ROLE OF SUBSURFACE FLOW PATHS FOR PHOSPHORUS LOSSES IN A DAIRY-GRAZED HEADWATER CATCHMENT

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The objective of this study was to identify flow pathways and link them to phosphorus (P) transport in the 8.7-ha Kiwitahi dairy-grazed pastoral catchment, Waikato. Our hypothesis was that P transport is equally influenced by saturation-excess (SE) and infiltration-excess (IE) runoff during storm flow and by shallow subsurface flow or in-stream exchanges during base flow. The occurrence of surface runoff was ascertained by localized surface runoff samplers, and the dynamics of the shallow subsurface flow system during and between rainfall events were captured by continuously recording shallow groundwater levels in five shallow wells installed at 2, 4, 8, 15 and 25 m distance from the stream along a transect perpendicular to the stream. Stream flow was continuously recorded at the outlet of the catchment. In monthly intervals, grab samples from the stream and the shallow wells were collected. Additional flow-proportional stream-water samples were taken during storm events. All samples were analyzed for reactive phosphorus (DRP) and total phosphorus (TP) concentrations. In the year December 2007 to December 2008, P losses totaled 695 g ha^{-1} TP and 169 g ha^{-1} DRP. The dynamics of the shallow groundwater table and the occurrence of SE areas were influenced by proximity to the stream. The limited presence of the water table at the surface and the limited extent of impervious areas generating IE runoff (0.7% of total catchment area) indicated that flow sources and transport of P during rainfall events was not limited to surface runoff. In fact, subsurface flow appeared to dominate both storm and base flow periods. Base flow accounted for 42% of annual flow, and contributed 37 and 52% to the DRP and TP loads, respectively. The match in P concentrations between groundwater and stream samples during baseflow inferred the importance of shallow groundwater for stream flow, but also the role of exchange via the hyporheic zone. Management strategies should focus at decreasing Olsen P to minimize leaching of P via subsurface flow to streams. Research is needed for both, quantifying the role of subsurface flow and expanding management strategies to include P transport during storm flow and base flow conditions.

Introduction

'Critical source areas' (CSAs) were defined by Pionke et al. (2000) as areas of the landscape where a large P source (e.g., elevated soil P concentrations) coincides with a high risk for surface runoff generation, and focused primarily on P transport via overland flow to streams. A few key assumptions relating to P transport shaped this concept of CSAs at the catchment scale including (1) that the majority of P transport from land to water happens via surface runoff (Sharpley et al., 1993); (2) that, annually, a few large storms events are typically responsible for the majority of P export (McDowell and Srinivasan, 2009); and (3) that saturation-excess (SE) runoff is the major transport mechanism controlling P movement (Needelman et al., 2004). There is, however, a growing body of literature that suggests other pathways of P loss may also contribute substantial P to surface waters (Heathwaite and Dils, 2000a; Toor et al., 2004). Unlike surface flow paths, which are dominantly active only during storm events, in catchments with perennial streams, the subsurface flow paths (including seepage zones) can be active over timeframes beyond storm periods (Heathwaite and Dils, 2000b). Moreover, management activities such as all-year grazing can significantly increase the importance of infiltration-excess (IE) runoff during storm events (e.g., McDowell and Srinivasan, 2009; Srinivasan and McDowell, 2009). To extend the applicability of the CSA concept to a wider range of catchments, one needs to consider P losses via surface and subsurface pathways during stormflow and baseflow conditions and SE and IE runoff mechanisms during storm events. These other potential P transport mechanisms (IE runoff and subsurface flows) have not been systematically investigated. In this study, we hypothesize that, in grazed, pastoral catchments, the transport of P is a function of both SE and IE runoff under storm flow conditions and of subsurface flows under base flow conditions. We investigated the need to expand the definition of CSAs to include both base flow and storm flow conditions. For this purpose, we examined the dynamics of shallow subsurface flow systems during and between rainfall events and analyzed the occurrence of various storm flow generation processes in a dairy-grazed pastoral catchment and linked the storm flow sources to phosphorus transport.

Methods

Description of the catchment

To improve our understanding of P transfer from land to surface water, we studied a subcatchment of the Toenepi catchment, the Kiwitahi subcatchment (area, 8.7 ha; outlet, N 6380645, E 2738580) (Fig. 1).

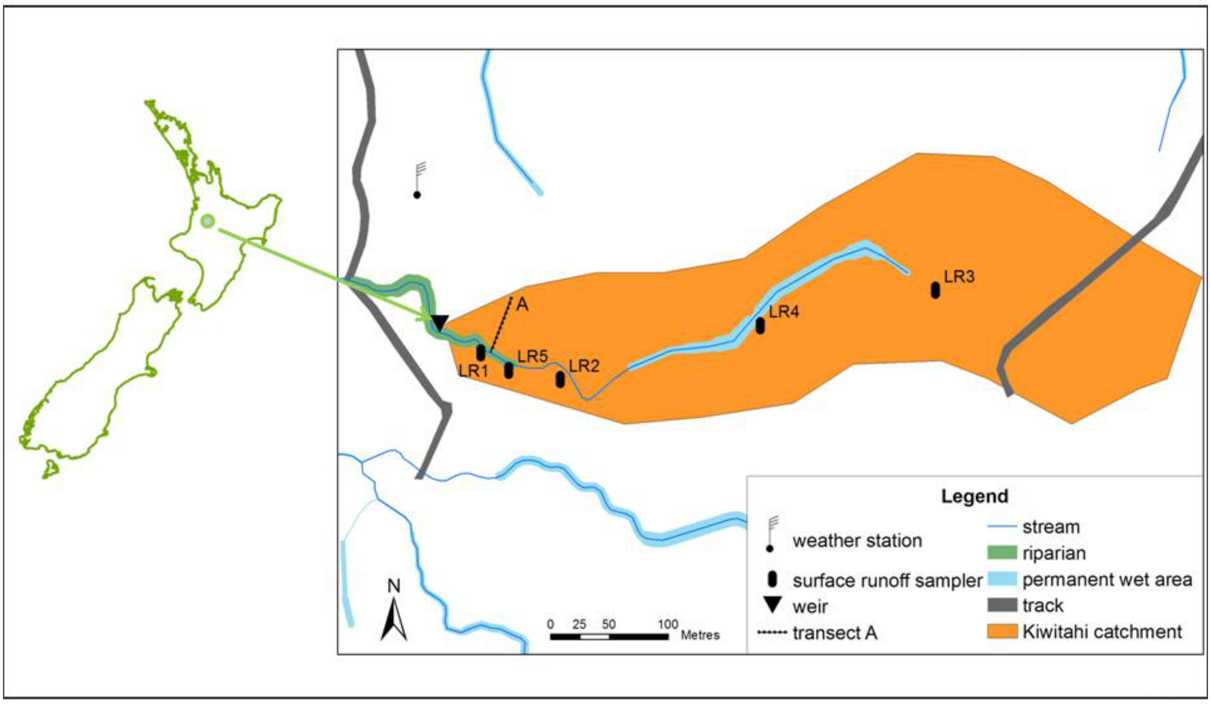

Figure 1. *Location of the Kiwitahi subcatchment and instrumentation of the catchment.*

A permanent wet area marked the head of the perennial stream. The subcatchment is under permanent pasture, and is grazed year-round by dairy cows at a medium stocking density (2.6 to 3.2 cows ha^{-1}). The dominant soils are silt loam-textured ash soils (Morrinsville soils; NZ Soil Classification: Typic Orthic Granular Soils) on the rolling slopes where the younger ash soils have been eroded, and gley soils (Topehaehae silt loam; NZ Soil Classification: Typic Recent Gley Soils). The latter generally occur in the lowest areas close to the streams and in valleys between hills (Wilson, 1980). The Morrinsville soils are characterized by a clay-illuvial B horizon, while the Topehaehae soils have a naturally high water table (Singleton and Addison, 1996). Topsoils (0 - 75 mm) of all paddocks were sampled at intervals of 4 m along GPS transects of 80 m, starting in the middle of each paddock in January 2009, and analyzed for Olsen P (Olsen et al., 1954).

In summer 2009, the extent of permanent water features (e.g., wetlands) and the stream network were recorded and geo-referenced. Furthermore, the locations of IE runoff areas such as farm tracks connected to the stream were also mapped. Superphosphate fertilizer was applied in spring (October) and autumn (April) at rates ranging between 20 and 35 kg P ha^{-1}.

P-losses during base flow and storm flow conditions

During 2008, automated flow recorders at the outlet of the Kiwitahi sub catchment recorded stream discharge at 10-min intervals. From the streamflow hydrograph, the proportions of storm- and base flow were determined using a recursive digital filter technique (Lyne and Hollick, 1979), as modified by Nathan and McMahon (1990). Following Arnold *et al.* (1995), a single filtering step was applied to separate the high frequency signals (storm flow) from the low frequency signals (base flow). While this automated method used to separate total stream flow into surface runoff and base flow (= groundwater flow), it has no true ‘physical meaning’, but has the advantage over manual techniques of being objective and reproducible. Water samples were collected at the outlet on a monthly basis. The monthly sampling was supplemented with storm event sampling. Flow sample collection was triggered by stage-height, initiated at 2, 4 and 8 cm changes in stage height over the rising limbs of the hydrographs. All water samples were refrigerated at 4ºC until analysis. Samples were analyzed for dissolved reactive P (DRP, P measured following filtration through a 0.45 μm filter within 24 h of collection), and for total P (TP), after a persulphate digestion (Jeffries et al., 1979). P measurements were made by flow injection and colorimetry (Murphy and Riley, 1962). Detection limits were 0.003 and 0.006 mg L^{-1} for DRP and TP, respectively. Annual DRP and TP loads were estimated by a linear interpolation method, where the average flow rate (L s^{-1}) during two subsequent sampling times was multiplied with the time period (s) to give the discharge volume (L), which was multiplied with the average concentration (mg L^{-1}) from the two subsequent sampling times (Kronvang and Bruhn, 1996). Specific yields were calculated by dividing annual loads by the respective catchment areas. Phosphorus concentrations were analyzed with summary statistics. All collected monthly stream flow samples were classified as base flow or storm flow samples. Data were tested for normality and log transformed, if necessary, prior to ANOVA to test for significant differences ($P < 0.05$) in mean base- and storm flow concentrations.

Rainfall and hydrological responses

Cumulative rainfall during the year 2008 amounted to 1377 mm, respectively (Fig. 2). Annual total flow represented 45% of rainfall. Runoff response was very variable and ranged from 0.4% of total (monthly) rainfall in February 2008 to 125% of the rainfall in August 2008. The limited number of calibration measurements at high flow for the weir might have led to an overestimation of high flow volumes. Stream flow during winter accounted for 77% of annual flow.

Nineteen rainfall events with depth greater than 20 mm were recorded. These events (spread over 97 days; 26% of the year) accounted for 78% of the total rainfall, and produced 347 mm stormflow (160 mm baseflow), which represented 98% of the total stormflow. Separation of base- and storm flow indicated that base flow accounted for 42% of total flow. A mean base flow index of 0.5 means that 50% of the rainwater reaches the stream via subsurface pathways. The Kiwitahi subcatchment is dominated by Granular soils characterized by a clay-illuvial Bt-horizon, which encourages lateral subsurface flow towards the stream. The seasonal contributions of base-and storm flow to total flow are summarized in Table 1. Storm flow was slightly less important than base flow during spring, with 43%.

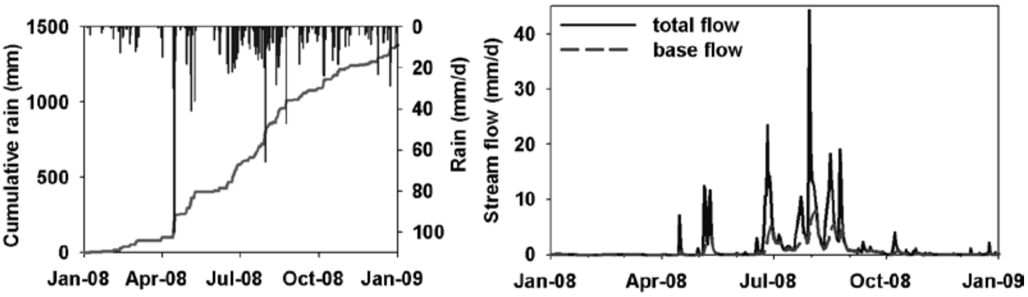

Figure 2. *Cumulative and daily rain (left), total stream flow and base flow in the Kiwitahi subcatchment (right) during 2008.*

Table 1. *Seasonal base flow and storm flow volumes and their percentage of total seasonal flow in italics, average concentrations of total phosphorus (TP) and dissolved reactive phosphorus (DRP) during 2008. The figures in parentheses refer to one standard deviation.*

	Rain	**Base flow**			**Storm flow**		
	(mm)	**Flow (mm)**	**TP (mg L^{-1})**	**DRP (mg L^{-1})**	**Flow (mm)**	**TP (mg L^{-1})**	**DRP (mg L^{-1})**
Spring	246	23	0.08	0.05	17	0.11	0.02
		57	(0.11)	(0.07)	*43*	(0.13)	(0.01)
Summer	171	3	0.59	0.02	5	0.11	0.01
		39	(0.47)	(0.02)	*61*	(0.07)	(0.00)
Autumn	350	20	0.41	0.09	50	0.11	0.04
		29	(0.45)	(0.13)	*71*	(0.10)	(0.04)
Winter	610	207	0.04	0.01	271	0.09	0.04
		43	(0.02)	(0.01)	*57*	(0.05)	(0.02)

Phosphorus losses during storm- and base flow

P losses totalled 695 g ha^{-1} TP and 169 g ha^{-1} DRP, respectively. Each of the nineteen rainfall events that recorded more than 20 mm and produced greater than 1% of the total storm flow were flow-proportionally sampled at the outlet. As a percentage of total loads, storm flow accounted for 63 and 48% of the DRP and TP losses, respectively. In autumn, however, the percentage of P loads in storm flow was much higher and reached 91% for both P fractions (18 and 15% of the annual DRP and TP losses, respectively). The high fraction of P losses in storm flow during autumn was explained as incidental P loss following the classification of losses into incidental and background losses (McDowell et al., 2004). Incidental losses are classified as those where a concentrated and readily available (e.g., a recent fertilizer application) source of P and a flow event (e.g., surface runoff) coincide, whereas background losses result from events where either the concentration or the availability of P is low. Most paddocks of the Kiwitahi subcatchment were fertilized with superphosphate ten days after the year's largest single rainfall event of 146 mm (15 April 2008). About 108 mm rain, spread over two events, started three days after this fertilizer application and led to 85% of the total P losses in autumn. It is very difficult to design practices targeting such infrequent, unpredictable extreme events.

Distinguishing between SE and IE surface runoff

A transect consisting of five shallow wells (1.5 m deep) was installed. The wells (3.2 cm diameter PVC pipe) were cut with 0.7 mm slits in a spiral pattern and wrapped in 200 µm nylon mesh for their entire length. Each well monitored changes in water table status at 10-min intervals. These data were used to determine when the soil profile was completely saturated (water table at the surface), a prerequisite for SE runoff. When samples were drawn monthly, the wells were purged to dryness and subsequently sampled using a low flow peristaltic pump. Furthermore, five localized surface runoff samplers (LR) were installed to ascertain the occurrence of surface runoff by collecting the first flush of runoff. The LR sampler is described in detail in Müller et al. (2010). They were located in areas dominated by different surface runoff generating mechanisms (Fig. 1). LR1 was installed next to the near-stream well and provided additional evidence for the occurrence of SE runoff. LR2 and LR4 were located at the bottom of a gully that often hydraulically connects to the stream, while LR3 was situated at a spring. LR5 was installed where a dirt track connected to the stream that was thought to represent a typical IE runoff generation zone.

The depths to the water table in the shallow wells differed in their responses to rainfall depending on the proximity of wells to the stream (Fig. 3). The mean depths to the water table were 0.4, 1.2, 1.4, 1.5 and 1.5 m below the ground surface for W1, W2, W3, W4 and W5 located at 2, 4, 8, 15 and 25 m distance from the stream, respectively.

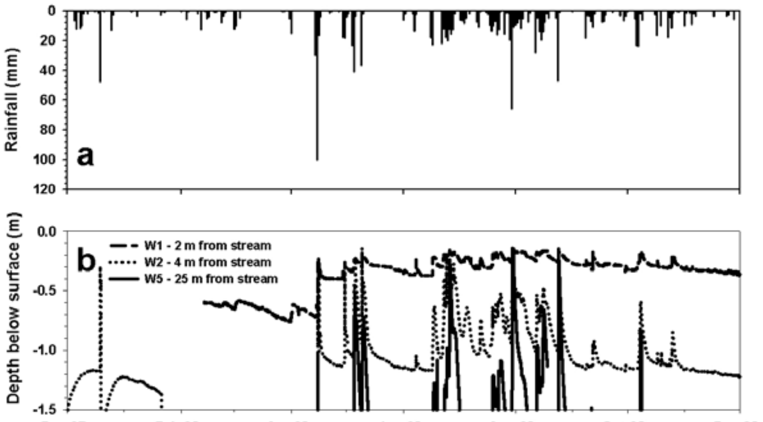

Figure 3. *Daily rainfall (a) and shallow water table responses as recorded at well W1, W2 and W5 at 2, 4 and 25 m distance from the stream (b).*

Seasonal fluctuations in the depths to the water table within the transect ranged from 0.2 m below the surface in June/July 2008 to more than 1.5 m in January/February 2008. From June to September 2008, during and immediately following rainfall events, the water table rose to within 0.2 m of the surface at the near-stream well, but it also occurred several times in the far-stream well (Fig. 3). Between April and December 2008, the mean depth to the water table at the near-stream well W1 was 0.4 m below the ground surface and rose rapidly to as close as 0.05 m from the surface during events. For the other four wells, the responses to rainfall were less pronounced, and the mean depths to the water table increased with increasing distance from the stream (Fig. 3). This kind of response from far-stream wells was limited to heavy rainfall during winter with high antecedent soil moisture conditions. The water table in none of the wells rose to the surface even for storm events larger than 100 mm (Fig. 3). A water table at the surface indicates complete saturation of a soil profile, a precondition for saturation-excess runoff to occur. The surface runoff sampler LR1 located on the same hill close to the stream (Fig. 1) was active during most heavy rainfall events (data not shown). The water table recordings combined with the surface runoff sampler observations indicated that IE rather than SE caused the surface runoff at this location.

Identifying storm flow generation processes

Storm flow sources were estimated for selected rainfall events based on the base flow separation of measured flow, and mapping of the extent of the permanent wet areas and the stream (Table 2). Channel precipitation and precipitation on the permanent near-stream wet areas were assumed to contribute directly to storm flow (Cooke and Dons, 1988). The stream and the permanent wet areas in the Kiwitahi subcatchment totalled 209 and 2,680 m^2 (0.2 and 3.1% of the catchment area), respectively. Moreover, an area of approximately 600 m^2 of dirt roads was directly connected to the stream, and, thus, functioned as an impervious area producing IE runoff. The surface runoff sampler LR5 located in these impervious areas (Fig. 1) were generally active (collecting samples) during the nine storm events. We assumed that rainfall onto these impervious areas would contribute directly to storm flow via surface runoff, as they were connected to the stream.

Table 2. *Estimated stormflow components and the extents of critical source areas (CSA) for selected rainfall events in the Kiwitahi subcatchment (8.7 ha). RC, the runoff coefficient, is the ratio of the runoff volume to the rainfall volume.*

Date[1]	Rain (mm)	Storm flow[2] (m^3)	RC (%)	Estimated contribution (m^3) from				CSA[7] (m^2)
				precipitation onto			other sources[6]	
				stream[3]	wet areas[4]	IE areas[5]		
19/12/07	48.8	212	5	10	130	29	43	4,340
14/04/08	146.6	686	5	31	393	88	174	4,679
29/04/08	40.0	98	3	8	107	24		2,458
4/05/08	67.8	2,174	37	14	182	41	1,937	32,071
15/06/08	40.4	358	10	8	108	24	218	8,866
29/07/08	136.0	6,650	56	28	364	82	6,176	48,899
24/08/08	47.8	2,656	63	10	128	29	2,489	55,571
27/09/08	3.4	19	7	1	9	2	7	5,626
5/10/08	59.6	742	14	12	160	36	534	12,453

[1] The duration of the events ranged from 1 to 8 days.

[2] Storm flow volume estimated from measured total stream flow at the catchment outlet.

[3] Precipitation onto the stream was assumed to become storm flow.

[4] Precipitation onto permanent near-stream wet areas was assumed to become storm flow.

[5] Precipitation onto dirt farm tracks directly connected to the stream was assumed to become storm flow.

[6] The contribution of other sources was calculated by subtracting the above described storm flow components from the total measured storm flow. These other sources are undefined and not fully investigated.

[7] The extent of CSA is estimated as RC/100 x catchment area (Gburek *et al.*, 2002).

Until May 2008, at least 70% of the storm flow was derived from channel precipitation, IE runoff from dirt roads and precipitation onto the permanent wet areas in the Kiwitahi subcatchment. The near-stream wells W1 and W2 responded to rainfall during the summer months (Fig. 3) but the water table did not reach the surface. It thus is very likely that subsurface contributions to stormflow accounted for the remainder of the storm flow measured. As the extent of catchment with saturated soil conditions increased following a rainfall event of 147 mm between 14 and 19 April 2008, the contributions from direct precipitation on wet areas and runoff from IE areas accounted only for small portions (6 - 43%) of total storm flow (see events from May to October 2008, Table 2). The remainder of the storm flow thus originated from other subsurface and/or SE runoff contributions. To test the hypothesis that SE surface runoff generated the remaining storm flow volumes, we applied Gburek *et al.*'s approach (2002) to estimate the extent of the surface runoff transport areas by multiplying the catchment area by the runoff coefficient. The estimated areas ranged from 3 to 63% of the catchment area. However, because the water table in the wells never rose to the surface, surface runoff from such large saturation areas is highly unlikely. Even though the surface runoff samplers located in seepage areas throughout the catchment were active during various events from May to October, their response was very sporadic, pointing towards contributions via exfiltration flows. Cooke and Dons (1988) found sufficient evidence for subsurface flow contributions to stormflow in a pastoral catchment developed on ash soils in New Zealand. Srinivasan *et al.* (2002), measuring runoff contributions in a hillslope-scale study, concluded that less than 5% of storm flow contributions came via overland, thereby inferring an active subsurface system. It is very likely that there was an active hydraulic connection between land and stream via shallow subsurface flow pathways during many large events in the Kiwitahi subcatchment.

Linking stormflow sources to phosphorus sources and transport

We found strong hydrologic evidence for an active shallow subsurface groundwater system. We hypothesize that subsurface flow might have contributed significantly to P losses to the stream. The DRP concentrations in the shallow groundwater wells remained relatively unchanged throughout the year (mean 0.02 mg L^{-1}; standard deviation 0.01 mg L^{-1}). Cooke (1988) reported mean DRP concentrations of 0.1 mg L^{-1} in samples collected from piezometers at 0.3 m depth in a pastoral headwater catchment in New Zealand. Conditions favouring enriched DRP concentrations in groundwater include high soil fertility, soils with poor P retention, and a shallow groundwater table (Atkinson, 1974). Our catchment exhibited both enriched topsoil P (54 mg kg^{-1}, average Olsen P of topsoils) and a shallow groundwater table. Groundwater as a source of P to streams has been identified in several other studies (e.g., McMahon et al., 1994; Taniguchi et al., 1997). Indeed, the mean DRP concentration from shallow groundwater samples were not significantly different (P = 0.061) from the average DRP concentration in stream water samples collected at the Kiwitahi outlet.

Summary

We examined the applicability of the CSA concept, a concept widely recommended for identifying and controlling P transport at catchment scale, to a pastoral catchment. Based on the water table data from shallow groundwater wells and the frequency of samples collected in surface runoff samplers, it appeared that IE runoff was the more relevant runoff-generating mechanism. The limited extent of impervious areas generating IE runoff and the limited presence of the water table at the surface indicated that IE and SE runoff played a smaller role in P transfer from land to stream in this catchment than expected. Detailed hydrometric data from near- and far-stream wells provided evidence of the significance of shallow subsurface contributions to stormflow.

For the period December 2007 to December 2008, baseflow accounted for 42% of total streamflow in the Kiwitahi subcatchment. It was estimated that 52 and 37% of the annual TP and DRP losses, respectively, occurred during baseflow conditions. These large P loads during baseflow highlighted that CSAs for baseflow might be as important as CSAs for stormflow in this catchment. A high spatial variability of shallow groundwater levels was observed. Our knowledge of subsurface flow systems, their response times, flow characteristics is incomplete and indicates that further field research and monitoring of these flow paths is needed as the next step in mapping transport areas in catchments dominated by subsurface flow.

Phosphorus-enriched groundwater can become a source of P to streams through shallow subsurface flow. This pathway may contribute to stream flow for the majority of the year. Subsurface runoff, thus, needs to be further explored and tied to management. While the quality of surface runoff can be altered with filter strips and riparian buffers, there are fewer tools to manage subsurface water quality. It is crucial to control Olsen P concentrations in soils to prevent P leaching.

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References

Arnold, J.G., Allen, P.M., Muttiah, R., Bernhardt, G., 1995. Automated base flow separation and recession analysis techniques. Ground Water 33, 1010-1018.

Atkinson, J.C., 1974. Orthophosphate in ground water, Hall County, Nebraska. Ground Water 12, 291-295.

Cooke, J.G., 1988. Sources and sinks of nutrients in a New Zealand hill pasture catchment II. Phosphorus. Hydrological Processes 2, 123-133.

Cooke, J.G., Dons, T., 1988. Sources and sinks of nutrients in a New Zealand hill pasture catchment I. Stormflow generation. Hydrological Processes 2, 109-122.

Gburek, W.J., Drungil, C.C., Srinivasan, M.S., Needelman, B.A., Woodward, D.E., 2002. Variable-source-area controls on phosphorus transport: Bridging the gap between research and design. Journal of Soil and Water Conservation 57, 534.

Heathwaite, A.L., Dils, R.M., 2000a. Characterising phosphorus loss in surface and subsurface hydrological pathways. Sci. Total Environ. 251-252, 523-538.

Jeffries, D.S., Dieken, F.P., Jones, D.E., 1979. Performance of the autoclave digestion method for total phosphorus analysis. Wat. Res. 13, 275-279.

Kronvang, B., Bruhn, A.J., 1996. Choice of sampling strategy and estimation method for calculating nitrogen and phosphorus transport in small lowland streams. Hydrological Processes 10, 1483-1501.

Lyne, V., Hollick, M., 1979. Stochastic time-variable rainfall-runoff modeling. In: I.E. Austr. Nat. Conf. Publ., Inst. of Eng, 89-93.

McDowell, R.W., Biggs, B.J.F., Sharpley, A.N., Nguyen, L., 2004. Connecting phosphorus loss from land to surface water quality. Chemistry and Ecology 20, 1-40.

McDowell, R.W., Srinivasan, M.S., 2009. Identifying critical source areas for water quality: 2. Validating the approach for phosphorus and sediment losses in grazed headwater catchments. Journal of Hydrology 379, 68-80.

McMahon, P.B., Litke, D.W., Paschal, J.E., Dennehy, K.F., 1994. Groundwater as a source of nutrients and atrazine to streams in the south platte river basin. Water Resources Bulletin 30, 521-530.

Müller, K., Srinivasan, M.S., Trolove, M., McDowell, R., 2010. Identifying and linking source areas of flow and P transport in dairy-grazed headwater catchments, North Island, New Zealand. Hydrological Processes DOI: 10.1002/hyp.7809.

Murphy, J., Riley, J.P., 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27, 31-36.

Nathan, R.J., McMahon, T.A., 1990. Evaluation of automated techniques for base flow and recession analyses. Wat. Resourc. Res. 26, 1465-1473.

Needelman, B.A., Gburek, W.J., Petersen, G.W., Sharpley, A.N., Kleinman, P.J.A., 2004. Surface runoff along two agricultural hillslopes with contrasting soils. Soil Sci. Soc. Am. J. 68, 914-923.

Olsen, S.R., Cole, C.V., Watanabe, F.S., Dean, L.A., 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. United States Government Print Office, Washington, D.C., USA.

Pionke, H.B., Gburek, W.J., Sharpley, A.N., 2000. Critical source area controls on water quality in an agricultural watershed located in the Chesapeake Basin. Ecological Engineering 14, 325.

Pionke, H.B., Gburek, W.J., Sharpley, A.N., Schnabel, R.B., 1996. Flow and nutrient export patterns for an agricultural hill-land watershed. Wat. Resourc. Res. 32, 1795-1804.

Sharpley, A.N., Daniel, T.C., Edwards, D.R., 1993. Phosphorus movement in the landscape. Journal Prod. Agric. 6, 492-500.

Singleton, P.L., Addison, B., 1996. Water quality in a dairy farming catchment, distribution and hydraulic characteristics of the Topehaehae soil. AgResearch Consultancy Report No. 194/96. AgResearch Ltd., Hamilton, New Zealand.

Srinivasan, M.S., McDowell, R., 2009. Identifying critical source areas for water quality: 1. Mapping and validating transport areas in three headwater catchments in Otago, New Zealand. Journal of Hydrology 379, 54-67.

Taniguchi, M., Sharma, M.L., Herne, D., Byrne, J., 1997. Assessing groundwater nutrient discharge into Lennard Brook, Western Australia. Freshwater Contamination 243, 195-201.

Toor, G.S., Condron, L.M., Di, H.J., Cameron, K.C., 2004. Seasonal fluctuations in phosphorus loss by leaching from a grassland soil. Soil Sci. Soc. Am. J. 68, 1429-1436.

Wilson, A.D., 1980. Soils of Piako County, North Island, New Zealand. NZ Soil Bureau.