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Transport and retention of phosphorus in surface water in an urban slum area

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Abstract

The transport of excessive phosphorus (P) discharged from unsewered informal settlements (slums) due to poor on-site sanitation is largely unknown. Hence, we investigated the processes governing P transport in a 28 km^2 slum-dominated catchment in Kampala, Uganda. During high runoff events and a period of base flow, we collected hourly water samples (over 24 h) from a primary channel draining the catchment and from a small size tertiary channel draining one of the contributing slum areas (0.5 km^2). Samples were analyzed for orthophosphate (PO_4–P), particulate P (PP), total P (TP) and selected hydro-chemical parameters. Channel bed and suspended sediments were collected to determine their sorption potential, geo-available metals and dominant P forms. We found that P inputs in the catchment originated mainly from domestic wastewater as evidenced by high concentrations of Cl (36–144 mg L^{-1}), HCO_3 and other cations in the channels. Most P discharged during low flow conditions was particulate implying that much of it was retained in bed sediments. Retained P was mostly bound to Ca and Fe/Al oxides. Hence, we inferred that mineral precipitation and adsorption to Ca-minerals were the dominant P retention processes. Bed sediments were P-saturated and showed a tendency to release P to discharging waters. P released was likely due to Ca-bound P because of the strong correlation between Ca and total P in sediments ($r^2 = 0.9$). High flows exhibited a strong flush of PP and SS implying that part of P retained was frequently flushed out of the catchment by surface erosion and resuspension of bed sediment. Our findings suggest that P accumulated in the channel bed during low flows and then was slowly released into surface water. Hence, it will likely take some time, even with improved wastewater management practices, before P loads to downstream areas can be significantly reduced.

1 Introduction

Phosphorus (P) derived from urban catchments in growing cities in sub-Saharan Africa is increasingly becoming a major cause of eutrophication of urban fresh water bodies (Nhapi et al., 2002; Nyenje et al., 2010). In unsewered low-income areas, where the provision of sanitation services is usually poor, eutrophication problems are even greater because nutrients are directly discharged into streams as untreated/partially treated wastewater from households (NWSC, 2008; Kulabako et al., 2010; Isunju et al., 2011; Katukiza et al., 2010; Bere, 2007; Nhapi and Tirivarombo, 2004; Nhapi et al., 2002; Foppen and Kansiime, 2009). Several studies have investigated the fate of P in streams in order to seek ways of effectively managing its transport. These studies have, on one hand, focused on understanding the seasonal variations of P transported during low flow and high flow conditions (e.g. Stutter et al., 2008; Zhang et al., 2007; Blanco et al., 2010; Peters and Donohue, 2001; Jordan et al., 2005). They generally show that high flows due to storm runoff exhibit higher concentrations of phosphorus predominantly in particulate form compared to base flows. This phenomenon is attributed to the first-flush effect, where the first part of the storm runoff has substantially higher concentrations of pollutants than later parts (Deletic, 1998; Gupta and Saul, 1996). A view therefore exists that during the rising limb of the hydrograph, there is an initial flushing of P-rich sediments generated from terrestrial runoff and from re-suspension of channel bed sediments (e.g. Zhang et al., 2007; Rodríguez-Blanco et al., 2013; Blanco et al., 2010; Evans et al., 2004; Stutter et al., 2008). P transport during high flows is usually strongly associated with suspended sediment and hence both parameters tend to exhibit first-flush effects. Some studies, however, report that the first-flush effect may not be present for certain forms of P, such as dissolved nutrients, owing to dominance of other mechanisms such as leaching, dilution and discharge from base flows (Chua et al., 2009; Zhang et al., 2007; Blanco et al., 2010; Evans et al., 2004; Jordan et al., 2005).

Other studies have focused on understanding chemical processes such as redox reactions, precipitation and dissolution and adsorption by soil and sediments, which can affect the transport of phosphorus in streams and rivers (Froelich, 1988; Evans et al., 2004; Bedore et al., 2008). For example, mineral precipitation reactions with Fe, Al, Ca and Mn can cause P retention in sediments (Evans et al., 2004; Bedore et al., 2008; Golterman and Meyer, 1985; Reddy et al., 1999). In hard and alkaline fresh waters, most P is often retained by precipitating as hydroxyapatite (Olli et al., 2009; Golterman, 1995). The sorption of P to iron and aluminium oxides and hydroxides is, however, considered one the most important process contributing to retention of P in bed sediments in river systems (Froelich, 1988; Golterman, 1995). P can also adsorb and co-precipitate with calcite in Ca-rich waters hence contributing to P retention (e.g. Bedore et al., 2008; Olli et al., 2009; Golterman, 1995). P retained in bed sediments can, however, be released back to discharging waters either by mineral dissolution or ion exchange (Olli et al., 2009; Fox et al., 1986) or by breakdown of organic matter (Watts, 2000), hence contributing P loads to downstream ecosystems. Existing literature shows that most P studies have been carried out in agricultural and forested watersheds where the transport of P is mostly associated with sediments and agricultural fertilizers (Evans et al., 2004; Rodríguez-Blanco et al., 2013; Blanco et al., 2010; Pionke et al., 1999). To our knowledge, studies on P transport in streams and/or channels draining unsewered informal settlements (or slums), where most P discharges are associated with untreated or poorly treated domestic wastewater discharge from on-site sanitation, have not been published.

The main objective of this paper is to identify the processes affecting the transport and fate of phosphorus in drainage channels in an unsewered slum-dominated catchment in Kampala, Uganda. More specifically, our objectives were to: (i) quantify, during high and low flow conditions, the contribution of various forms of phosphorus in channels draining the catchment, (ii) identify the effect of rainfall runoff on the discharge of phosphorus, and (iii) identify the mechanisms controlling the fate of phosphorus in these channels.

2 Catchment description

The study area is the upper Lubigi catchment (28 km^2) located North of Kampala, the capital city of Uganda (Fig. 1). The catchment is largely urbanized with a number of illegal informal settlements or slums such as Bwaise, Mulago, Kazo and Kamwokya, located in low-lying areas (Fig. 1). The catchment is largely unsewered (not provided with a sewer) implying that most people rely on on-site sanitation for wastewater disposal (NWSC, 2008; Kulabako et al., 2004). On-site sanitation in slums is, however, very poor and is characterized by poorly constructed pit latrines, open defecation, disposal of untreated wastewater in drainage channels during rain events, flying toilets (use of polyethylene bags for excreta disposal in drainage channels and waste dumps) and poor solid waste management (Kulabako et al., 2007; Nyenje et al., 2013; Katukiza et al., 2010; Isunju et al., 2011; CIDI, 2006). As a result, most wastewater generated in the catchment ends up in the drainage system hence introducing a number of pollutants and nutrients to downstream ecosystems. The drainage system consists of small open drains or tertiary channels located between buildings, which convey a combination of runoff and wastewater into a system of larger channels, or secondary channels. Finally, the secondary channels discharge into the primary Nsooba channel (about 3 m wide), which eventually discharges through Bwaise slum to Lubigi swamp (not shown in Fig. 1). Lubigi swamp is one of the largest wetlands in Kampala city and provides a good buffer against floods and pollutants from informal settlements and industries in the catchment. However, increasing degradation and pollution are affecting the ability of Lubigi swamp to buffer nutrients and other pollutants from upstream areas (e.g. Natumanya et al., 2010; Okiror et al., 2009). A similar problem is faced with other wetlands in Kampala, hence threatening the survival of vital ecosystems like Lake Victoria due to eutrophication (Kansiime et al., 2005; Kansiime and Nalubega, 1999; Kelderman et al., 2007).

The catchment is underlain by Precambrian basement rocks consisting of predominantly granite-gneiss that have been deeply weathered to lateritic regolith soils (Taylor and Howard, 1999). The regolith soils and fractured rocks are important spring water aquifers in the catchment, which also form head waters of secondary drainage channels (Nyenje et al., 2013). The mean annual rainfall measured at Makerere University weather station (see location in Fig. 1) is 1450 mm a^{-1} with two rain seasons (March–May and September–December). During heavy storms, low-lying areas experience a lot of flooding because the catchment is highly urbanised. In slum areas like Bwaise (Fig. 1), flooding is even worse because of heavy siltation and blockage of drainage pipes due to poor solid waste disposal (Kulabako et al., 2010).

3 Methodology

3.1 Discharge monitoring and precipitation

A stream gauge, equipped with a Mini-Diver data logger (Schlumberger water services, Delft, the Netherlands), was installed in Nsooba channel at the outlet of the catchment (B1) to monitor discharge (Fig. 1). The diver continuously recorded water levels at 20 min intervals. The stream water levels were compensated for atmospheric pressure using a Baro-Diver (Schlumberger water services, Delft, the Netherlands) installed near the stream gauge. The compensated water levels, H (cm) were converted to discharge, Q ($m^3\,s^{-1}$) using a rating curve ($Q = 0.0006H^2 - 0.0076H$; $r^2 = 0.99$), which was developed from a series of discharge measurements carried out. These discharges were measured at the outlet of the catchment during different hydrological situations using the salt dilution method (Moore, 2004). Discharge measurements in the tertiary drain in Bwaise slum (Fig. 1) were not possible. Long term daily precipitation data, which were used to estimate the annual average precipitation, were provided by the Uganda meteorological department whose nearest weather station is located in Makerere University, about 2 km from the outlet of the catchment (Fig. 1). During storms, rainfall data at 5 min intervals and 0.2 mm resolution were provided by the CREEC project (the Centre for Research in Energy and Energy Conservation; http://creec.or.ug/) located next to the College of Engineering, Design, Art and Technology, Makerere University, about 2 km from the catchment outlet.

3.2 Water quality sampling and analysis

Water quality sampling was initially carried out 2–3 times a month during low flow conditions between March and July 2010 to understand the background concentrations of P forms, and of selected hydro-chemical parameters (i.e. EC, pH, DO, temperature, suspended solids, NO_3–N, HCO_3, Cl, Ca, Mn and Fe) in the drainage channels. A total of 19 water samples were manually collected using 1-litre plastic bottles at the outlet of the catchment (B1) and in one of the tertiary drains (B4) in Bwaise III slum (0.5 km^2) located near the outlet of the catchment (Fig. 1). Prior to sampling, the bottles were first washed with detergent, then soaked in dilute hydrochloric acid and finally rinsed with tap water and then with demineralized water. To establish the behavior of phosphorus during high and low flows, event water quality monitoring rounds were carried out at intervals of 1–2 h for 24 h during a low flow period on 26 May 2010 (depicting base flow conditions) and during two rainfall events on 28 June and 28 July 2010.

All water samples were analyzed on-site for Electrical Conductivity (EC), temperature, pH, dissolved oxygen (DO) and Alkalinity (HCO_3). EC and temperature were measured with an EC electrode (TetraCon 325, WTW) connected to an EC meter (WTW 3310), pH with a pH electrode (SenTix 21, WTW) connected to pH meter (WTW 3310) and DO with a DO sensor (CellOx 325, WTW) connected to a DO meter (WTW 3310). All meters were calibrated before taking measurements. HCO_3 was determined by titrating with 0.2M sulphuric acid. The samples were then kept in a cool box at 4 °C, transported to Makerere University Public Health and Environmental Engineering Laboratory and analyzed for total phosphorus (TP), orthophosphate (PO_4–P) and total dissolved phosphorus (TDP) in less than 24 h after collecting the samples. Particulate phosphorus (PP) was calculated as the difference between concentrations of TP and TDP. TP was determined on unfiltered samples using the Ascorbic acid method after digestion with persulphate (APHA/AWWA/WEF, 2005), TDP on filtered samples using the same method as TP and PO_4-P determined on filtered samples using the Ascorbic acid method (Murphy and Riley, 1962). Samples were also analysed for NO_3-N using the cadmium reduction method. Final readings were carried out on a HACH DR/4000 U spectrophotometer (USA). Samples collected during the two rainfall events were also analysed for total solids (TS), which were determined by evaporating an unfiltered sample in an oven at 105 °C for 24 h, and then determining the mass of the dry residue per liter of sample (APHA/AWWA/WEF, 2005). Total dissolved solids (TDS) were not directly measured but estimated by multiplying the electrical conductivity (EC) with a conversion factor of 0.56. The conversion factor was calculated from a linear relationship ($n = 31$, $r^2 = 0.99$) of a series of TDS and corresponding EC values, which were measured during background water quality sampling. The factor we used was within acceptable limits (0.55–0.7; APHA/AWWA/WEF, 2005). Total suspended solids (SS) were then calculated as the difference between TS and TDS concentrations. Other dissolved analytes were also measured on filtered samples at UNESCO-IHE laboratory in the Netherlands: Ca, Mn and Fe using an Inductively Coupled Plasma spectrophotometer (ICP – Perkin Elmer Optima 3000) and Cl by ion-chromatography (IC – Dionex ICS-1000).

3.3 Sediment sampling and analysis

Shallow and deep sediments were sampled in Nsooba channel at the outlet of the catchment (B1, Fig. 1). Shallow sediment (0–30 cm) was sampled using a 1 m long multi-sampler long with a 40 cm internal diameter (Eijkelkamp, the Netherlands) while deep bed sediments (30–60 cm) were sampled using a hand auger. In the tertiary drain (B4, Fig. 1), only the shallow sediment was sampled because the sediment layer present in this lined channel was thin (< 10 cm). Suspended sediments were collected from the outlet of the catchment (B1) during the first rainfall event by settling and decanting water samples collected in 20 L jerry cans. The samples were then poured in glass beakers and oven dried at 105 °C. All samples were kept in plastic bags and transported to UNESCO-IHE, the Netherlands, for analysis. For suspended sediment, only the sample collected during the peak flow at 11:30 a.m. (event 1) was analysed because the other samples did not contain enough useable sediment for the soil experiments. Sediments were analysed for geo-available metals (available Fe, Ca, Mg and K), pH, organic matter, available phosphorus and grain size distribution. Geo-available metals were extracted with 0.43 M HNO_3 (Rauret, 1998; Novozamsky et al., 1993) and analyzed using an Inductively Coupled Plasma spectrophotometer (ICP – Perkin Elmer Optima 3000). Available phosphorus was extracted using the Bray 2 method (Bray and Kurtz, 1945) and analysed by spectrophotometry using the Ascorbic acid method. Grain size distribution was determined at the Vrije Universiteit, Amsterdam by laser diffraction technique using the Helos/KR Sympatec instrument (Konert and Vandenberghe, 1997). The pH was measured on a 2.5 : 1 water to soil suspension. Soil organic carbon (OC) was determined using the Walkley–Black method (Walkley and Black, 1934). Soil organic matter (OM) was estimated from OC using a conversion factor of 1.722 based on the assumption that OM contains 58 % carbon (Kerven et al., 2000).

3.4 Sequential extraction of phosphorus species from selected sediments

To determine the different forms of phosphorus in the stream sediments, we used a sequential extraction technique described by Ruban et al. (2001). The technique was slightly modified to adapt to the equipment available at UNESCO-IHE whereby the sediment-solution ratio of 10 : 1 ($mg\,mL^{-1}$) was maintained, but the amount of soil used was 500 mg instead of 200 mg. The following forms of P were extracted: P bound to Fe and Al oxides and hydroxides (Fe/Al bound P), P associated with Ca (Ca-bound P), Inorganic P (IP), organic P (OP), total P and, loosely bound P (available P). The sediment was first air-dried at room temperature and then oven dried at 60 °C for 2 h. For each form of P, extractions were carried out by adding 50 mL of extracting solution to 500 mg of sediment (or the residue of a previous extraction) and the mixture stirred for 16 h. The samples were centrifuged at 4000 rpm for 15 min and P in the extract determined by spectrophotometry using the ascorbic acid method. Fe/Al-bound P was extracted from 500 mg of dry sediment using 1 M NaOH. The residue from this extraction was used for the extraction of Ca-bound P using 1 M HCl. Total P was extracted from 500 mg of dry sediment using 3.5 M HCl. IP was extracted from 500 mg of dry sediment using 1 M HCl. The residue of the IP extraction was washed with distilled water and calcinated at 450 °C for 3 h and then the ash used for extraction of OP using 1 M HCl. All extractions were carried out in duplicate.

3.5 Phosphorus sorption experiments on selected sediments

Sorption experiments were carried out using duplicate batch experiments. Thereto, 25 mg of sediment samples were accurately weighed and mixed with 500 mL of 0.01 M $CaCl_2$ solution of varying initial P concentrations of 0, 20, 40, 80, 100 and 200 $mg\,L^{-1}$. The electrolyte $CaCl_2$ minimizes the competition for sorption sites between phosphate ions with other ions (Froelich, 1988). The mixtures were gently shaken on an orbital shaker at 100 rpm to equilibrate. After 24 h equilibrium time, pH, EC, temperature and DO were measured using portable meters (WTW, Germany: Model 3310), and the final P concentration in solution measured by spectrophotometry using the ascorbic acid method. The amount of phosphate sorbed was calculated by:

$$C_{\mathrm{ads}} = \frac{(C_{\mathrm{o}} - C_{\mathrm{eqm}}) \cdot V}{m} \cdot 1000 \tag{1}$$

where C_{ads} is the sorbed amount of P ($mg\,kg^{-1}$), C_{o} is the initial P concentration in solution ($mg\,L^{-1}$), C_{eqm} is the measured P concentration in solution after equilibrium ($mg\,L^{-1}$), V is the volume of the sample in liters (0.5 L in this experiment) and m is the mass of the dried soil sample (kg).

To establish which sorption isotherm provided the best fit, the Langmuir (Eq. 2) and Freundlich (Eq. 3) equations were fitted to the data. These two equations are often employed to describe adsorption processes (Appelo and Postma, 2007; Golterman, 1995):

$$C_{\mathrm{ads}} = \frac{S_{\max} C_{\mathrm{eqm}}}{K_{\mathrm{L}} + C_{\mathrm{eqm}}} \tag{2}$$

$$C_{\mathrm{ads}} = K_{\mathrm{F}} \cdot C_{\mathrm{eqm}} \tag{3}$$

where $S_{\max}$ is the maximum adsorbed amount possible (mg kg^{-1}) and K_L, K_F and n are adjustable constants (–).

4 Results

4.1 Background hydrochemistry of drainage channels

Table 1 presents the background hydrochemistry of surface water in the drainage channels of the studied catchment. Surface water in the primary Nsooba channel (B1) was near neutral (pH = 7.1 ± 0.2) with EC values of 523 ± 46 µS cm^{-1} and Cl concentrations of 36 ± 13 mg L^{-1}, HCO_3 concentrations of 183 ± 32 mg L^{-1} and Ca concentrations of 9.7 ± 3.6 mg L^{-1}. The tertiary channel which drains Bwaise slum (0.5 km^2) was also near neutral (pH = 7.6 ± 2.3). However, this channel had much higher background values than in Nsooba channel with EC values of 1527 ± 663 µS cm^{-1} (about 3 times higher), HCO_3 concentrations of 528 ± 318 mg L^{-1} (about 3 times higher), Cl concentrations of 144 ± 123 mg L^{-1} (about 4 times higher) and Ca concentrations of 10 ± 4 mg L^{-1} (about 2 times higher) (Table 1). NO_3–N concentrations were generally low (< 5 mg L^{-1}) and DO in both the Nsooba channel and the tertiary drain was less than 1 mg L^{-1}, which implied that surface water was reduced. Fe and Mn concentrations were also low, which showed that surface water was not strongly reducing. The mean background concentration of PO_4–P in Nsooba channel was 0.23 mg L^{-1} whereas in the tertiary channel, it was 0.8 mg L^{-1} (Table 1). PO_4–P accounted for only 19 % of TP in the Nsooba channel and 23 % of TP in the tertiary drain implying that particulate phosphorus was the dominant form of P in both the primary drain (75 % of P) and the tertiary drain (79 %) during low flows.

4.2 Phosphorus concentrations during events in Nsooba channel (primary channel)

We successively collected water samples over 24 h (at 2–3 h intervals) at the catchment outlet during one baseflow and two high flow events (Fig. 2). High flows in Nsooba channel were characterised by a very flashy response whereas base flows were relatively constant with an average discharge of 0.22 $m^3 s^{-1}$ (Fig. 2).

During base flow conditions, high concentrations of phosphorus were measured in the channels, with values ranging 0.5–1.6 $mg L^{-1}$ for TP, 0.08–0.9 $mg L^{-1}$ for PP and 0.11–0.78 $mg L^{-1}$ for PO_4–P. The dominant form of P was PP accounting for 56 % of TP whereas PO_4–P accounted for 31 % of TP. Concentrations of P seemed to vary slightly during the day with relatively higher concentrations ($> 1 mg L^{-1}$ as TP) occurring between 10:00 a.m. and midnight, and lower concentrations after midnight ($< 1 mg L^{-1}$ TP) (Fig. 3). The presence of Mn suggested that surface water was generally Mn-reducing (Fig. 3).

During the first rainfall event of 8.9 mm (E1), the discharge increased to a peak of 6.7 $m^3 s^{-1}$ within one hour and then gradually decreased to base flow conditions (0.22 $m^3 s^{-1}$). Subsequently, the concentrations of TP and PP increased and decreased with discharge. A concentration peak of 4.0 $mg L^{-1}$ was realized for TP and 3.66 $mg L^{-1}$ for PP. Base flow P concentrations were restored when the discharge returned to base flow values (Fig. 3). PO_4–P concentrations, however, did not vary significantly and only decreased to zero after the peak flow suggesting that dilution was taking place. The mean contribution of PP to TP increased to 87 % from 56 % whereas that of PO_4–P was only 9.7 % down from 31 % of the base flow. NO_3–N concentrations were lower during E1 compared to base flow conditions implying that dilution was likely taking place.

In the second event (E2), 14.8 mm of rainfall produced two peaks of 1.3 and 1.4 $m^3 s^{-1}$. The surprisingly low peak discharge in the second event was attributed to rainfall variability in the area. The responses of TP and PP were therefore also weaker compared to those of E1. Two peak concentrations of TP and PP were observed with the first occurring at about 4 h after the peak discharge. The first peak had 3.0 $mg L^{-1}$ of TP and 2.4 $mg L^{-1}$ of PP. The second peak had 2.1 $mg L^{-1}$ of TP and 1.5 $mg L^{-1}$ of PP. PO_4–P concentrations also varied slightly in response to discharges contrary to the first event where variations were not evident (Fig. 3). For this event, the contributions of PP and PO_4–P to TP were 70 % and 28 % respectively. In both events (E1 and E2), SS concentrations increased with discharge, with SS peaks almost coinciding with peaks of TP, PP and discharge.

4.3 Phosphorus concentrations during events in the tertiary drain

Base flow concentrations of phosphorus in the tertiary drain were much higher than in the primary Nsooba channel and ranged between 3.5–7.7 $mg L^{-1}$ for TP, 0.9–4.8 $mg L^{-1}$ for PP and 2–4.8 $mg L^{-1}$ for PO_4–P. PP accounted for 42 % of TP whereas PO_4–P accounted for 58 %. P concentrations varied throughout the day with lowest concentrations occurring after midnight. During the first event, there was a sharp increase in all P concentrations with peaks of 19.7 $mg L^{-1}$ for TP, 14.1 $mg L^{-1}$ for PP and 4.9 $mg L^{-1}$ for PO_4–P (almost 4 times higher than base flow concentrations). Afterwards, there was a sharp reduction in concentrations and then base flow concentrations were gradually restored. For this event, average PO_4–P accounted for 36 % of TP whereas PP accounted for 59 % of TP. In the second event, variations in P were not readily evident; instead there was a slight reduction in P concentrations after the rain event (possibly due to dilution), and restoration of base flow concentrations thereafter. PO_4–P accounted for 52 % whereas PP accounted for 47 % of TP.

4.4 Soil tests and experiments

4.4.1 Characteristics of bed and suspended sediment

Table 2 shows that the bed sediments in the channels were generally sandy clay loams whereas suspended sediments were silty loams. The pH of the sediments was generally alkaline (7.1–7.3). Organic matter content ranged between 1.8 and 3 % and was highest in deep sediments. Ca was the most dominant cation followed by Fe. Hence Ca and to a small extent Fe were most capable of adsorbing or precipitating P. Suspended sediments contained the highest composition of Ca and Fe.

4.4.2 Sequential P extraction

The results of sequential P extraction of bed and suspended sediments in Fig. 5 show that inorganic phosphorus was the dominant form of P in sediments. Most P was associated with Ca followed by Fe/Al. Adsorbed P (i.e. available P) accounted for the smallest fraction contributing less than 10 % of the total amount of P in the soil. Suspended sediment collected during the peak of the first rain event had the highest content of phosphorus, which was mostly bound to Ca. The results also showed that shallow sediments contained more phosphorus (e.g. B1 shallow and B4 shallow) than deep sediments, which was attributed to high concentrations of Ca-bound P and OP in shallow sediments.

4.4.3 Sorption isotherms

The Langmuir isotherm provided the best fit of the data (Fig. 6). Deep sediments collected from Nsooba channel (B1) had the best fit ($r^2 = 0.98$). The shallow sediments in Nsooba channel had the second best fit ($r^2 = 0.85$). The poorest fit was obtained for shallow sediments collected from the tertiary drain, B4 ($r^2 = 0.43$), which was likely due to the lower Fe content in the soils (Table 2). The Maximum P (S_{max}) that can be sorbed on the sediments ranged from 820 to 2350 $\mathrm{mg\,kg^{-1}}$ with deeper sediments having the highest sorption potential ($S_{\mathrm{max}} = 2350\,\mathrm{mg\,kg^{-1}}$; Fig. 5). Shallow sediments had lower values of S_{max} than the deeper sediments (e.g. $S_{\mathrm{max}} = 1550\,\mathrm{mg\,kg^{-1}}$ for shallow sediments in Nsooba channel and 850 $\mathrm{mg\,kg^{-1}}$ in the tertiary drain; Fig. 5). This suggested that shallow sediments had a lower sorption potential than the deep sediments. The Nsooba and the tertiary drainage channel system (results of Figs. 3–5) plotted above the sorption isotherms (see Fig. 6) suggesting that the sediments were less likely to sorb P.

5 Discussion

According to Dodds et al. (1998), streams are eutrophic when TP exceeds 0.075 $\mathrm{mg\,L^{-1}}$. The mean background concentrations of TP in Nsooba channel at the outlet of the catchment was 1.2 $\mathrm{mg\,L^{-1}}$, which equals 16 times the minimum required to cause eutrophication. The tertiary channel which drains Bwaise slum had phosphorus concentrations ($\mathrm{TP} = 3.5\,\mathrm{mg\,L^{-1}}$) which were 45 times more than the eutrophication limit. These findings along with the high Cl concentrations (36–144 $\mathrm{mg\,L^{-1}}$) demonstrated the adverse pollution impacts owing to wastewater discharges into the tertiary channels and subsequently in the Nsooba channel. High Cl concentrations in urban rivers are usually associated with anthropogenic pollution from domestic wastewater due to NaCl used in households for cooking or Cl-treated drinking water (Appelo and Postma, 2007; Thornton et al., 1999). Furthermore, P originating from domestic wastewater is usually in dissolved form as $\mathrm{PO_4{-}P}$ (Bedore et al., 2008; Olli et al., 2009). This was also observed in this study where $\mathrm{PO_4{-}P}$ concentrations in the tertiary channel accounted for 58 % of TP during base flow conditions and 52 % of TP during E2. In Nsooba channel, most P during low flows was present in particulate form (56 %) which implied that gradual deposition of P to shallow bed sediments was taking place. Hence, a significant amount of P was likely retained in the channel bed during low flow conditions. Most P in the sediment was inorganic associated mostly with Ca and Fe/Al oxides, although organic P was also relatively high (Table 2; Fig. 5). It is likely that precipitation of calcium phosphate or sorption of P on calcite and Fe/Mn oxides contributed significantly to P deposition and storage to bed sediments. The precipitation of P as calcium apatite is actually common in high Ca and alkaline waters (Reddy et al., 1999). Since deep sediment contained more Fe than Ca while shallow sediment contained more Ca than Fe (Table 2), we inferred that Fe-associated P was permanently stored in the sediments whereas Ca-bound P was temporally stored. The temporal storage of Ca-bound P in sediments can explain why deeper sediment contained less Ca-bound P than shallow sediment whereas Fe-bound P was approximately equal in both deep and shallow sediment (Figs. 5 and 7). Organic matter deposition also likely contributed to P storage because the sediment contained relatively high content of OM (1.8–3 %; Table 2) and organic bound P (up to 20 %; Fig. 5).

Results from this study further showed that increase in discharge in both events resulted in flushing of phosphorus, which was characterised by higher TP concentrations largely because of higher PP concentrations (e.g. 87 % of TP during E1 was particulate). This flush was reflected by a sharp increase in concentrations of TP and PP during the rising limb of the hydrograph and the subsequent decrease during the falling limb and finally restoration of base flow concentrations. Responses in suspended solids (SS) during both events coincided with those of TP and PP (Figs. 3 and 4) which implied that most phosphorus was associated with SS during these events. This finding is in agreement with the fact that P is strongly adsorbed onto fine sediments (Thornton et al., 1999). This also explains why PO_4–P did not show significant variations during E1 when the amount of SS transported was very high. It is only during moderate increases in discharge and SS that variations in PO_4–P were seen (e.g. Event 2, Fig. 3). Suspended sediments were likely mobilised from resuspension of stream bed sediments and erosion of material stored on the urban surface. The first-flush effect, a phenomenon where the rising limb contains higher concentrations than the falling has been reported in several studies. This phenomena is considered present if the percentage of total load of pollutant transported by the first 20 % of runoff is significantly higher than 20 % (Deletic, 1998). Particulate phosphorus and SS exported from agriculutral and forested catchments have been shown to exhibit strong first-flush effects and clockwise hysterisis patterns (e.g. Stutter et al., 2008; Zhang et al., 2007). However, results from this study show that the first-flush effect was only present for SS whereas PP did not exhibit the first flush effect. A signifant amount of SS load (44 %) was discharged by 20 % of the runoff volume whereas only 23 % of PP load was discharged in 20 % of the runoff volume (Fig. 8). It is, however, possible that we missed the real peaks because the time interval for discharge measurements (20 min) was relatively large. We also had few water quality samples during event peaks and the rising limb of the hydrograph due to logistic and safety reasons. But, it is clear from Fig. 3 that P concentration peaks were generally realised after the peak discharge, which supports our earlier presumption that the first-flush effect was not present.

Hence, we conclude that particulate P did not exhibited a first-flush effect and that most of it was discharged after the peak runoff as has been noted in related studies in urban areas (e.g. Chua et al., 2009). There are two possible explanations for this finding:

- The flooding of primary Nsooba channel in low-lying areas, where slums are typically found, often causes backflow in the tertiary drains. Hence, flood waters are temporarily stored in these low-lying areas. When the hydrograph recedes, the flood water flows back into the Nsooba channels carrying with it nutrient-rich wastewater initially stored in these informal settlements (personal observation). Solid waste also often blocks pipes and drainage channels and holds back the water in the slums, hence causing a delay in delivery of high P concentrations from the slums.

- Most pit latrine contents are discharged into the adjacent tertiary drains during rain events (particularly when increased flows are observed) as a cheap way of emptying the latrines. This practice is common in the slum areas of Kampala

(Isunju et al., 2011; Katukiza et al., 2010; NWSC, 2008; Kulabako et al., 2004) and can cause high P discharge to the primary channel during and after the event peaks.

Another interesting finding of this study was that the stream bed sediments, which were almost pH neutral, seemed unlikely to adsorb PO_4–P because the concentrations of PO_4–P in both the tertiary and the main drain plotted above the sorption isotherms (Fig. 6). This finding concurs with Golterman's (2004) argument that the sorption capacity of soils decreases with increase in pH. In addition, the total amount of P sorbed on the sediments was almost equal to the maximum the sediments can sorb. For example, the maximum sorption potential of the shallow bed sediments in Nsooba channel was $1550\,mg\,kg^{-1}$ yet the total amount of phosphorus in the sediments was $1668\,mg\,kg^{-1}$ (Fig. 5 and 6). The results therefore suggested that bed sediments in the channels were saturated with phosphorus. Moreover, adsorbed P (or available P) accounted for only 10 % of the total P in the bed sediment. Hence, we concluded from these findings that desorption was likely taking place resulting in release of PO_4–P from sediments to discharging waters. PO_4–P release may also have been facilitated by the anoxic conditions (manganese-reducing) through reductive mineral dissolution because of the presence of mobile Mn. The break down of organic matter also likely contributed to release of P, since sediments had a relatively high organic matter content (1.8–3 %, Table 2). However, as shown in Fig. 7, P storage and release from bed sediment was more attributed to Ca mineral chemistry, because Ca and total P in sediments were strongly correlated ($r^2 = 0.9$). The release of P from bed sediment by desorption could explain why total P content in deep sediment ($1375\,mg\,P\,kg^{-1}$) was generally less than that in shallow sediment ($1668–1840\,mg\,P\,kg^{-1}$) (Fig. 5). We hypothesize that slow desorption was taking place and that deep sediments represent sediments that had undergone desorption over a long time. This can also explain why deep sediment had a higher sorption potential than the shallow P-saturated sediment (Fig. 6).

Overall, our findings suggest that there were two main sources of P inputs in Nsooba channel (i) external loading from wastewater releases from slums and (ii) internal loading from P released from bed sediments. During storm events, however, suspended sediments and P (in particular PP) increased with magnitude of runoff events suggesting that resupension of bed sediment and erosion from the urban surface were likely the dominant factors controlling P discharge during high flow events. The transport processes described above are illustrated in Fig. 9.

The implication of our findings is that even if P loads from slum areas are reduced through sanitation improvements or by removal of slums, it will take time for P in discharging waters to reduce, because P-saturated bed sediments will continue to release P. Previous studies suggest that internal P loads can last for decades depending on the P loading history (Søndergaard et al., 1999). Fortunately, the studied catchment drains into a papyrus wetland where most P (particulate or dissolved) is removed either by biological uptake or sedimentation (Kansiime et al., 2005; Kelderman et al., 2007; Kyambadde et al., 2005). Wetlands should therefore be conserved. In addition, implementing P load reduction measures in slum areas can contribute to reduction of P loads in the near future. Katukiza et al. (2012) suggested that grey water was the largest wastewater stream and is thus a major source of P in drainage systems in urban slum catchments. Hence, providing localised low-cost greywater treatment units can be considered a good starting point to mininise P loads in slum areas.

6 Conclusions

In this study, we attempted to understand the transport and fate of P in channels draining a 28 km^2 unsewered slum catchment in Kampala, Uganda during different hydrological conditions. We found that:

1. The drainage channels in the catchment were highly eutrophic with very high concentrations of P, primarily attributed to wastewater discharges from poor on-site sanitation, especially in low-lying informal settlements (slums).

2. During low flow and base flow conditions, the total P discharged from the catchment (up to 0.5 to 1.6 mg L^{-1}) was predominantly particulate (about 56 % of TP). Hence, we inferred that most of it was retained in the channel bed sediment. This retention appeared to be controlled by adsorption of P to calcite and mineral precipitation reactions with Ca and Fe owing to the fact that most P in bed and suspended sediments was inorganic and bound to Ca and Fe/Al oxides.

3. The channel bed sediments were saturated with P. Total P concentrations in both shallow and deep sediments (1375–2316 mg P kg^{-1}) were almost equal to the maximum sorption capacity of sediments (1550–2350 mg P kg^{-1}). We concluded that desorption was slowly taking place and that there were two main sources of P inputs to the primary channel: point sources and P released from the satured sediments. The release of P appeared to be controlled by Ca mineral chemistry whereas Fe-bound P was permanently stored in sediment.

   During storm flow events, large amounts of P (up to 4 mg L^{-1} as TP) were flushed out of the catchment owing to resuspension of P-rich sediment initially accumulated in the channel during low flows and surface erosion from the urban surface. First flush effects were not observed for P, which we attributed to the common practice of releasing wastewater into drainage channels during rain events in slum areas (i.e. emptying of pit latrines).

4. Our findings suggest that most P discharged from the studied slum-dominated catchment is retained along the main channel bed. However, because the bed sediment are P-saturated, they will continue to release P in discharing waters even with improved wastewater management practices. Preservation of downstream wetlands along with P-reduction interventions (e.g. grey water treatment) can in the long run result in reduced P loads out of the catchment.

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Table 1. Background concentrations of selected hydro-chemical parameters and phosphorus forms at the outlet of the catchment (B1) and in the tertiary drain (B4) between March and September 2010 ($n = 3$ for Cl and $n = 10$ for the rest of the variables).

Water quality parameter	Outlet of slum (B1)		Tertiary drain (B4)	
	Mean	stdev	Mean	stdev
EC (μS cm^{-1})	523	46	1527	663
pH (–)	7.1	0.2	7.6	2.3
Temperature (°C)	25.4	2.1	24.9	7.7
DO (mg L^{-1})	1.0	1.0	0.7	0.5
HCO_3 (mg L^{-1})	183	32	528	318
Cl (mg L^{-1})	36	13	144	123
NO_3-N (mg L^{-1})	2.7	2.2	5.5	5.7
Ca (mg L^{-1})	9.7	3.6	17.6	8.8
Fe (mg L^{-1})	0.1	0.1	0.5	0.7
Mn (mg L^{-1})	0.4	0.2	0.3	0.4
Phosphorus forms (mg L^{-1}, $n = 8$)				
TP	1.2	0.2	3.4	4.4
PP	0.9	0.1	2.7	3.7
PO_4-P	0.23	0.11	0.77	0.96

TP = Total phosphorus, PP = Total particulate phosphorus (= TP-TDP) and PO_4-P = orthophosphate.

Table 2. Physical and chemical properties of bed and suspended sediments in Nsooba channel at the outlet of the catchment (B1) and in the tertiary drain in Bwaise slum (B4).

Sediment sample				Geo-available metals $(\mathrm{mg\,kg^{-1}})$				Grain size distribution[b]			
	pH	OM[a] (%)	OC[a] (%)	Ca	Mg	K	Fe[a]	Sand (%)	Silt (%)	Clay (%)	Class (USDA)
Deep (B1)	7.1	3.0	1.7	3636	173	105	3761	79	14	7	Sandy clay loam
Shallow (B1)	7.3	2.0	1.2	8505	375	311	3437	63	26	11	Sandy loam
Shallow (B4)	7.3	1.8	1.1	7620	292	381	2262	83	12	5	Loamy sand
Suspended (Event 1, 11:30 a.m.)	–	–	–	18 125	939	1405	5755	23	56	21	Silt loam

[a] Extractable Fe in $\mathrm{mg\,kg^{-1}}$. Note that OM and OC refers to soil organic matter and soil organic carbon.

[b] Clay (< 2 µm), silt (2–5 mm) and sand (> 5 mm).

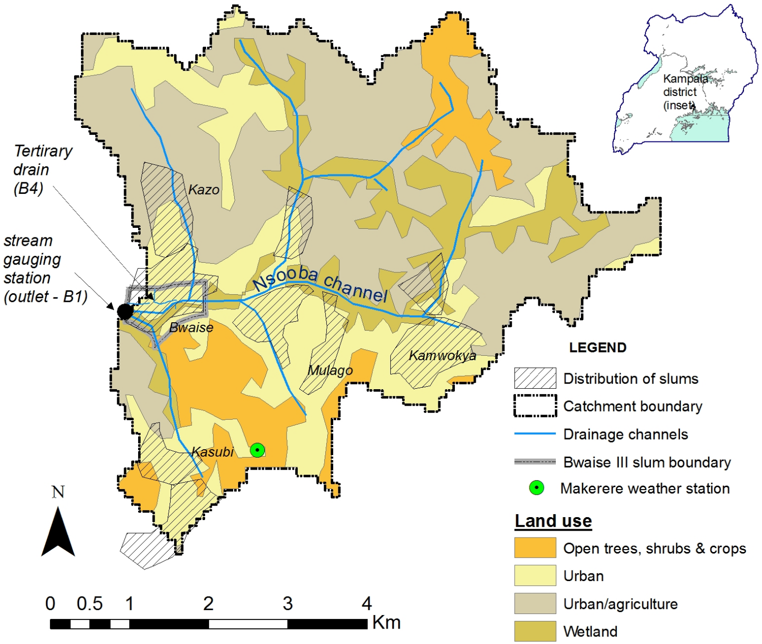

Fig. 1. Location of the study area (upper Lubigi catchment) in Kampala district, the capital city of Uganda.

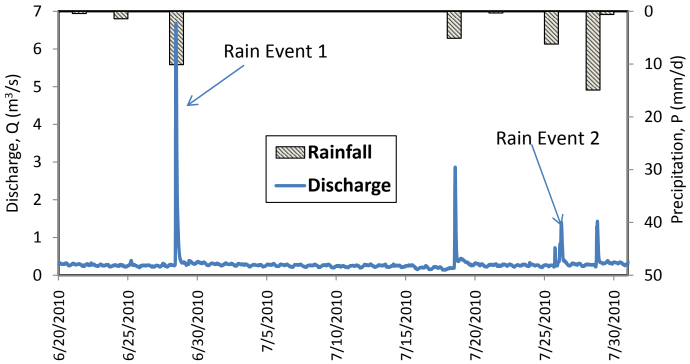

Fig. 2. Discharge hydrograph at the outlet of the upper Lubigi catchment (B1, Fig. 1) near Bwaise slum and precipitation measured at Makerere University. These were based on discharge measurements carried out by the author between January–December 2010.

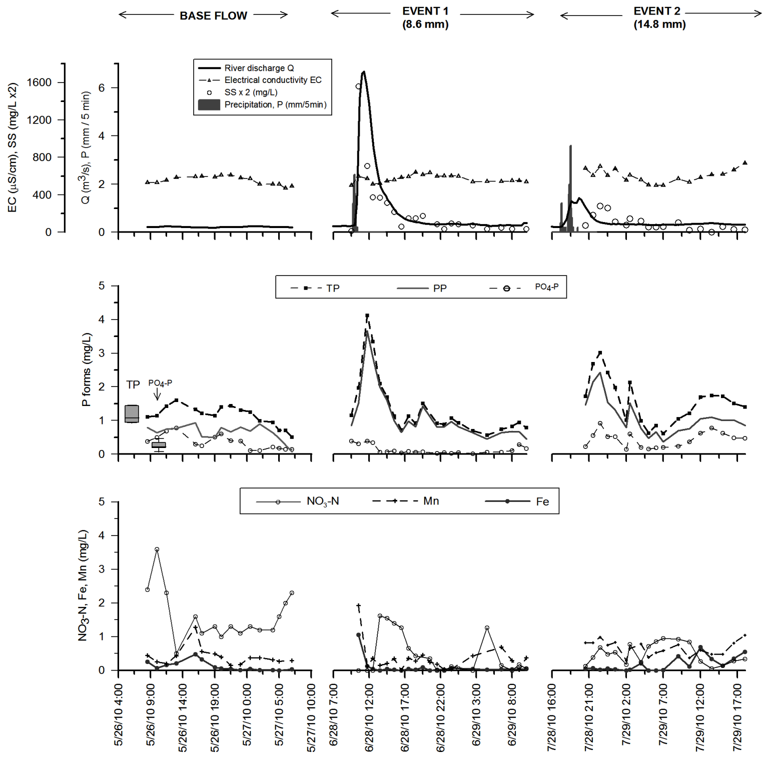

Fig. 3. Changes in concentrations of phosphorus and selected hydro-chemical parameters during base flow and rainfall events at the outlet of the upper Lubigi catchment located in Bwaise slum. The two box plots of TP and PO_4–P represent the background concentrations (mg L^{-1}, $n = 11$) of these forms of phosphorus, which demonstrate that the event samples collected are representative of seasonal variations.

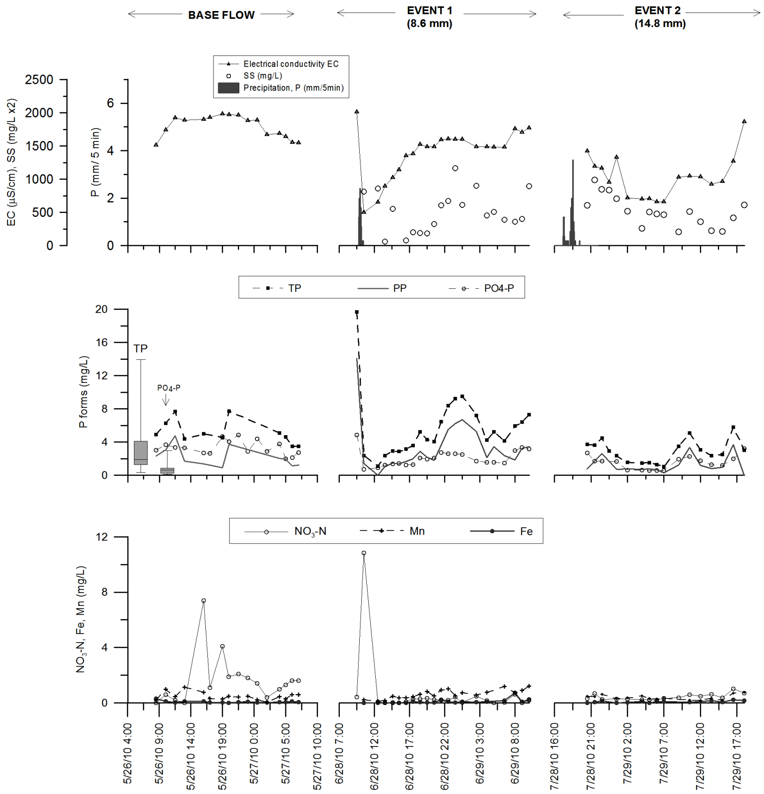

Fig. 4. Changes in concentrations of phosphorus and selected hydro-chemical parameters in a tertiary drain discharging Bwaise slum during base flow and rain events. Note, discharge measurements were not possible at this site.

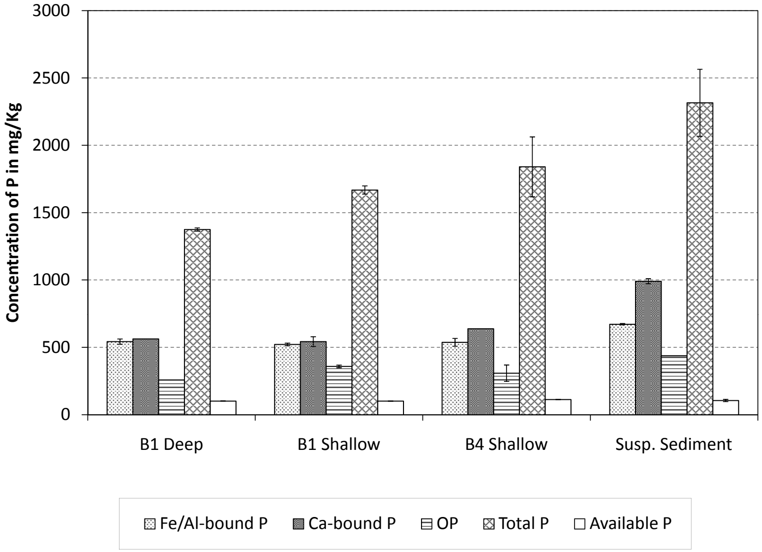

Fig. 5. Mean concentrations of P forms in deep, shallow, and suspended sediment in Nsooba (B1) and tertiary (B4) drainage channels. The P forms included Fe/Al-bound P, Ca-bound P, OP (Organic P), Total P and available P. Suspended sediments were only collected at peak flow during Event 1 (Error bars represent standard error, $n = 2$).

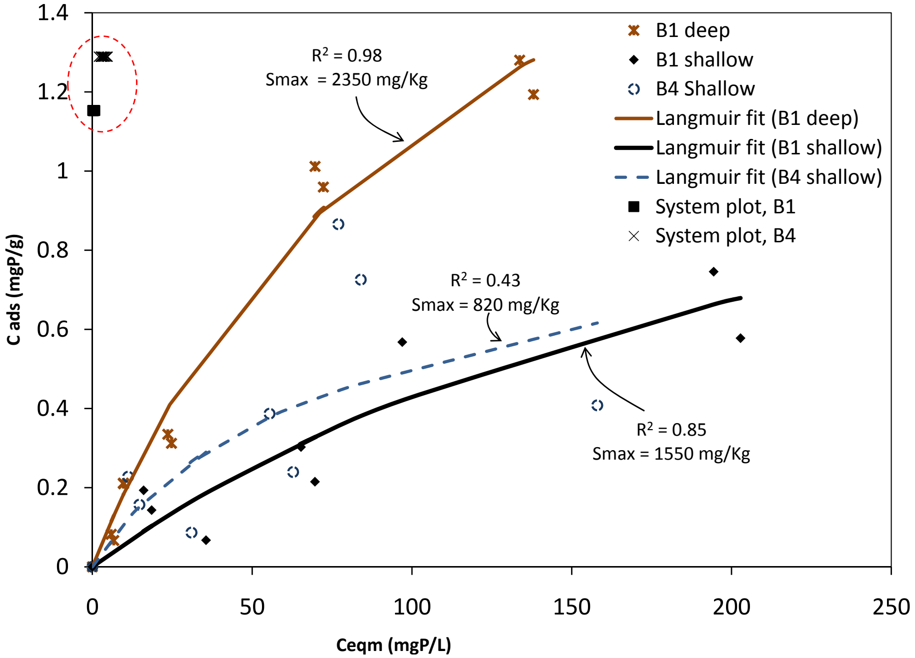

Fig. 6. Equilibrium sorption Isotherms of sediments sampled at the outlet of Nsooba channel (B1) and the outlet of the tributary drain (B1) from Bwaise slum. At the outlet of the catchment, both shallow (B1 shallow) and deep (B1 deep) sediments were analyzed. The figure also shows where the system plots (see encircled plots) in the isotherm graphs where C_{eqm} are base flow orthophosphate concentrations in the primary and tertiary drains and C_{ads} the sum of inorganic phosphorus in the sediments.

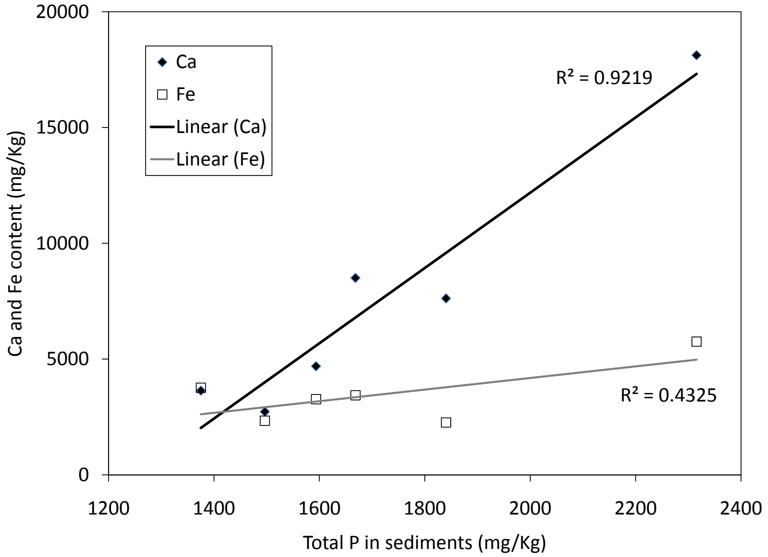

Fig. 7. Concentrations of Ca and Fe vs. total phosphorus in the bed and suspended sediment. (Note that this plot includes two additional sediment samples which were collected in Nsooba channel at the inlet of Bwaise slum but are not presented in the results).

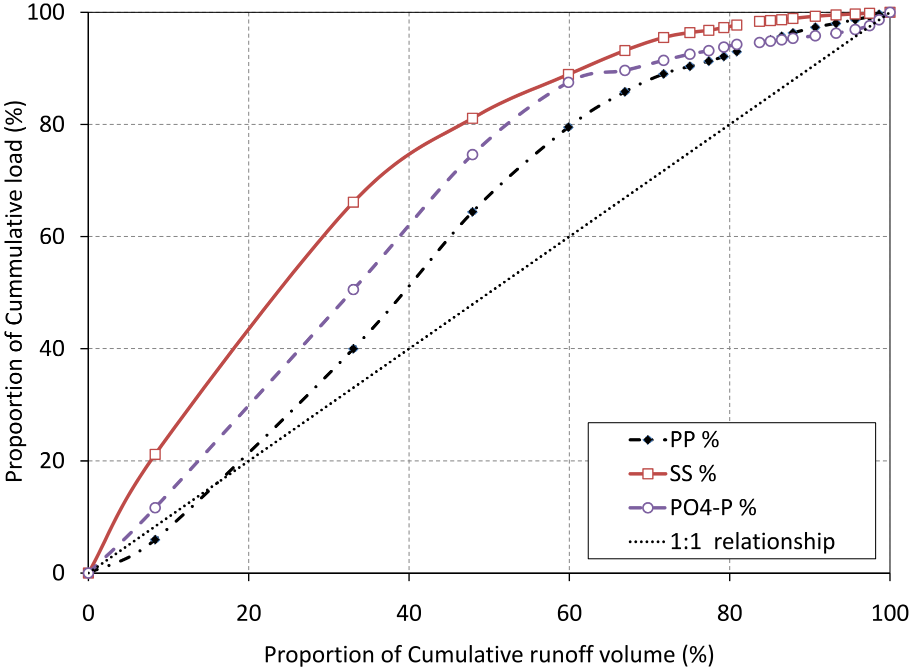

Fig. 8. Relationship between cumulative mass transport and cumulative discharge of total suspended solids (SS), particulate phosphorus (PP) and orthophosphate (PO_4-P) at the outlet of the catchment during event 1.

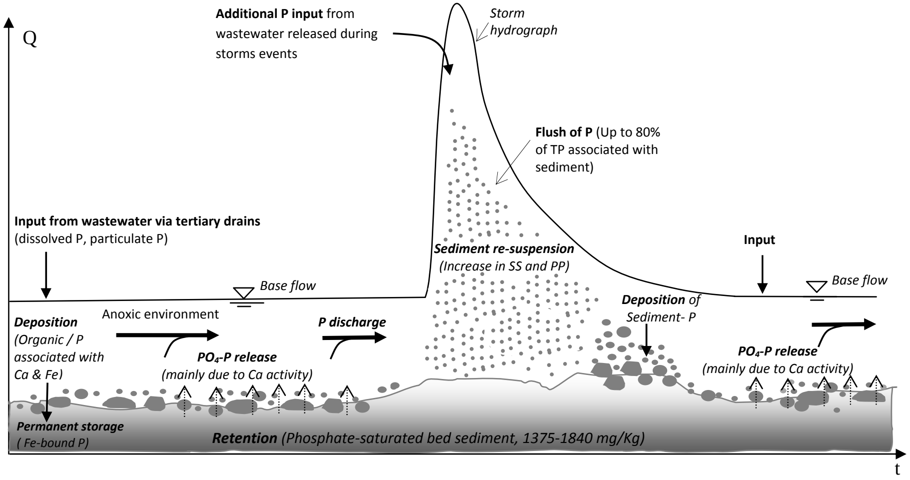

Fig. 9. Schematic presentation of phosphorus transport in the slum catchment during a low flow and high flood event. The grey oval shapes of different sizes illustrate settling and re-suspension of particulate P in sediments.