern'.

Several strategies have been proposed in Ireland as a means of identifying areas within a landscape that are vulnerable to P loss. An 'export coefficient' approach was used by Daly *et al.* (2000); they used data collected from plot-sized experiments to develop catchment scale relationships between catchment characteristics and nutrient concentrations in surface waters. The resulting 'national P model for Ireland' (Daly *et al.*, 2000) combined data on soil P levels and soil type, with environmental and agricultural land use data sets in a Geographical Information Systems (GIS) format. However, as with all empirical approaches, export coefficients developed in one catchment and applied to different catchments can lead to inaccurate predictions. For example, Irvine *et al.* (2003) reported that 'seemingly reasonable' export coefficients used to predict diffuse P loss in Lough Carra, which were developed from a catchment with similar characteristics, resulted in an estimated P export rate that was 3 times greater than the measured load.

Approaches based on multi-criteria analysis also have been suggested as a means of catchment-based planning in Ireland (Kirk *et al.*, 2001; MCOS, 2002; Magette, 1998). Multi-criteria analyses, widely used in fields such as land use planning (Voogd, 1983), and engineering infrastructure implementation (Rogers, *et al.*, 2000), identify various criteria that affect a decision (*e.g.* an evaluation of risk), assign scores to the criteria and weight them according to priority, and then utilise a mathematical relationship to integrate criteria scores and weights into a single, "bottom line", quantitative evaluation measure. As the vulnerability of a particular area to P loss is dependent on numerous factors, multi-criteria analysis can provide a rational means of assessing the potential for P loss of an area, which, depending on the scale can be either a field or a catchment. In contrast to mathematical models, for which detailed information on site hydrology, soils and soil chemistry are usually necessary, multi-criteria approaches are largely non-mathematical techniques that utilise readily accessible information.

At the field scale, a multi-criteria analysis approach has been widely adopted in the U.S., where many states have developed regional Phosphorus Site Indices based on the work of Lemunyon and Gilbert (1993). The Lemunyon and Gilbert (1993) P index was designed to rank fields according to the relative risk for contributing P to surface waters. However, because regions vary with respect to geologic, hydrologic and climatic factors, as well as agricultural management practices and surface water characteristics, Lemunyon and Gilbert (1993) intended their P index to serve as a template that would require modification on a regional basis. This approach is currently being evaluated for use in Norway (Bechmann *et al*., 2003). Recent adoption of P Indices by forty-seven states in the U.S. as part of their required nutrient management planning strategies has shown the flexibility and robustness of this site assessment approach (Sharpley *et al*., 2003).

Based on the Lemunyon and Gilbert (1993) approach, Magette (1998) developed a Phosphorus Ranking Scheme (PRS) specifically adapted for use in Ireland (Tables 1 and 2), where grass-based agricultural production systems comprise 90% of the agricultural land use. Unlike the Lemunyon and Gilbert (1993) P index, the Magette PRS (Magette, 1998) was designed for use at both the catchment and farm scales, and included factors associated with both. The Magette PRS was based on three premises: (1) the source and transport of P from agricultural areas to surface waters is affected by a combination of factors; (2) some factors have a greater impact ('weight') on P loss than others; and (3) the effect of a factor on the overall risk for P loss depends on the magnitude of that factor. The nine factors in the Magette PRS were each assigned a relative 'weight' ranging from zero to one, designed to account for the importance of that factor on the overall potential for P loss and transport. Depending on the magnitude of each factor, a numerical 'risk level' (*i.e*., score) was assigned. Products of factor weightings and scores were summed to provide a numeric value that represented the relative likelihood that P would be lost from the area being evaluated, and subsequently transported to surface water.

The rationale for selecting the factors used in the Magette PRS is described in detail in Magette (1998) and summarised in Magette (2002). Using Lemunyon and Gilbert's (1993) P index as a framework, Magette (1998) conducted an exhaustive review of scientific literature to identify those factors that were reported to have critical influence over P loss from the landscape *and* for which data might reasonably be expected to exist. The objective was not to produce a deterministic description of P movement in the terrestrial environment, but rather a simple decision support tool, which, when applied consistently, would yield an objective metric with which areas within catchments (or, indeed, entire catchments) could be compared against one another based on the relative likelihood that they would contribute P to surface water. Weightings and scores for individual factors were assigned using professional judgement, which was then critiqued by approximately a dozen different scientists in Europe and the U.S. In general, factors that were judged to be particularly influential in determining P loss and transport were given the highest weightings, and particularly so if the magnitude of a factor (*e.g.*, P application rate) could be easily controlled. In the case of farmyard assessments (Table 2), recommended ‘best practices’ (*e.g.*, manure storage capacity) provided logical scoring categories. Thinking that the most likely application of the Magette PRS would be at catchment scale, Magette (1998) used an additive process to sum weight-score products, an approach that assumed at catchment scales, hydrologic pathways would always exist for the transport of P from source areas to receiving waters. The extent to which this assumption was relevant in a particular catchment was determined by what was essentially a stream density factor (*i.e.*, ratio of land area to surface water). Magette (1998) also assumed that on highly productive and well-managed pastureland, P losses as a consequence of soil erosion would be minimal, an assumption subsequently shown to be true elsewhere (DeLaune *et al.* (2001).

Unfortunately, applying the Magette PRS (Magette, 1998) was not straightforward, chiefly because data did not in fact, exist in Ireland for several of the factors used in the scheme. In addition, after some testing, it was suggested that the use of both field *and* catchment scale measures for factors such a P usage amounted to ‘double counting’, which distorted the importance of these factors (Hubbard *et al*., 2001). These shortcomings, and subsequent recommendations for improvement suggested in evaluations by Hughes *et al.* (2003), Magette (2002), and Hubbard *et al*. (2001) provided the impetus for modifying the Magette PRS (Magette, 1998) by splitting and simplifying the PRS into two P ranking schemes: a ‘Field PRS’ for use at field scale, and a ‘Catchment PRS’ for use at catchment scale. Modifications needed to take into account the availability of data for both catchment and field assessments. Also, emphasis was placed on keeping the Field PRS as simple as possible, recognising that it was unlikely an agricultural advisory service would be available in Ireland to advise all pasture owners on implementation of the revised ranking scheme. Hence the field scale PRS was designed for use by individual farmers having minimal training in site assessment techniques.

The objective of this research was to evaluate these modified ranking schemes by comparing the predicted relative likelihood for P loss against measured edge-of-field P exports (at the field scale) and in-stream median P concentrations (at the catchment scale).

Methods

Field Scale PRS Evaluation

The Field PRS (Table 3) was designed for field scale application. Five of the Field PRS factors (P usage rate, P application time, soil test P, runoff risk, and condition of receiving waters) were adopted directly from the Magette PRS (Magette, 1998), following the same logic as applied in that scheme. Using guidance described by Coale and Layton (1999), the overland flow distance factor was modified for field application to account for both measured distance between a field and receiving waters and the presence or absence of a vegetative buffer. An indirect use of the 'farmyard conditions' factor of the Magette PRS (Magette (1998) was made in Field PRS, as the 'P application rate' and 'P application time' factors were evaluated in relation to farmyard conditions. In the Field PRS, if farmyard conditions were rated as 'high' risk, P usage rate and time factors were also assigned a 'high' risk, assuming that improper farmyard conditions (*i.e.* lack of adequate manure storage) would result in high risk practices for P application. A factor for soil erosion was added to expand the applicability of the Magette PRS to include fields under tillage, row cropping, or fields that are poorly managed as pasture (*i.e.* overgrazed), where soil erosion would be expected to contribute to P loss. Nevertheless, the soil erosion factor was assigned a weight of just '0.5' to reflect the low intensity of rainfall in Ireland (Keane, 1992). Additionally, a risk value of '0' was allowed for P usage and application timing factors on fields where no P was applied.

While many factor weightings were adopted directly from the Magette PRS (Magette, 1998), attempts were made to more objectively assign a weighting for the 'overland flow distance' factor, which replaced the 'ratio of land to water' factor used in the original Magette PRS. The overland flow distance factor received special attention in the development of Field PRS because it was believed to be of critical importance as a 'transfer function', moderating P losses from source areas prior to their delivery to surface water. In essence, a sensitivity analysis of weightings for the overland flow distance factor was conducting by assigning a range of values for this weighting (0.8, 0.9, 1.0 and 1.1), and assessing the impact on the resulting rank scores, as calculated using the additive procedure described in Magette (1998).

Unfortunately, data on edge-of-field losses of pollutants are virtually non-existent in Ireland; even worse, there are no synchronous measures of field losses and in-steam water quality. Field PRS was tested on three fields using data on edge-of-field P exports of DRP in overland flow reported by Kurz (2000). The three fields, located in Southeast Ireland on government-owned research facilities in County Wexford, were managed as pastures and had varying concentrations of soil P (Table 4), and differing management (Table 5). All three fields were hydrologically isolated from surrounding land areas with respect to surface overland flow. Automatic samplers were used to collect samples of surface overland flow, which were then analysed for DRP, Total P (TP) and Total Dissolved P (TDP). Concentration data were combined with flow measurements to calculate mass P exports. Details of data collection and analysis are described more fully by Kurz (2002) and Kurz *et al*. (2004).

Overland flow from two fields, one with high (Cowlands) and one with low (Warren 1) Morgan's (Morgan, 1941) soil test P (17 and 4 mg L^{-1}, respectively), was collected for a period of sixteen months. Overland flow was collected and analysed from Warren 2 (with medium STP of 8 mg L^{-1}) for five of the sixteen months in which sampling at Cowlands and Warren 1 was conducted. Measured P exports indicated that the highest rates of P loss occurred from the Cowlands, followed by those from Warren 2 and Warren 1. For the sixteen-month monitoring period, DRP exports were 778g ha^{-1} for the Warren 1 and 5,300g ha^{-1} for the Cowlands. For the five-month monitoring period, DRP exports were 300g ha^{-1} for the Warren 2.

Catchment Scale Evaluation

The second modification of the Magette PRS (Magette, 1998) was called Catchment PRS (Table 6), and was designed for use in catchment scale P risk assessment. This modification utilised six of the original nine Magette PRS factors. The three factors eliminated were 'overland flow distance', 'field P usage rate' and 'P application time'. Overland flow distance was eliminated because it is related to the ratio of land to water, and also is difficult to average for an entire catchment. The P application time factor was eliminated because data were generally not available at the catchment scale, while the field P usage rate factor was eliminated because in practice it is often similar to the catchment P usage rate factor. Because information on farmyard conditions for an entire catchment was also difficult to obtain, this factor was modified. In Catchment PRS, if farmyard conditions for a catchment were known, the factor was the same as in the Magette PRS (Magette, 1998). If farmyard condition data were not available, 'farmyard density' was used as a surrogate measure, as described by Magette (2002).

The timing of P application is a critical factor in predicting the risk for P loss, yet in practice in Ireland, data for this factor are virtually unavailable on a catchment scale. However, this factor is indirectly accounted for in the Catchment PRS through the risk associated with farmyard conditions/density factor, at least for animal manure. Inadequate manure storage (and/or poor manure management) often leads to spreading manure during inappropriate times, *i.e.* during the rainy winter season. Although obtaining information on farmyard conditions such as manure storage is also difficult, these data often do exist from 'needs assessments' or similar evaluations of farmyard facilities made by local or central authorities. These data can be used as an indirect measure of risks associated with the timing of P usage associated with manure.

Soil erosion, a factor that was proposed as a component of the Field PRS, was not included in the Catchment PRS for several reasons. Identification of overgrazed pastures or areas with poor pasture management requires an on-site visit and as such, may not be possible at the catchment scale. As the majority of agricultural lands in Ireland are managed as pastures, it is relatively rare for a catchment to be dominated by tillage. DeLaune *et. al.* (2001) suggest that "well-managed pasture systems would be expected to have negligible annual loss of soil due to erosion"

The Catchment PRS was tested on a total of thirty-one Irish catchments and sub-catchments (Table 7) for which catchment characteristics and in-stream P data were available in published reports. The purpose of this testing was to determine whether the likelihood of P loss and transport predicted by Catchment PRS was correlated with in-stream MRP concentrations. Data for this evaluation were provided by a variety of researchers (Kurz, 2002; Morgan *et al.,* 2000; Kirk *et al*., 2001; MCOS, 2002). Numerous datasets were provided from recently completed large-scale studies of water quality in Ireland: the Lough Derg and Lough Ree Catchment Monitoring and Management System Project (Kirk *et al*., 2001), and the Three Rivers Project (MCOS, 2002). Kurz (2002), Morgan *et al.* (2000), Kirk *et al*. (2001), and MCOS (2002) describe catchment characteristics, water quality monitoring and other data management techniques used to generate these datasets. A range of catchment sizes from tens of hectares to thousands of hectares (Table 7) was represented in the datasets, allowing both catchments and sub-catchments to be evaluated. Specifically, the Bellsgrove catchment was assessed together with six individual sub-catchments within the Bellsgrove system, as was the Yellow River catchment and twelve sub-catchments within it. For the Dripsey catchments, D1 is a sub-catchment of D2.

Application of the Magette PRS generally followed guidelines given in Magette (2002). When detailed information regarding the risk assignment for a given factor was not available, an estimate was made using professional judgement based on available data. However, this evaluation method differed from the Magette (2002) approach with respect to the assignment of 'P application time' scores when no information was available. Magette (2002) assumed that best management practices were being followed on all farms in lieu of actual application time data. However, on reviewing water quality data from the thirty-one catchments used in this study, adherence by farmers to best agricultural practice seemed to be limited. Aside from the farms associated with Irish government research (*i.e.,* the Beef Farm and Dairy Unit, Table 7), many catchments contained a significant number of farms with inadequate manure storage. In this study, it was assumed that inadequate manure storage would necessitate spreading manure during the late summer, autumn and winter seasons. In an attempt to neither underestimate nor overestimate risk associated with the timing of manure application, when no data were available for P application time, a risk value of 'medium' was assigned for this factor.

Water quality was classified as ‘acceptable’ or ‘unacceptable’ based on median MRP levels, as streams with median MRP levels > 30µg L^{-1} generally show signs of eutrophication (Bowman *et al.*, 1996). Another rationale for using median MRP values was that this value was reported for all but two of the sub-catchments used in this analysis (specifically, the Beef Unit and Dairy Farm subcatchments, for which median MRP was estimated to be approximately 50µg L^{-1}). The Derg/Ree study (Kirk *et al.*, 2001) also used median in-stream MRP as the criterion by which their ranking scheme was evaluated.

Correlation analysis and a Spearman's Rank correlation were performed on all catchments as well as on the Yellow River subcatchments only, so as to measure the association between the total Magette PRS rank value and median in-stream MRP (Statistical Analysis System Institute, 1985).

Results and Discussion

Field PRS Evaluation

In the absence of synchronous edge-of-field overland flow and in-stream water quality measurements, testing Field PRS was a challenge that required reasoned professional judgement to interpret results. ‘Professional judgement’, as applied in this study, was synonymous with ‘expert opinion’. Results from the Field PRS evaluations are given in Table 8. The P usage rate factor was assigned a ‘high’ risk for the Warren 2 and Cowlands sites, and application time was assigned a ‘low’ risk, as P was applied in March. Soil test P factor was assigned a ‘low’, ‘medium’ and ‘high’ risk for Warren 1, Warren 2, and Cowlands, respectively. The Warrren 1 site was given a ‘0’ value for P usage rate and timing because no P was applied to this site. The gleyed soils present at these sites indicated high water tables and frequent wetting, hence runoff risk was considered to be ‘high’ at all three sites.

The overland flow distance factor was assigned a ‘low risk’ value for all three fields, as the distances to nearby streams (or, in the case of Warren 1, to an open drain) was 100, 75 and 250m from Warren 1, Warren 2 and Cowlands, respectively. The ‘condition of receiving waters’ factor for all three fields was assigned a ‘low risk’ value to reflect that receiving waters are freshwater streams and not specifically designated for remediation. The soil erosion factor for all three sites was also assigned a ‘low’ risk, reflecting the fact that all three sites are well-managed pastures.

The Field PRS categorised the Warren 1 site as having a ‘low’ potential for P loss and transport, while both the Warren 2 and Cowlands fields were categorised as having a ‘medium’ potential (Table 8). This might seem initially to be a failure of the Field PRS to distinguish between the Warren 2 and Cowlands fields. However, edge-of-field DRP exports from the Cowlands field, although high in comparison to exports from Warren 2, must be transported across 250m to reach the nearest stream. While DRP exported from the Cowlands field may be high, the overland flow distance could mitigate against the transport of edge-of-field P losses to receiving waters, unless the intervening landscape itself was P saturated, as sometimes occurs with vegetated buffers (Magette *et al*., 1989). For the conditions existing at the Cowlands site, a ‘medium’ overall potential for P loss *and* transport to receiving waters seems appropriate.

Results from the sensitivity analysis (Table 9) indicate that both an overland flow factor weighting of 0.75, as used in the original Magette PRS (Magette, 1998), and a weighting of 0.8 appropriately categorised the three fields in terms of their potentials to lose and transport P. Weightings of 0.9, 1.0 and 1.1 categorised the Warren 2 site as having a 'high' potential for P loss and transport, and the Warren 1 site as having a 'medium' potential when the fields were evaluated using 'medium' overland flow distance risk assumptions. Using professional judgement, one would interpret the low measured P transport and runoff from the Warren 1 site as suggesting that this site should be categorised as having a 'low' potential for P loss/transport *if* it were in locations remote from a stream, and/or where a vegetative buffer separated the field and receiving water. Otherwise, this field should have a ‘medium’ potential for P loss and transport, *if* the field overland flow distance were categorised as ‘high’ risk. Professional judgement also supports the assignment by Field PRS of a 'high' potential for P loss and transport to the Cowlands site, *if* it were located adjacent to a stream. The same reasoned evaluation would endorse the Field PRS categorisation of the Cowlands site as having a 'medium' potential for P loss and transport, *if* the field were in a 'medium' overland flow risk scenario. Under the management guidelines suggested by Coale and Layton (1999), a 'medium' potential to lose and transport P suggests that P usage should be limited to either those amounts actually required by plants for normal growth, or to those amounts required to satisfy soil test-based P recommendations. Additionally, steps should be taken to reduce P loss from the site. Both are valid recommendations for the Cowlands site given its high STP value and P export rate (5,300g ha^{-1} over sixteen months).

It is important to note that the sensitivity analysis of weightings for the overland flow distance factor was conducted when all other factors were assigned their appropriate values, one of which was a 'low risk’ assignment for the ‘condition of receiving waters’ factor. Had this factor been assigned (based on water quality assessments) a 'medium' or 'high' risk, the potential for P loss and transport assigned by Field PRS to both the Warren 2 and Cowlands sites would also have been 'high' (under 'high' risk overland flow distance assumptions). Also, Field PRS would have classified the Cowlands site as having a 'high' potential for P loss and transport (under 'medium' overland flow risk assumptions), a classification that professional judgement would confirm to be entirely appropriate.

Catchment Scale Evaluation

Catchment PRS rank scores, rank order, categorisation of potential for P loss and transport, corresponding water quality (median MRP) and water quality rating for the thirty-one test catchments/sub-catchments are given in Table 10. Figure 1 illustrates the relationship between Catchment PRS rank and median MRP values. Average median MRP for catchments classified as having a ‘high’, ‘medium’ and ‘low’ potential for P loss and transport was 60, 40 and 17µg L^{-1}, respectively. Of the thirty-one catchments analysed, Catchment PRS ranked three ‘high’, two ‘low’ and twenty-six ‘medium’ for their potential to lose P and transport it to surface water. All corresponding water quality for ‘high’ and ‘low’ risk catchments was characterised as ‘unacceptable’ and ‘acceptable’, respectively. For the twenty-six catchments ranked by Catchment PRS as having a ‘medium’ potential to lose and transport P, water quality was rated as ‘unacceptable’ in 46% cases, and ‘acceptable’ in 54%. Examining these same twenty-six catchments based on their numerical rank orders revealed that for eight out of nine (88%) of the most highly ranked catchments in this ‘medium’ category *(i.e.*, ranks four through twelve) water quality was classified as ‘unacceptable’. Conversely, in seven out of nine 78%) of the lowest ranked catchments in this ‘medium’ category (*i.e.*, ranks twenty-one through twenty-nine) water quality was classified as ‘acceptable’. These results suggest that a higher correspondence might be achieved between actual water quality and Catchment PRS classifications if the ranges of scores that encompass ‘high’, ‘medium’ and ‘low’ classifications were modified.

Nevertheless, correlation analysis proved a significant positive correlation between the Catchment PRS and in-stream median MRP ($r = 0.51$, $P <0.05$). Spearman's Rank correlation also indicated a positive relationship between Catchment PRS rank order and in-stream median MRP ($R= 0.61$, $P < 0.05$).

While effective at predicting the potential for P loss and transport in the group of *all* thirty-one catchments, the classification provided by Catchment PRS rank was not significantly correlated with in-stream median MRP when *only* the Yellow River sub-catchments were considered. In this system of sub-catchments, both correlation analysis and Spearman's Rank correlation indicated that there was no statistically significant relationship between either Catchment PRS rank score or rank order and in-stream P concentrations.

Nevertheless, for a number of these sub-catchments, the rank orders of catchments based on median MRP concentration and those based on Catchment PRS rank score were closely associated (data not shown), even if this association was not statistically significant.

Evaluation of the results from the group of thirty-one catchments, as well as from the Yellow River catchment, highlights both strengths and limitations of the Catchment PRS. While the Catchment PRS rank score was positively correlated with in-stream median MRP for the group of thirty-one catchments evaluated, there were several anomalous catchments where the final rank score was not closely correlated with in-stream P (such as the Yellow-B, with a Catchment PRS rank score of 11.9 and the highest measured median MRP of 130μg L^{-1}, or alternatively, the Clonshanbo with a Catchment PRS rank score of 10.2 and median MRP of 18μg L^{-1}).

There are a number of possible reasons for the anomalies with respect to Catchment PRS rank compared to ranks based on in-stream median MRP. One possible reason has to do with the use of a singular type of P measurement (median MRP concentrations) to determine the P status of a stream). Although MCOS (2002) found this parameter to be the best predictor of stream P status, it is still possible for normal statistical variation, or for that matter, equipment, sampling or analysis error, to generate a median MRP value that does not accurately represent P exported from the catchment. For example, the Dripsey D1 catchment, which exported 1.61– 1.64 kg P ha^{-1} yr^{-1} and was the third highest ranked catchment with respect to Catchment PRS rank score for its potential to lose and transport P, had measured median MRP values of only 26μg L^{-1} (Morgan *et al.*, 2000), thus qualifying it as an 'acceptable' stream despite the high Catchment PRS rank score and P export rate.

Inclusion of other rating schemes may improve the accuracy of the 'acceptable' versus 'unacceptable' water quality ranking. Magette (2002) used median in-stream MRP as well as P export values to evaluate the Catchment PRS on the Bellsgrove catchments. As for the Dripsey-D1 catchment, Magette (2002) found that these two rankings did not always correspond. The Irish Environmental Protection Agency categorises water quality in streams using a biological classification system, based on a correlation between community diversity and water quality (Bowman *et al.*, 1996). If more detailed stream P status data were available, further evaluations of the Catchment PRS using additional measures of P loss and water quality would be valuable. However, to do this sort of analysis, the criteria selected for rating water quality would need to be available for all catchments being compared. In Ireland, biological monitoring is limited to a statistically representative proportion of surface waters on a rotational basis, thus under present circumstances it is difficult to foresee how a biologically based water quality classification might be used in Catchment PRS.

Another issue relating to use of median in-stream MRP as a metric against which to evaluate Catchment PRS predictions involves the implicit assumption in this technique that water quality at a downstream location is affected only by landscape losses of P within the catchment, and not by other sources of P, such as those delivered from upstream locations. For example, in the Yellow River, the Yellow-C catchment discharged 60μg L^{-1}, which was ranked as 'unacceptable' according to the criterion reported by Bowman *et al.* (1996). Yet, inflows into the Yellow-C from the Yellow-B contained a median MRP concentration of 130μg L^{-1}, and inflows from the Yellow-I contained a median MRP concentration of 30μg L^{-1}. It is difficult to judge whether the Yellow-C sub-catchment itself contributed P to the stream, or if P was being stored in this catchment (as for example, when a stream flows through a wetland). That the Yellow-C catchment serves as a sink for P is suggested by the fact that water quality shows significant improvement with respect to 'upstream' *versus* 'downstream' median MRP values. If P was being stored in this catchment, there would be no way to account for this using a water quality ranking scheme based on median MRP of discharge from the catchment. The problem was also identified by the Three Rivers risk assessment model analysis (MCOS, 2002), in which the amount of P flowing *into* the catchment was found to be the most critical factor in determining catchment water quality. They noted that the Derg/Ree model for ranking landscapes for the potential to lose and transport P (Kirk *et al.*, 2001) failed to account for the P loading from upstream waters, and cited this as a potential reason for the failure of the Derg/Ree model to effectively predict high risk areas in the Boyne, Liffey and Suir catchments (MCOS, 2002).

Lack of information regarding point sources within some catchments may also have contributed to the lack of agreement between Catchment PRS rank scores and in-stream water quality. While the high in-stream P concentrations in the Yellow-B sub-catchment could possibly be due to errors in either data collection or analysis, it is also possible that there was a point source for P within this catchment that was not identified. Point sources from farmyards (provided information is available) would be accounted for in the 'farmyard conditions' factor, however in the case of the Yellow-B sub-catchment, no farmyards were present. In any case, if a point source of P emanates from somewhere other than a farmyard, the Catchment PRS does not account for it. The Lough Derg-Lough Ree Catchment Monitoring and Management Project (Kirk *et al*., 2001) also hypothesized that the inability of their model to identify and account for point sources contributed, in some cases, to poor correlation between risk as predicted by their ranking scheme and catchment water quality (Kirk *et al*, 2001).

The difficulties just described highlight a fundamental limitation of any 'simple' ranking scheme such as Catchment PRS, all of which attempt to provide valid decision support using a limited number of data. The accuracy and availability of those data is crucial, and in many cases, the type of data needed requires an evaluation of privately owned property. Catchment PRS was designed to assess the potential for P to be lost from diffuse agricultural sources and transported to surface water. P pollution, and is not appropriate for catchments significantly impacted by urban or industrial discharges.

Conclusions

Field PRS

Like similar, yet more complex, P loss evaluation procedures used widely in the U.S., Field PRS has the potential to identify critical source areas of P loss in catchments. Although the data available for evaluating Field PRS were very limited, they facilitated classifications to be made by this tool that agreed with evaluations produced using professional judgement. Information necessary for assigning risk levels to individual factors in the Field PRS should be readily available from farm records and/or field site evaluation. As it is, the Field PRS appears to be suitable for use as a self-assessment tool directly by farmers. An initial consultation with someone familiar with the ranking scheme may be enough to enable a farmer to apply the Field PRS to the farm without further assistance. Research should be done to investigate this, possibly involving a survey of farmers designed to identify barriers and/or benefits of using the Field PRS. Application of the Field PRS voluntarily by individual farmers may represent the greatest possibility of targeting critical source areas at the field scale so that appropriate nutrient management strategies can be implemented. As more data become available, further modifications of the Field PRS could improve the predictive capability of this ranking scheme.

Catchment PRS

Despite limitations highlighted during the course of this study, the Catchment PRS demonstrated potential as a tool by which to identify catchments at risk for P loss. As more data on Irish catchments become available with respect to land and nutrient use characteristics and in-stream P, modification of the Catchment PRS will be likely. For example, if data on P application timing became widely available, given its presumed influence on the risk of P transport to surface waters, this factor could be included as suggested in the original Magette PRS (Magette, 1998). Also, work by Daly *et al*. (2000) is generating P sorption profiles for soils across Ireland. When this work is completed, incorporating this information as a factor into the Catchment PRS should be investigated. Evaluations of Catchment PRS in catchments dominated by arable agriculture suggest the need to incorporate a factor for soil erosion. Likewise, an assessment should be conducted as to whether a multiplicative function for integrating weight-score products into a rank score might produce superior classifications to an additive function.

A significant challenge for any assessment scheme striving to produce qualitative classifications from quantitative scores involves the appropriate delineation of boundaries that define ‘low’, ‘medium’ and ‘high’ classifications. The same can be said for describing the ranges for a particular factor that correspond to ‘low’, ‘medium’ and ‘high’ risk associated with that factor. Sharpley *et al.* (2001) suggested a protocol by which this delineation can be accomplished. To do this accurately, several things are needed: (1) a large number of samples where field and land use information is collected simultaneously with measured P export, and (2) a ‘range’ of acceptable P exports (which varies depending on the status of the receiving waters). Because obtaining data of this breadth is costly and time consuming, synchronous datasets are relatively rare (and are virtually non-existent in Ireland). Hence validation and improvement of P ranking schemes such as those developed in this project are limited by not only the availability of detailed data, but also by the lack of information on the delineation of the boundaries between acceptable versus unacceptable P loss rates *at site specific locations within a catchment*. While there is scope for future modifications that may improve the accuracy of both Field PRS and Catchment PRS, the evaluations described herein have demonstrated the potential of these techniques for predicting the potential for P to be lost from Irish fields and catchments.

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Table 1. Magette phosphorus ranking scheme (Magette, 1998).

Catchment or Field Factor	Weight for Factor	Phosphorus Loss and/or Transport Risk		
		Low (1)	**Medium (2)**	**High (4)**
P usage in catchment	0.5	0-5 kg P ha^{-1}	5-10 kg P ha^{-1}	>10 kg P ha^{-1}
Condition of receiving waters	0.5	Saline waters, non-impounded waters, free flowing rivers and streams w/o nutrient problems	Oligotrophic and Mesotrophic lakes	Eutrophic and Hypertrophic lakes, other special designation waters
Ratio of land to water	0.75	Ratio < 36:1	36:1 < Ratio < 44:1	Ratio > 44:1
Farmyard conditions	0.8 (0 if no animals)	See supplement (Table 2), below		
P usage rate	1.0	0-5 kg P ha^{-1}	5-10 kg P ha^{-1}	>10 kg P ha^{-1}
P application time	0.9	Spring or just prior to crop needs	Late Summer or Early Fall	All other times
Soil test P (based on Morgan's test)	0.8	0-6 mg P l^{-1}	6.1-15 mg P l^{-1}	>15 mg P l^{-1}
Overland flow distance	0.75	Further than catchment average	Catchment average	Less than catchment average
Runoff risk	1.0	Soil groups: 6a, 6b, 6c; 7a, 7b; 8 but excluding peats	Soil groups: 4; 5 but excluding peats	Soil groups: 1;2;3a, 3b, 3c, but excluding peats

For a low magnitude, the assigned risk is 1, medium = 2, and high = 4. The final score is obtained by multiplying the risk level by the weight for each factor, and then summing these products. Interpretation of the final scores is as follows: < 10.8 = low risk, 10.8-21.6 = medium risk, > 21.6 = high risk.

Table 2. Supplemental Scoring[1] System for Farmyards (Magette, 1998).

Factor	Excellent (3 points each)	Good (2 points each)	Poor (1 point each)
Manure/slurry storage*	> 24 weeks	20-24 weeks	<20 weeks
Dirty water storage	≥12 weeks	12 weeks>x>2 weeks	<2 weeks
Silage effluent	greater than 3 days	3 days	<3 days
"dirty areas"**	100% covered	50% covered	<50% covered
Managerial Level***	Top 5% of producers	5%<x<50%	<50%
"Fatal Flaw"****	No		Yes

* Applicable to operations with animals only; allocate 3 points if no animals present; storage periods may require regional adjustment to take account the shorter winter in southern compared to northern areas

** Implies that roofed areas are fitted with gutters that divert all clean water.

*** Characteristics of exceptional managers would be attention to detail in terms of environmental as well as production issues, *e.g.* active use of nutrient management planning, well maintained equipment and facilities (*e.g.* non-leaking waterers), *etc.*

**** A "fatal flaw" is a situation that poses an imminent pollution threat (such as a cracked slurry store, a stream running through a farmyard, or a 'clean' water drain very near a pollutant source) and is cause to assign the farmyard an overall high pollution potential, regardless of other factors.

[1] Scoring - Add points. 13 or more = low ranking; 8-12 = medium ranking; less than 8 = high risk.

Table 3. Field PRS, developed from Magette (1998) for field scale application.

Factor	Weight for Factor	Phosphorus Loss and/or Transport Risk		
		Low (1)	**Medium (2)**	**High (4)**
P usage rate*	1.0 (0 if no P applied)	0-5 kg P ha^{-1}	5-10 kg P ha^{-1}	>10 kg P ha^{-1}
P application* time	0.9 (0 if no P applied)	Spring or just prior to crop needs	Late Summer or Early Autumn	All other times
Soil test P (Morgan's test)	0.8	0-6 mg P l^{-1}	6.1-15 mg P l^{-1}	>15 mg P l^{-1}
Runoff risk	1.0	Soil groups: 6a, 6b, 6c; 7a, 7b; 8 but excluding peats	Soil groups: 4; 5 but excluding peats	Soil groups: 1;2;3a, 3b, 3c, but excluding peats
Overland flow distance	0.75	> 30 m, or < 30 m and >15 m of vegetated buffer	< 30 m and > 8m vegetated buffer	< 30 m and < 8 m vegetated buffer
Condition of receiving waters	0.5	Saline waters, non-impounded waters, free flowing rivers and streams w/o nutrient problems	Oligotrophic and Mesotrophic lakes	Eutrophic and Hypertrophic lakes, other special designation waters
Soil Erosion	0.5	Well managed pastures	Poorly managed pastures with either overgrazing, direct access of animals to surface waters, or bare soil areas. or No-till crop systems	Row crops under tillage

*****P application rate and time factors should be assigned a 'high' risk if farmyard conditions indicate a 'high risk' farmyard (assessed using Table 2) is associated with the field being evaluated.
Final rank scores are classified as follows: <8.2 = 'low', 8.2-16.4 = 'medium' and >16.4 = 'high' potential of P loss from the site.

Table 4. Site characteristics and monitoring periods of field sites on which Field PRS was tested (from Kurz, 2000).

Site	Area (ha)	Morgan's P (mg/l)	Soil Type	Average Slope	Monitoring Period
Cowlands	0.46	17 (high)	Gley	3°	24.11.96 to 31.3.98
Warren 1	1.54	4 (low)	Gley	3°	24.11.96 to 31.3.98
Warren 2	1.09	8 (medium)	Gley	4°	8.11.97 to 31.3.98

Table 5. Management practices at field sites on which Field PRS was tested (from Kurz, 2000).

Site	Livestock Activity and Density	Silage Cuts	P Additions
Cowlands Jan. to Dec. 1996	Grazed (6.6 LU ha^{-1}) for 27 days from the end of March to the end of October.	None	P: 30kg P ha^{-1} on 25.3.96 as superphosphate
Jan.-Dec. 1997	Grazed (6.6 LU ha^{-1}) for 27 days from the end of March to the end of October.	None	P: 30kg P ha^{-1} on 20.3.97 as superphosphate
Jan.-Mar. 1998	None	None	None
Warren 1 Jan. to Dec. 1996	None	Cut for hay (June)	None
Jan. to Dec. 1997	Grazed (10.8 LU ha^{-1}) 2.7.97 to 14.7.97, and (5.2 LU ha^{-1}) 12.9.97 to 19.9.97	None	None
Jan. to Mar. 1998	None	None	None
Warren 2 Jan. to Dec. 1997	Grazed (18.3 LU ha^{-1}) for 30 days in July and August.	Cut for silage (end of May)	Slurry spread in March (33.7 m^3 ha^{-1}), which is approximately 26kg P ha^{-1}.
Jan. to Mar. 1998	None	None	None

Table 6. Catchment PRS, developed from Magette (1998) for catchment-scale evaluation of P loss risk.

Factor	Weight for Factor	Phosphorus Loss and/or Transport Risk		
		Low (1)	Medium (2)	High (4)
P usage in catchment	1.0 (0 if no P applied)	0-5 kg P ha^{-1}	5-10 kg P ha^{-1}	>10 kg P ha^{-1}
Condition of receiving waters	0.5	Saline waters, non-impounded waters, free flowing rivers and streams w/o nutrient problems	Oligotrophic and Mesotrophic lakes	Eutrophic and Hypertrophic lakes, other special designation waters
Ratio of land to water	0.75	Ratio < 36:1	36:1 < Ratio < 44:1	Ratio > 44:1
Farmyard conditions/ density	0.8 (0 if no animals)	> 1 yard / 30 ha and/or as assigned by the Magette PRS	1 yard / 15-30 ha and/or as assigned by the Magette PRS	< 1 yard / 15 ha and/or as assigned by the Magette PRS
Soil test P (based on Morgan's test)	0.8	0-6 mg P l^{-1}	6.1-15 mg P l^{-1}	>15 mg P l^{-1}
Runoff risk	1.0	Soil groups: 6a, 6b, 6c; 7a, 7b; 8 but excluding peats	Soil groups: 4; 5 but excluding peats	Soil groups: 1;2;3a, 3b, 3c, but excluding peats

Final rank scores were categorised according to guidelines in Magette (1998), as follows: <7.3 = 'low', 7.3-14.6 = 'medium' and >14.6 = 'high' potential for P loss from the site and transport to receiving water.

Table 7. Indicative characteristics of catchments on which Catchment PRS was tested.

Subcatchment or Catchment	**Area, ha**	**Average Morgan's Soil Test P, mg L^{-1}**	**Predominant Landuse**	**Runoff Risk Based on Soils/Geology**
Annesbrook	1,100	4	Pasture	High
Ara	2,806	5	Pasture	Low
Ballina	124	3	Pasture	Medium
Ballyheelan	219	3	Pasture	Medium
Beef Unit	24	8	Pasture	High
Bellsgrove	108	5	Pasture	High
Clarianna	2800	6	Pasture	Low
Clonmore	2,807	9	Pasture	Medium
Clonshanbo	2,100	7	Pasture	Low
The Cottage	288	3	Pasture	Low
Dairy Farm	80	8	Pasture	Medium
Dawn	1,130	4	Pasture	Low
Dripsey-D1	15	9	Pasture	Medium
Dripsey – D2	23	11	Pasture	Medium
Drumnavrick	304	3	Pasture	High
Grange Rahara	1200	4	Pasture	Low
Lossetkillew	208	4	Pasture	High
Omard	1250	5	Pasture	High
Yellow (entire)	2,440	3	Pasture / Tillage	Low
Yellow-A	102	6	Tillage	Low
Yellow-B	116	6	Tillage	Low
Yellow-C	330	3	Pasture	Low
Yellow-D	256	6	Tillage	Medium
Yellow-E	503	3	Tillage	Medium
Yellow-F	119	6	Tillage	Medium
Yellow-G	34	6	Tillage	Low
Yellow-H	107	6	Tillage	Low
Yellow-I	135	6	Tillage	Low
Yellow-K	148	6	Pasture / Tillage	Medium
Yellow-L	173	6	Pasture / Tillage	Low
Yellow-M	421	6	Pasture / Tillage	Low

Table 8. Field PRS applied to Kurz's (2000) field sites.

Catchment or Field Factor	Weight for Factor	Factor Risk: Low = 1;, Medium = 2; High =4		
		Warren 1	Warren 2	Cowlands
P usage rate[*]	1.0 (0 if no P applied)	1 (with 0 weight as no P applied)	4	4
P application[*] **time**	0.9 (0 if no P applied)	1 (with 0 weight as no P applied)	1	1
Soil test P (based on Morgan's test)	0.8	1	2	4
Runoff risk	1.0	4	4	4
Overland flow distance	0.75	1	1	1
Condition of receiving waters	0.5	1	1	1
Soil Erosion	0.5	1	1	1
Final Score[*]		6.55	12.25	13.85
Final Rank[**]		LOW	MEDIUM	MEDIUM
Measured Field P Loss[***]		778 g ha^{-1} (16-months)	300 g ha^{-1} (5-months)	5,300 g ha^{-1} (16-months)

[*] Final score equals the sum of all (factor risk * factor weight) (Magette, 1998).

[**] Final rank score was categorised as 'high', 'medium', or 'low' based on the procedure used in Magette (1998). The categories are: <7.4 = 'low', 7.4-14.9 = 'medium' and >14.9 = 'high' potential for P loss from the site.

[***] *From Kurz (2000).*

Table 9. Final rank scores from the Field PRS applied to Kurz's (2000) field sites using various overland flow distance weights to calculate the final score.

Overland Flow Risk	Field ID	Overland Flow Factor Weightings				
		0.75[*]	0.8	0.9	1.0	1.1
Low	Warren 1	LOW	LOW	LOW	LOW	LOW
	Warren 2	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM
	Cowlands	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM
Medium	Warren 1	LOW	LOW	MEDIUM	MEDIUM	MEDIUM
	Warren 2	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM
	Cowlands	MEDIUM	MEDIUM	HIGH	HIGH	HIGH
High	Warren 1	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM
	Warren 2	MEDIUM	MEDIUM	HIGH	HIGH	HIGH
	Cowlands	HIGH	HIGH	HIGH	HIGH	HIGH

*This weighting represents the weight assigned in the original Magette PRS (Magette, 1998), *c.f.* Table 1, and was included for comparison.

Table 10. Summary of final Catchment PRS rank orders and risk categorisations as compared to median in-stream MRP and water quality rating.

Sub-catchment or Catchment	**Rank Score from Catchment PRS**	**Rank Order**	**Catchment PRS Categorisation**[*]	**Measured Water Quality Median MRP (μg L^{-1})**	**Water Quality Rating**[**]
Dripsey – D2	15.8	1	HIGH	91	Unacceptable
Annesbrook	15.5	2	HIGH	40	Unacceptable
Beef Unit	15.4	3	HIGH	50	Unacceptable
Lossetkillew	13.9	4	MEDIUM	58	Unacceptable
Dripsey-D1	13.4	5	MEDIUM	26	Acceptable
Omard	13.2	6	MEDIUM	68	Unacceptable
Clonmore	12.0	7	MEDIUM	56	Unacceptable
Ballyheelan	12.0	8	MEDIUM	35	Unacceptable
Bellsgrove	11.9	9	MEDIUM	35	Unacceptable
Yellow-K	11.9	10	MEDIUM	40	Unacceptable
Yellow-B	11.9	11	MEDIUM	130	Unacceptable
Yellow-D	11.9	12	MEDIUM	50	Unacceptable
Dawn	11.8	13	MEDIUM	18	Acceptable
Yellow-G	11.4	14	MEDIUM	30	Acceptable
Yellow-H	11.4	15	MEDIUM	50	Unacceptable
Dairy Farm	10.9	16	MEDIUM	50	Unacceptable
Clonshanbo	10.2	17	MEDIUM	18	Acceptable
Yellow-A	9.9	18	MEDIUM	30	Acceptable
Yellow-L	9.9	19	MEDIUM	30	Acceptable
Yellow-I	9.9	20	MEDIUM	30	Acceptable
Yellow-C	9.4	21	MEDIUM	60	Unacceptable
Ara	9.2	22	MEDIUM	60	Unacceptable
Yellow-F	8.9	23	MEDIUM	30	Acceptable
Yellow-E	8.9	24	MEDIUM	10	Acceptable
Drumnavrick	8.7	25	MEDIUM	18	Acceptable
Clarianna	8.7	26	MEDIUM	16	Acceptable
Yellow-M	8.7	27	MEDIUM	20	Acceptable
Yellow (entire)	8.4	28	MEDIUM	30	Acceptable
Ballina	7.9	29	MEDIUM	29	Acceptable
Grange Rahara	6.7	30	LOW	5	Acceptable
The Cottage	6.4	31	LOW	29	Acceptable

*Catchment PRS categorisations of the potential to lose and transport P were assigned based on the following ranges for the numerical rank scores arising from Catchment PRS: <7.3 = 'low', 7.3-14.6 = 'medium', and >14.6 = 'high'.

**Water quality was classified as 'acceptable' if MRP < 30 μg L^{-1}; otherwise, water quality was classified as 'unacceptable'.

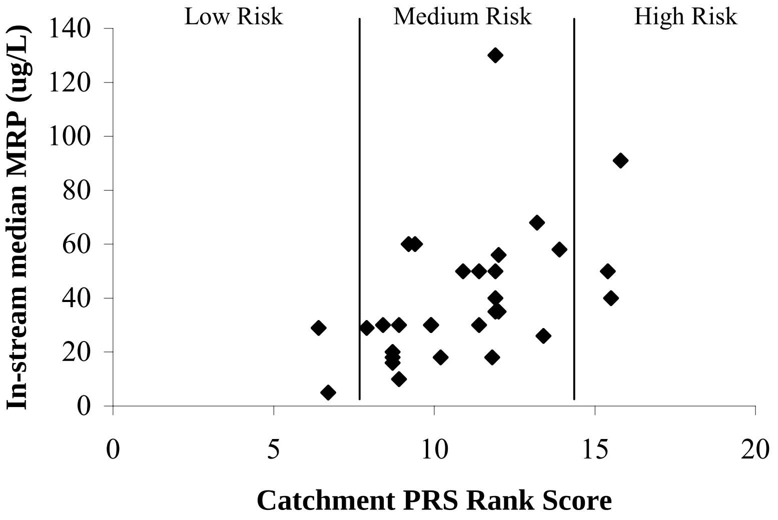

Figure 1. Catchment PRS rank score compared to in-stream median Molybdate Reactive Phosphorus (MRP) in μg L^{-1}. Catchment PRS risk categorisation was based on the following delineations: <7.3 = ‘low’, 7.3-14.6 = ‘medium’, and >14.6 = ‘high’ overall risk of P loss from the catchment.