Phytostabilization of metals by indigenous riparian vegetation

Klaudia Schachtschneider[1,2]*, Jessica Chamier[1,3] and Vernon Somerset[1,4]

[1] *CSIR, Natural Resources and the Environment, PO Box 320, Stellenbosch 7599, South Africa*

[2] *WWF-SA PO Box 23273, Claremont 7735, Cape Town, South Africa*

[3] *HySA Catalysis, University of Cape Town, Rondebosch 7701, South Africa*

[4] *Cape Peninsula University of Technology, Chemistry Department, Bellville 7535, Cape Town, South Africa*

ABSTRACT

Given the increasing pressure of man-made activities on riparian zones, the capacity of the riparian vegetation along the Upper Olifants River, South Africa, to phytoextract and phytostabilize aluminium (Al), manganese (Mn) and iron (Fe) from the soil was investigated. The aim of the study was to gain better understanding of the capacity of indigenous vegetation in riparian zones to immobilize metals in the soil, thereby improving river water quality and ecosystem services. Seven commonly-occurring pollution-tolerant riparian plant species were evaluated to establish their potential as bioaccumulators for Fe, Al and Mn. Species included: *Cyperus haspan, Schoenoplectus corymbosus, Typha capensis, Phragmites australis, Cynodon dactylon, Cyperus marginatus* and *Juncus effusus*, which were sampled in five riparian areas in the Upper Olifants catchment. The bioconcentration factor (BCF) for Mn was > 1 for all species investigated with a maximum of 5 for *Typha capensis*, which also showed the highest accumulation of Al (10.26) and Fe (7.03). The remaining species presented with Al and Fe BCF between 0.11 and 2.00, with minimal transfer from root to shoot. When measured against an ideal hypothetical buffer zone, the buffer zones under investigation varied between intact and severely compromised. Intact riparian zones showed elevated metal concentrations in the soil, yet significantly lower concentrations in the river water compared to areas with insufficient vegetative cover. A polluted riparian area overgrown by *P. australis* effectively phytoextracted 204 960 g/m^2 Al, 204 400 g/m^2 Fe and 27 887 g/m^2 Mn. The two indigenous *Cyperus spp.* were not ideal for metal immobilization with low bioaccumulation and transfer factors as well as low biomass. High biomass and Al, Fe and Mn phytostabilizing species: *P. australis, T. capensis, S. corymbosus and J. effusus*, should be considered in the rehabilitation of South African buffer areas.

Keywords: riparian vegetation, heavy metals, acid mine drainage, phytostabilization, bioaccumulation

INTRODUCTION

Riparian vegetation increases resistance and surface roughness, slowing, intercepting and otherwise influencing overland, subsurface and groundwater flows (Welsch, 1991). Natural plant species composition and the extent of the riparian zone vary from region to region and depend on factors such as climate, geology, geomorphology, slope and biome (Gregory et al., 1991; Tilman et al., 1997). An internationally recommended riparian buffer width, optimising the protection of water quality and all other ecosystem services, is 5–30 m (Broadmeadow and Nisbet, 2004; Fischer and Fischenich, 2000; Jontos 2004). Many riparian zones worldwide are being degraded by infringing land use practices such as livestock grazing, agriculture or urbanization, alien plant invasions or increased pollution levels in the catchment (Clericia et al., 2014; Wantzen et al., 2013). These activities reduce the capacity of riparian zones to perform their ecosystem services, further degrading the integrity of the surrounding ecosystem.

The Olifants River is one of South Africa's most polluted catchments, in which urbanisation, mining and agriculture have been ongoing and expanding for more than a century (Driescher, 2008; Oberholster et al., 2010). For the Olifants River catchment, the riparian vegetation not only provides bank stabilization and retains pollutants from surface runoff, it is also exposed to increasing metal concentrations accumulating in the soil, deposited from upstream mining practices. The most common metals prevalent in the Olifants River catchment are aluminium (Al), iron (Fe) and manganese (Mn) (Oberholster et al, 2010; Tiwary, 2001) leached from the earth by acid mine drainage (AMD). Both Fe and Mn are essential nutrients; their toxicity, however, depends on the dosage, and these metals can become toxic in acidic, sulphate-rich soils (Asch et al., 2005; DWAF, 1996; Duncan, 1999).

The ability of particular plant species to tolerate and remediate certain kinds of pollution, through either phytoextraction or phytostabilization, can be used advantageously in river pollution control and rehabilitation efforts. In phytoextraction, selected plants accumulate high concentrations of metals in their shoot tissue, making it possible to harvest and sometimes even use them as a metal resource (O'Niell and Nzengung, 2004; USEPA, 2000). Phytostabilization means that plants stabilize or immobilize the metals in the soil, thereby delaying and reducing metal transport downstream. Phytostabilization is achieved through the root growth and minimal translocation of metals from the root to shoot or organic litter (Mertens et al., 2004). Any restoration efforts that use phytoextraction and phytostabilization need to carefully consider that selected species are acclimatised to surrounding conditions and that selected plant species show rapid propagation and high biomass.

Firstly, the current study determined the water quality of riparian zones with varying degrees of intactness. Considering these study areas, the photostabilizing capacities of 7 species, common to the existing Olifants River's riparian vegetation zone, were established. These investigations then aimed to determine whether these species would prove useful in river rehabilitation efforts, possibly improving river water quality with depleting

*To whom all correspondence should be addressed.

Tel: +27 021 657 6600; E- mail: kschacht@wwf.org.za

Received 27 January 2016; accepted in revised form 6 March 2017

http://dx.doi.org/10.4314/wsa.v43i2.01

Available on website http://www.wrc.org.za

ISSN 1816-7950 (Online) = Water SA Vol. 43 No. 2 April 2017

riparian buffer zones. These species include; *Cyperus haspan, Schoenoplectus corymbosus, Typha capensis, Phragmites australis, Cynodon dactylon, Cyperus marginatus* and *Juncus effusus*. Many of these species have previously been recorded to take up various heavy metals to varying degrees. In addition, this study included two locally common species, *Cyperus haspan* and *Cyperus marginatus*.

METHODS AND MATERIALS

Study area

The Upper Olifants catchment receives summer rainfall, ranging between 550 mm/a to 900 mm/a, while winters are very dry. The upper catchment vegetation types are primarily grassland and bushveld (Mucina and Rutherford, 2006). Previous riparian vegetation assessments have classified different vegetation zones along the macrochannel, consisting of various combinations of trees, shrubs, dwarf shrubs, forbs (herbaceous) and grasses (Myburgh and Breedenkamp, 2004).

Two sampling trips and time series mapping were conducted for 5 study sites in the Upper Olifants catchment, Mpumalanga Province, South Africa (Fig. 1), over the course of June 2009 and November 2011.

Sample collection

After the initial species inventory, 7 common, indigenous and evidently pollution-tolerant riparian species were selected. *Phragmites australis*, *Typha capensis*, *Juncus effusus*, *Schoenoplectus corymbosus* and *Cynodon dactylon* have been previously recorded to take up various heavy metals (Batty et al., 2000; Deng et al., 2004; Demirezen and Aksoy, 2006; Fitamo and Leta, 2002; Tangahu et al., 2011), warranting their analysis for Al, Fe and Mn uptake; while *Cyperus haspan* and *Cyperus marginatus* are two locally common species but are unstudied in terms of their bioaccumulation potential.

The percentage abundance of each species was estimated through observation over a 200 m long and 60 m wide stretch of river around the study site (Table 1). It was assumed that 100% equals the sum of all species present in the 200 m x 60 m area.

For metal accumulation testing, shoot and root material were collected. Thereafter, 5 g of each specimen was placed into labelled HDPE sample tubes (Remon et al., 2005). Soil samples were taken from the immediate root zone of each plant sample. Biomass data were collected once-off in 2011. Between 3 and 10 samples of each species were sampled at the 5 sites where they occurred. A square sample size of 20 cm x 20 cm was dug out per specimen, ensuring that all root and shoot material was sampled. Samples were rinsed, wrapped into refuse bags and

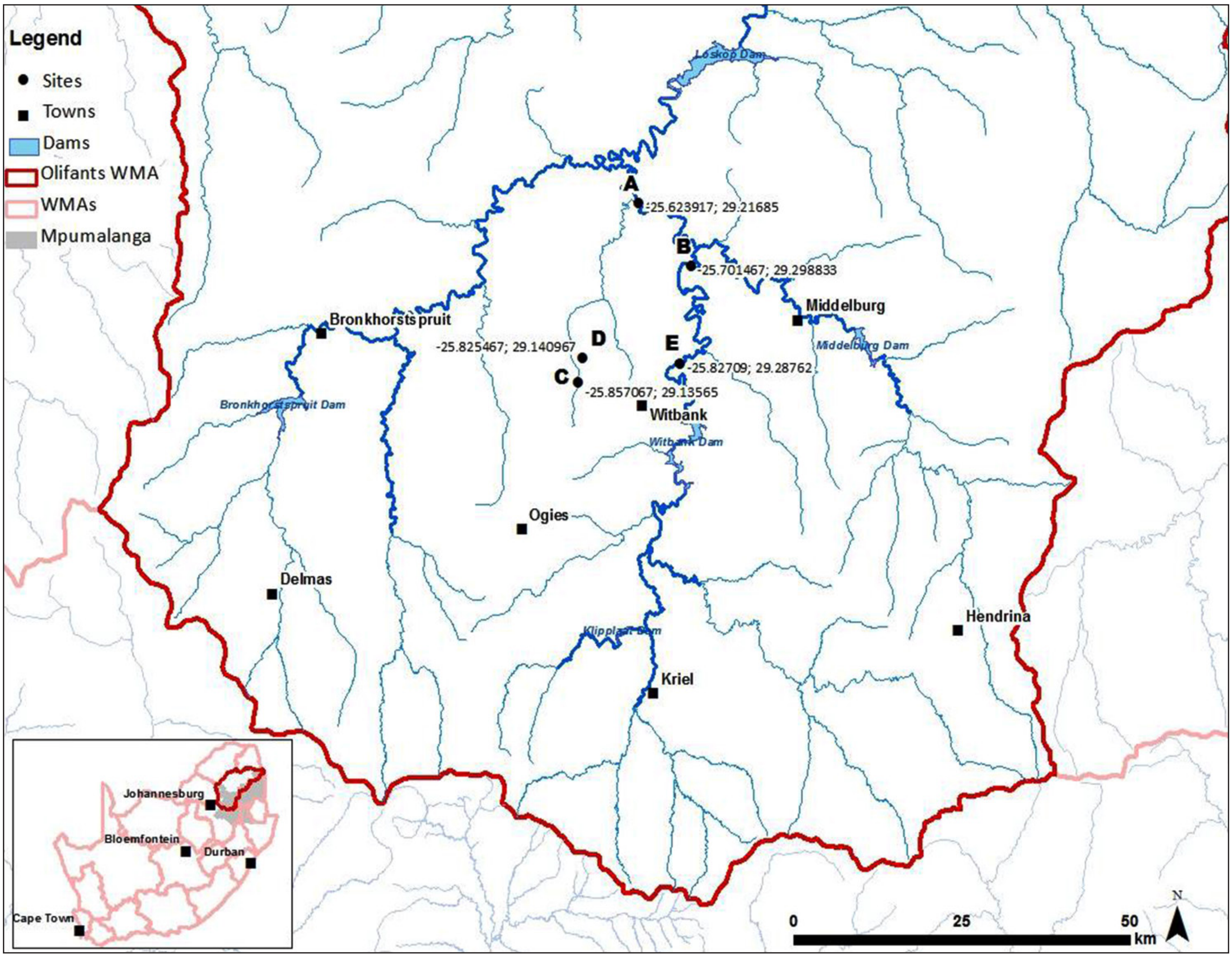

Figure 1

Sampling sites along the Upper Olifants River, Mpumalanga Province, South Africa

TABLE 1 Species and plant families, their growth form and local abundance (% of all species present) per site in a 200 m x 60 m area						
Species	**Growth form**	**Site A**	**Site B**	**Site C**	**Site D**	**Site E**
Cynodon dactylon Linnaeus (Poaceae)	Perennial grass, vegetative cluster	< 1%		2%		
Cyperus haspan L. (Cyperaceae)	Annual sedge, vegetative cluster	< 1%	< 1%			
Cyperus marginatus Thunb. (Cyperaceae)	Perennial sedge, vegetative cluster	35 %	10%			
Juncus effusus Linnaeus (Juncaceae)	Perennial, individual specimen		5%	<1%	5%	20%
Phragmites australis (Cavanilles) Trinius ex Steudel (Poaceae)	Perennial reed with annual shoots, both growth forms	25%	30%	98%	< 1%	5%
Schoenoplectus corymbosus (Roth ex Roemer & Schultes) (Cyperaceae)	Annual sedge, individual specimen			< 1%		
Typha capensis (Rohrbach) N.E. Brown (Typhaceae)	Perennial bulrush, both growth forms			1%	5%	1%

transported in portable ice chests to an accredited laboratory (CSIR, Stellenbosch, South Africa). There, the above-ground (AG) and below-ground (BG) plant parts were separated, washed and left to dry.

The pH and electrical conductivity values were measured in situ at the water surface using a Hach SensionTM 156 portable multiparameter (Loveland, USA). Duplicate water samples were collected in pre-rinsed, 1-L polyethylene bottles. Water samples were kept cool in the dark and sent to the laboratory for analysis. Total metal concentrations were determined by inductively coupled plasma optical emission spectroscopy (ICP-OES) instrumentation using the APHA et al. (1995) accredited methods.

Soil and plant analysis

Samples were oven-dried for 24 h and homogenised with a ball mill. Ground samples were microwave digested, acid diluted, filtered (Ip et al., 2007) and then freeze-dried at –80°C to remove any moisture content which may dilute the solid content metal concentration. Total metal concentrations were determined by ICP-OES instrumentation using the APHA et al. (1995) accredited methods. Data are reported as mg/kg dry weight (mg/kg dr. wt). The bioconcentration factor (BCF) (ratio soil: root), translocation factor (TF) (ratio root: shoot) and transfer coefficient (TC) (soil: shoot) were calculated (Yoon et al., 2006).

The extraction efficiency of a plant depends on the metal concentration and the dry weight of harvestable tissue (Bech et al., 2002; Fitamo and Leta, 2010). The capacity of a plant for phytoextraction and phytostabilization was calculated using Eq. 1:

$$TPML = (SL \times SBM) + (RL \times RBM) \quad (1)$$

where: TPML is the total plant metal levels (in g/m² of plant), SL is the shoot level (in mg/kg), SBM is the shoot biomass (in g m²), RL is the root level (in mg/kg), and RBM is the root biomass (in g/m²).

GIS mapping of riparian buffer zone

An area of 2 km x 2 km was set around the sampling points in which all human land use, including agriculture, mining and urbanization, were mapped. Hard copies of aerial photographs for each site were obtained from the Chief Directorate of National Geospatial Information (CD:NGI), covering aerial surveys undertaken since 1955. Each historical image was scanned and georeferenced using 3 to 5 ground control points (GCPs) and topographically corrected using a 15 m digital elevation model (DEM) created from 1:10000 scale contours and spot elevation heights. Orthorectification, geolocational and topographical correction were performed using PCI Geomatica software. The orthorectified images were integrated into GIS applications (ArcMap) to be overlapped and displayed with other GIS data. One of the overlays was the riparian zonation; the other was the 30 m buffer zone, delineating 30 m width on each river bank for up to 200 m upstream and downstream. Final maps compared the areas of actual riparian vegetation to a hypothetical buffer zone of 30 m. Layers were quantified in km². Statistical differences were analysed by computing the Pearson correlation; p-values lower than $p = 0.05$ were considered to be significant.

RESULTS AND DISCUSSION

Bioaccumulation of Al, Mn and Fe

The capacity of the seven abundant and widespread riparian plant species (Table 1) to bioaccumulate Al, Fe and Mn was investigated by determining the total metal concentration extracted per plant, root versus shoot tissue accumulation and overall plant biomass (Bech et al., 2002; Fitamo and Leta, 2010). Herein, the possible ecological service they could provide, and potential role in future rehabilitation and remediation efforts along rivers impacted by anthropogenic activities such as acid mine drainage (AMD), could be estimated.

The average root and shoot biomass for the plant species are given in Table 2. *Phragmites australis* (3 371 g/m²), *J. effusus* (1 986 g/m²) and *S. corymbosus* (1 545 g/m²) had the highest overall biomass (Table 2). Apart from *P. australis*, all plants had greater root than shoot biomass.

A plant's ability to accumulate or stabilize metals from soils to its root can be estimated by using the BCF, TF and TC ratios. The TF is the concentration ratio defining the translocation of metals from the roots to the shoots and the TC ratio is that between soil and shoot concentrations (Fitamo and Leta, 2010; Yoon et al., 2006). BCF and TF values greater than 1 are typical indicators for bioaccumulators (Baker, 1981; Baker and Brooks, 1989; Yoon et al., 2006). Plants are considered useful phytostabilizers if metal concentrations are particularly high in the root system (Fitamo and Leta, 2010). The bioaccumulation factors for the plant species investigated in the Olifants River catchment are shown in Table 2.

http://dx.doi.org/10.4314/wsa.v43i2.01
Available on website http://www.wrc.org.za
ISSN 1816-7950 (Online) = Water SA Vol. 43 No. 2 April 2017

TABLE 2
Mean, maximum (max) and minimum (min) shoot, root and surrounding soil metal concentrations for Al, Fe and Mn for 7 riparian species (mg/kg dry weight), including values for BCF, TF and TC

Species	Sample	Average biomass (g/m²)	Al (mg/kg dry weight)			Fe (mg/kg dry weight)			Mn (mg/kg dry weight)		
			Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
S. corymbosus (n = 10)	Shoot	489	558	114	3 688	801	165	3 755	522	280	1 090
	Root	1 055	7 205	1 024	98 027	10 808	2 567	61 477	563	155	3 564
	Soil		25 622	21 415	28 671	23 974	19 607	27 027	149	114.3	192.9
	BCF		2.14	1.21	3.57	2.33	1.6	3.13	2	1.03	3.32
	TF		0.08	0.03	0.4	0.09	0.03	0.25	1.11	0.31	2.95
	TC		0.14	0.11	0.17	0.17	0.13	0.21	2.63	2.04	3.05
C. dactylon (n = 7)	Shoot	72	1 662	237	7 434	1 629	211	7 697	268	169	535
	Root	688	10 750	3 662	44 522	11 186	3 486	52 883	339	71	1 252
	Soil		30 700	7 915	69 213	27 954	7 603	60 961	224	69.1	423
	B CF		0.62	0.46	0.75	0.79	0.45	1.05	1.55	0.65	2.96
	TF		0.43	0.03	1.34	0.43	0.02	1.13	1.05	0.27	2.86
	TC		0.2	0.02	0.53	0.2	0.06	0.51	1.57	0.81	2.95
P. australis (n = 12)	Shoot	1 709	358	80	1 598	264	72	955	74	39	223
	Root	1 661	9 312	7 136	18 031	6 494	1 007	18 323	686	207	4 481
	Soil		19 788	18 758	20 875	11 826	11 553	12 107	134	127	142
	BCF		0.44	0.29	0.65	0.11	0.07	0.14	1.23	0.82	1.63
	TF		0.04	0.01	0.18	0.14	0.01	0.64	0.22	0.61	0.65
	TC		0.08	0.07	0.08	0.05	0.04	0.05	0.77	0.53	1
T. capensis (n = 5)	Shoot	336	845	246	2 146	845	264	4 325	1 487	1 212	2 737
	Root	439	58 834	3 533	19 2155	47 262	3 491	108 941	448	257	727
	Soil		23 886	9 480	196 140	21 537	8 426	169 578	104	42	300
	BCF		10.09	0.6	18.5	7.03	0.63	12.9	5.84	2.42	12.2
	TF		0.04	0.01	0.12	0.04	0.01	0.12	3.91	1.67	6.51
	TC		0.09	0.01	0.23	0.11	0.01	0.29	29.69	4	59.6
C. marginatus (n = 6)	Shoot	222	176	71	409	220	66	367	176	29	421
	Root	369	1 539	133	7 405	1 948	610	4 554	134	26	1 069
	Soil		21 015	17 561	26 448	14 248	11 241	20 774	390	1 015	81
	BCF		0.35	0.09	0.7	0.08	0.06	0.1	0.39	0.2	0.81
	TF		0.17	0.03	0.53	0.15	0.04	0.4	2.57	0.2	6.53
	TC		0.01	0.01	0.02	0.02	0.01	0.02	0.08	0.02	0.14
C. haspan (n = 7)	Shoot	68	1 098	210	19 395	744	323	2 124	258	184	405
	Root	483	9 029	1 929	28 292	4 471	1 820	8 069	300	74	2 264
	Soil		24 746	19 919	29 573	18 176	17 052	19 375	202	72	569
	BCF		0.98	0.54	1.42	0.13	0.09	0.17	0.68	0.33	1.03
	TF		0.29	0.03	0.68	0.26	0.09	0.74	1.24	0.09	2.19
	TC		0.54	0.1	0.97	0.08	0.03	0.13	1.49	0.71	2.26
J. effusus (n = 7)	Shoot	449	367	149	2 656	391	167	2 987	103	35	403
	Root	1 536	11 824	9 241	27 712	10 015	1 245	34 628	314	135	738
	Soil		14 768	7 564	30629	13 073	7 591	17 760	197	53	375
	BCF		0.91	0.3	1.6	1.05	0.07	2.19	1.96	0.42	4.27
	TF		0.04	0.01	0.09	0.07	0.01	0.26	0.63	0.06	2.11
	TC		0.04	0.01	0.16	0.05	0.02	0.19	0.96	0.13	4.15

Given the varying degrees of human impact and pollution, the nature of the plants and the natural geology, the metal concentrations of plant materials varied hugely between specimens and sites. The average metal concentration in the soil varied between 16.047 mg/kg and 47.045 mg/kg for Al, 13.23 mg/kg and 41.719 mg/kg for Fe and 170 – 1200 mg/kg for Mn. The root concentrations of Al and Fe exceeded the shoot concentrations and only *T. capensis* (Al) and *J. effusus* (Al and Fe) presented root concentrations exceeding soil concentrations. Mn uptake patterns differed to those of Al and Fe, in that only *C. marginatus* did not have higher root concentrations of Mn than what was available in the soil (0.135 – 0.390 mg/kg). *Typha capensis* had Mn shoot concentrations (1.619 mg/kg) exceeding root concentrations (0.481 mg/kg).

Schoenoplectus corymbosus and *T. capensis* showed BCFs higher than 1 for all three metals. Additionally, *J. effuses* had a BCF > 1 for Fe and *C. dactylon* could bioaccumulate Mn with a BCF of 1.6. No species had TF and TC values above 1 for Al or Fe, whereas for Mn, *C. dactylon, S. corymbosus* and *T. capensis* had TF and TCs ranging from 1.05 to as high as 29. The plant species did not accumulate Al, Fe or Mn beyond 10 000 mg/kg of biomass, and are thus not considered hyperaccumulators of these particular metals. Al and Fe did not readily transfer into plant shoot tissue for any of the species, but were rather held within the root tissue zone. This would suggest that the species showed greater potential to adsorb and phytostabilize Al and Fe in the soil, rather than phytoextract these metals into the above-ground plant material.

Figure 2 depicts the extraction efficiency of all 7 species for Al, Fe and Mn. The metal concentrations in the respective shoot and root biomass were determined (g/m^2). Al and Fe are almost exclusively trapped in the roots of all species and none accumulate significant concentrations in their shoots. Mn is more readily accumulated in the shoots, especially by *T. capensis* (0.8 g/m^2) and *S. corymbosus* (1.1 g/m^2). Given their higher biomass, *S. corymbosus*, *T. capensis* and *P. australis* would be the most effective phytoextractors of Mn.

There are no previous reports on the metal accumulation ability of the 2 indigenous species, *C. haspan* and *C. marginatus*. In the current study, *C. haspan* and *C. marginatus* presented with the lowest biomass and neither of the species showed an affinity for the absorption of Al, Fe and Mn from the soil into the plant tissue. These species will therefore not be ideal for metal immobilization in contaminated soils and water.

Typha capensis, *S. corymbosus* and *J. effusus* present with the greatest potential to concentrate and phytostabilize Al and Fe. Given the greater biomass of *S. corymbosus* and *J. effusus* (Table 2), these 2 species proved to be the most effective of the 7 species to phytostabilize Al and Fe in the root zone (Fig. 2). Internationally, the genus *Juncus* is popular for use in constructed wetlands for margin and embankment stabilization (Tanner, 1996*)*. In particular *J. effusus* has shown accumulation of Fe, Pb, Zn, Cd and Cu in polluted soils and it is already used elsewhere in constructed wetlands for AMD remediation (Deng et al., 2004; Mays and Edwards, 2001). *Schoenoplectus* species, in comparison, are known for significant nutrient uptake in high-flow artificial wetlands (Vymazal, 2011); however, little is known regarding the metal uptake capacity of *S.corymbosus* specifically.

Although *P. australis* presents with a reasonably low BCF compared to the other plant species, its total biomass is between 2 and 7 times larger, allowing for larger areas of extraction. *Phragmites australis* have known benefits in wetlands, i.e., erosion control and filtering of sewage water (Armstrong and Armstrong, 1988; Bromilow, 2010). They are tolerant of extreme pH differences (Batty et al., 2000) and highly eutrophic conditions with nutrient and heavy metal accumulation (Cr, Ni, Cu and Zn) capability (Bragato et al., 2006; Wang and Jia, 2009).

Members of the genus *Typha* have also previously been shown to accumulate other metals (Cd, Cu, Ni and Pb) and are well-known species considered for wetland rehabilitation (Mays and Edwards, 2001). The large biomass of *P. australis* available for metal uptake and the high metal accumulation per m^2 of biomass observed for *T. capensis* should make these species key role players in rehabilitation scenarios.

Riparian vegetation zones

The GIS mapping to map the extent of the riparian zone against a hypothetical buffer zone of 30 m is shown in Fig. 3. The difference in area between the ideal buffer width

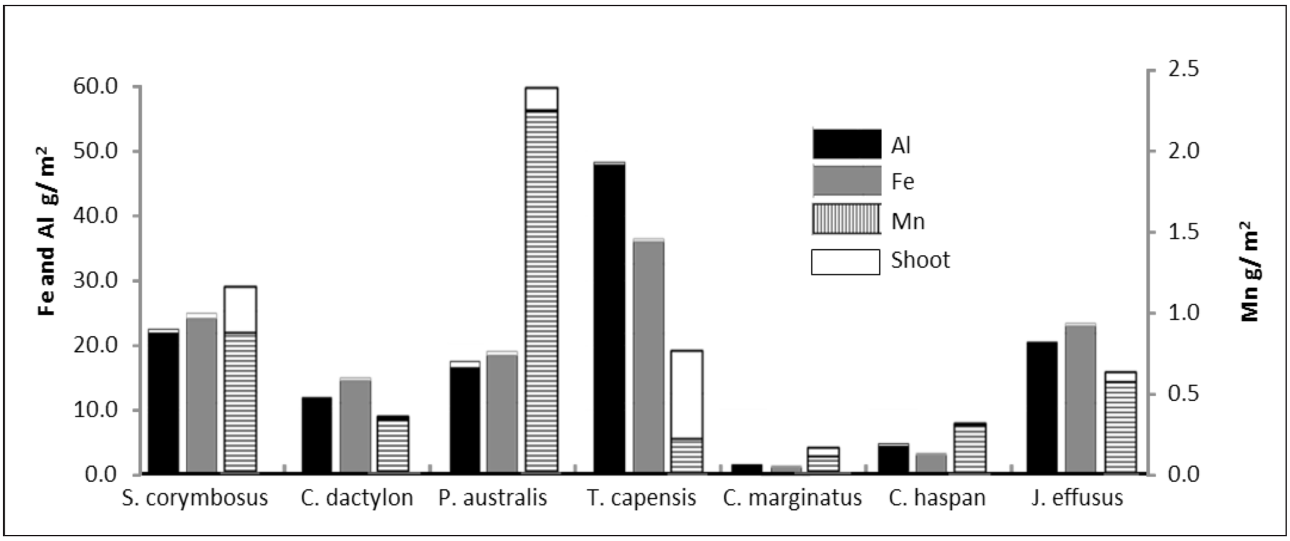

Figure 2
The accumulation potential for Al, Fe and Mn in g/m2 of each of the plant species.

http://dx.doi.org/10.4314/wsa.v43i2.01
Available on website http://www.wrc.org.za
ISSN 1816-7950 (Online) = Water SA Vol. 43 No. 2 April 2017

(200 m x 60 m) and the actual extent of the riparian zone is expressed as a percentage in Table 3. The ideal buffer increased over 100% for Site C, due to the included consideration of substantial in-stream vegetation, primarily *P. australis*.

The spatial analysis of the 5 sampling sites in the upper Olifants catchment suggests that the riparian zones within the catchment are in various states of degradation/intactness. From the natural distribution of species at the 5 study sites in the Olifants River catchment (Table 1) in a hypothetical riparian zone of 12 000 m^2, the total Al, Fe and Mn accumulated in the separate plant biomass per site is estimated in Fig. 4. Due to the high biomass and relative abundance, *P. australis* that was the main phytostabilizer of metals in Sites B and C whereas *T. capensis* and *J. effusus* were the primary stabilizers at Site D and Site E, respectively.

To qualify the possible ecological ecosystem service provided by the riparian species and their capability of photostabilizing Al, Fe and Mn in the study sites, the average water and soil metal concentrations were compared. The average water and soil concentrations of Al, Fe and Mn along with the intactness of the riparian area are presented in Fig. 6. Seasonal sampling had higher metal and nutrient concentrations during the high-flow months. The pH and electrical conductivity of water samples collected from Sites A and B ranged between pH 7.6 and pH 7.7 and 47 and 52.2 mS/m, respectively. The riparian zones in Sites A and B were mostly intact (70 and 77%, respectively) with minimal anthropogenic disturbances. Although the metal concentrations in the soil determined for these ranged in the medium to high end of the scale, the Al, Fe and Mn concentrations for Sites A and B were low and well within the recommended target water quality guidelines (DWAF, 1996). This is likely due to the absence of major anthropogenic activities and sufficient phytostabilization of the metals in the soil in near-neutral pH conditions. Sites A and B are reference sites which represent the more intact areas with fully functional ecosystem services.

The concentrations of Mn, Al and Fe found in the soil and water vary from site to site and are largely dependent on the surrounding anthropogenic activities as well as the natural geology. Site C and Site D showed the highest metal concentrations in water as well as a low pH (between pH 5.3 and 5.4) and high electrical conductivity, ranging on average between 199.5 and 209 mS/m. These water quality conditions coincide with the occurrence of AMD associated with mining activities. Al and Fe concentrations were similar for most sampling sites indicating that these most likely originated from the natural geology (Newman et al., 2007). Elevated concentrations of Al and Fe are likely due to AMD, which leach these metals from the natural geology, making them more bioavailable (McCauley et al., 2009). Al and Fe soil concentrations at Site C were more than twice as high as in any of the other sites, and can likely be ascribed to metal stabilization in soil through the prolific growth of *P. australis* in and around the river (Wong, 2003; Ashraf et al, 2011). The accumulation potential of *P. australis* in the ideal vegetation zone was effectively phytoextracting 204 960 g/m^2 of Al, 204 400 g/m^2 of Fe and 27 887 g/m^2 of Mn into its biomass. The comparatively low metal concentrations in the water could be due to a considerable ecosystem service performed by the naturally established riparian vegetation. The intact vegetation reduced the stream flow, and increased the water pH as well as phytostabilizing the metals into the soil.

Site D is just downstream of Site C with only 13% of its riparian vegetation intact. It is under severe pressure from ongoing industrial activities and AMD. Metal concentrations in water were high, while soil Al, Fe and Mn concentrations were lower than those of the reference sites, Sites A and B. One of the overt differences between Sites C and D is the difference in riparian growth, suggesting low to minimal soil metal stabilization. Comparing these sites, it is postulated that a revegetation of the riparian zone at Site D, including native species investigated in this study, may improve pollutant retention and phytostabilization of Al, Fe and Mn. As such, metals are retained in the soil and extracted into the plants, reducing metal concentrations in river water. Recommendations for a rehabilitation strategy to remediate elevated metal concentrations (Al, Fe and Mn) in this area include:

- Revegetation of the riparian zone to at least 80% intact (from ideal)
- Using a diversity of native, pH-tolerant plant species
- Increasing the total biomass in the riparian zone by introducing *P. australis*
- Including high metal uptake (BCF) plants such as *T. capensis*
- Introducing in-stream vegetation

TABLE 3
Most recent data on riparian vegetation, compared to an area calculation of a hypothetical 30 m buffer zone and the most prevalent land use activities in an area of 2 km x 2 km.

Site	Year	% Ideal vegetation intact	Land use practices
Site A	**2005**	80	Minimal grazing
Site B	**2005**	77	Game farming, limited agricultural activities, mostly undisturbed
Site C	**1991**	280	Major urbanisation, minimal agriculture, grazing, historical mining (AMD)
Site D	**2011**	13	Major livestock grazing, historical mining (AMD), industry (VanChem)
Site E	**2003**	38	Urbanization and agriculture, just below the outlet of a wastewater treatment works

CONCLUSIONS

The Al-, Fe- and Mn-sequestering ability of widely occurring species in the Upper Olifants Catchment, South Africa, was determined for their potential inclusion in water quality rehabilitation efforts. None of the plant species proved hyperaccumulators of Al, Fe or Mn. However, 4 species, *S. corymbosus, T. capensis, P. australis* and *J. effusus*, have accumulation and high phytostabilization potential. *S. corymbosus* and *T. capensis*, shoot accumulators of Mn, were considered the best candidates for phytoextraction of Mn. Site C provides an example of successful phytostabilization, aided by a prolific riparian zone, in a severely degraded landscape. Given the similar environmental impacts for Site D, the water quality may be improved by rehabilitating the riparian zone in degraded areas, using a combination of the widely-occurring, pollution-tolerant and Al-, Fe-, Mn-phytostabilizing species: *P. australis, T. capensis, S. corymbosus* and *J. effusus*. Furthermore, indigenous species, *Cyperus haspan* and *Cyperus marginatus* are less likely

http://dx.doi.org/10.4314/wsa.v43i2.01
Available on website http://www.wrc.org.za
ISSN 1816-7950 (Online) = Water SA Vol. 43 No. 2 April 2017

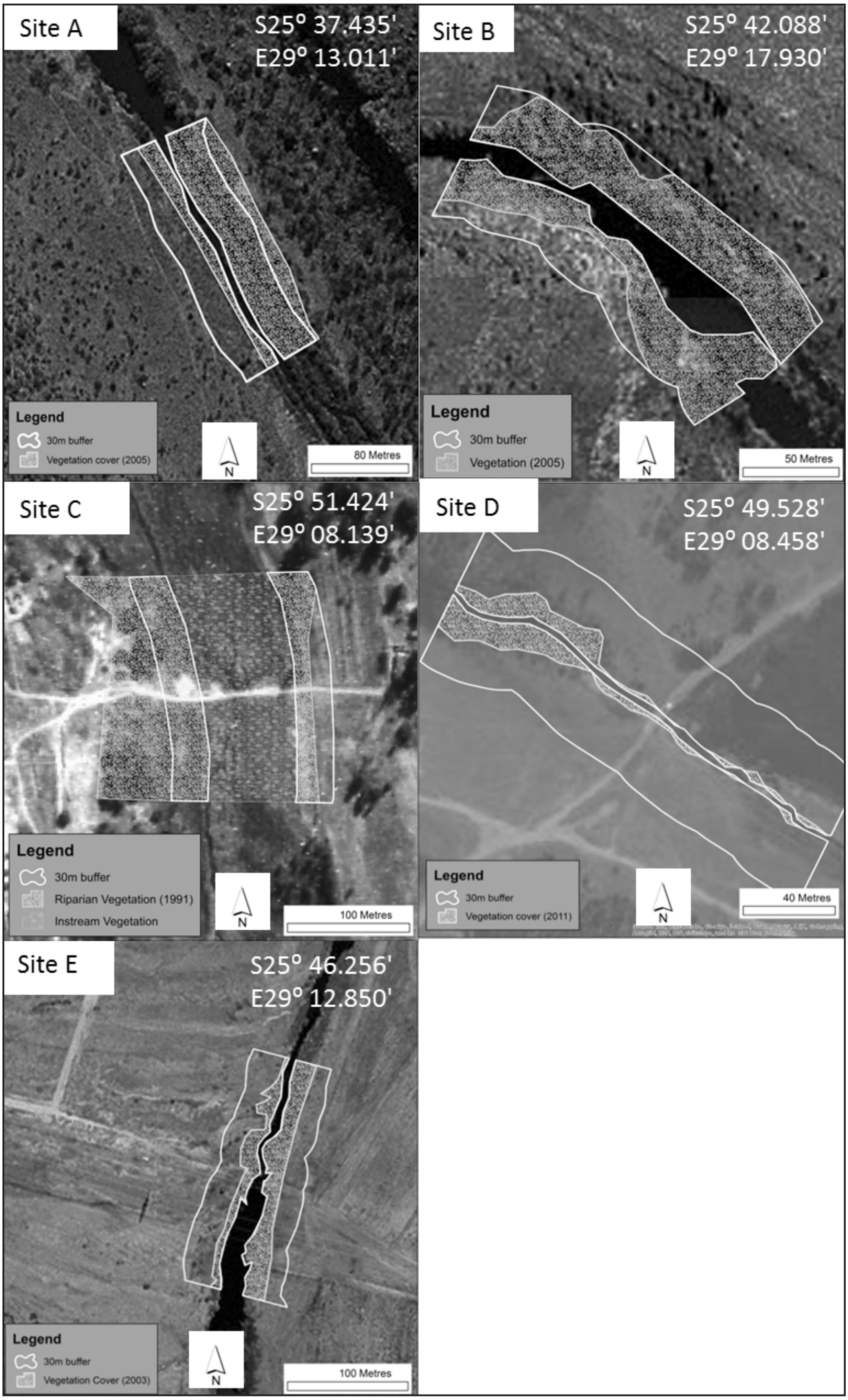

Figure 3

Extent of riparian vegetation zones relative to a hypothetical 30 m buffer zone for Site A, Site B, Site C, Site D and Site E

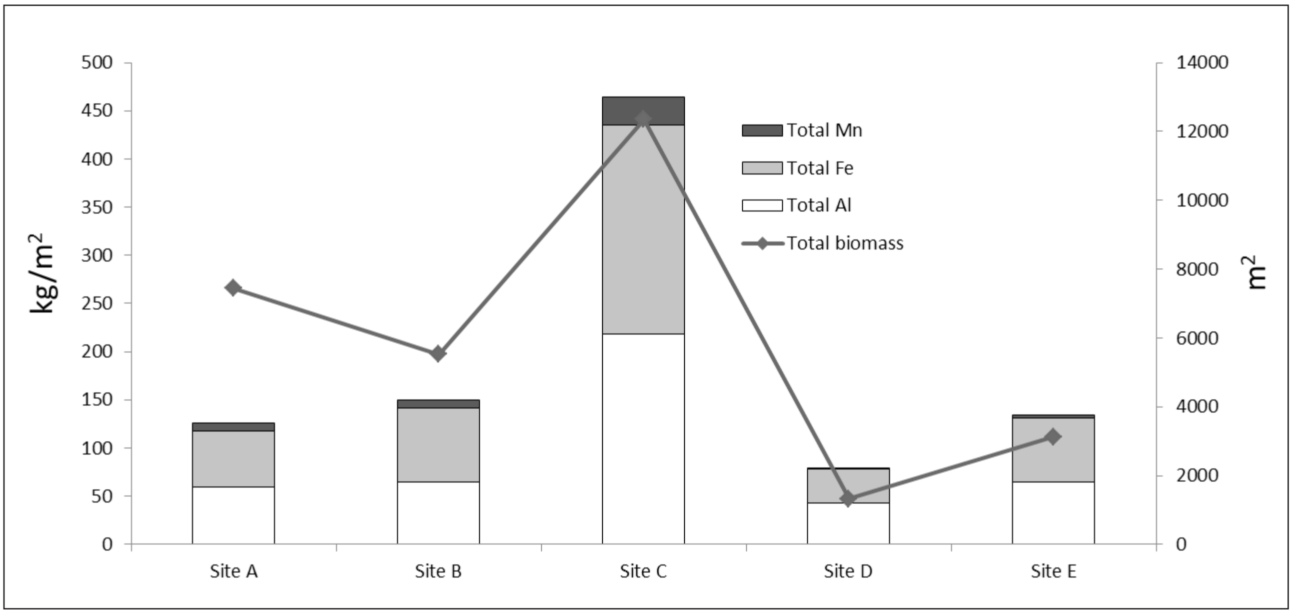

Figure 4
Estimated total metal amounts (g/m2) that the biomass determined from the surveyed distribution of the selected plant species could phytostabilize at the 5 study sites.

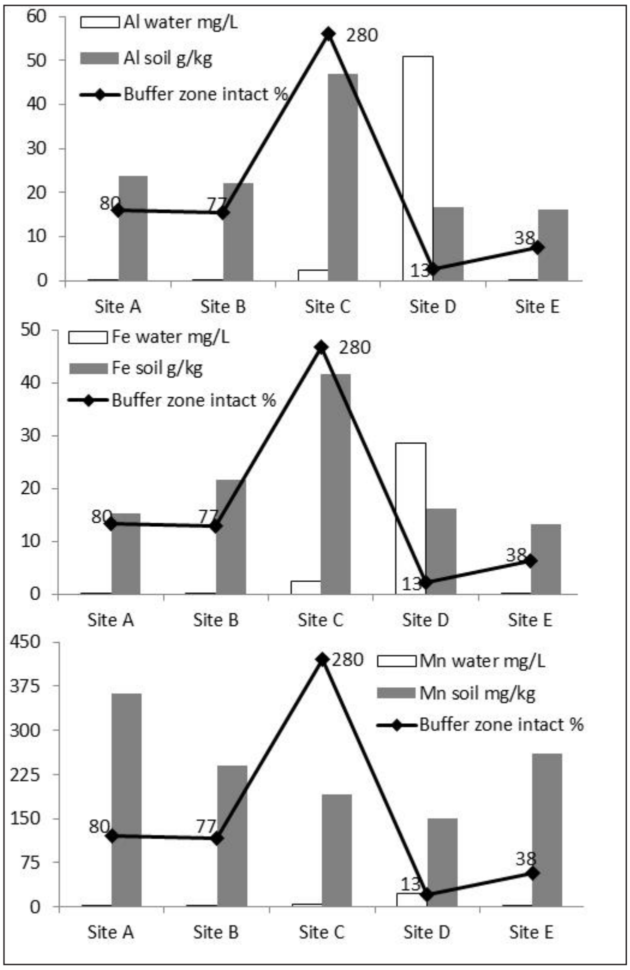

Figure 5
The average water and soil concentrations of Al, Fe and Mn determined for the sampling sites with corresponding intact % vegetated buffer area

to occur in areas contaminated by AMD. These species have low biomass and present with low BCF for Al, Fe and Mn. *C. haspan* and *C. marginatus* do present with translocation factors > 1 for the accumulation of Mn, which suggests for their inclusion in rehabilitation studies.

ACKNOWLEDGEMENTS

We would like to thank the Olifants River Forum for funding.

REFERENCES

APHA, AWWA and WEF (1995) *Standard Methods for the Examination of Water and Wastewater* (19th edn). American Public Health Association, Washington DC.

ARMSTRONG J and ARMSTRONG W (1988) *Phragmites australis* – a preliminary study of soil-oxidizing sites and internal gas transport pathways. *New Phytol.* **108** 373–382. https://doi.org/10.1111/j.1469-8137.1988.tb04177.x

ASCH F, BECKER M and KPONGOR DS (2005) A quick and efficient screen for resistance to iron toxicity in lowland rice. *J. Plant Nutr. Soil Sci.* **168** (6) 764–773. https://doi.org/10.1002/jpln.200520540

ASHRAF M, MAAH MJ and YUSOFF I (2011) Heavy metals accumulation in plants growing in ex tin mining catchment. *Int. J. Environ. Sci. Technol.* **8** (2) 401–416. https://doi.org/10.1007/BF03326227

BAKER AJM (1981) Accumulators and excluders – strategies in the response of plants to heavy metals. *J. Plant Nutr.* **3** (1–4) 643–654. https://doi.org/10.1080/01904168109362867

BAKER AJM and BROOKS RR (1989) Terrestrial higher plants which hyperaccumulate metallic elements – a review of their distribution, ecology and phytochemistry. *Biorecovery* **1** (2) 81–126.

BATTY LC, BAKER AJM, WHEELER BD and CURTIS CD (2000) The effect of pH and plaque on the uptake of Cu and Mn in *Phragmites australis* (Cav.) Trin ex. Steudel. *Ann. Bot.* **86** (3) 647–653. https://doi.org/10.1006/anbo.2000.1191

BECH J, POSCHENRIEDER C, BARCELO J and LANSAC A (2002) Plants from mine spoils in the South American area as potential sources of germplasms for phytoremediation technologies. *Acta Biotechnol.* **22** (1–2) 5–11. https://doi.org/10.1002/1521-3846(200205)22:1/2<5::AID-ABIO5>3.0.CO;2-B

BRAGATO C, BRIX H and MALAGOLI M (2006) Accumulation of nutrients and heavy metals in *Phragmites australis* (Cav.) Trin. ex Steudel and *Bolboschoenus maritimus* (L.) Palla in a constructed wetland of the Venice lagoon watershed. *Environ. Pollut.* **144** (3) 967–975. https://doi.org/10.1016/j.envpol.2006.01.046

BROADMEADOW S and NISBET TR (2004) The effects of riparian forest management on the freshwater environment: a literature review of best management practice. *Hydrol. Earth Syst. Sci. Discuss.* **8** (3) 286–305. https://doi.org/10.5194/hess-8-286-2004

BROMILOW C (2010) Problem plants and alien weeds of South Africa, third ed. Briza Publications, Pretoria.

CLERICI N, PARACCHINA ML and MAES J (2014) Land-cover change dynamics and insights into ecosystem services in European stream riparian zones. *Ecohydrol. Hydrobiol.* **14** (2) 107–120. https://doi.org/10.1016/j.ecohyd.2014.01.002

DWAF (Department of Water Affairs and Forestry, South Africa) (1996) South African Water Quality Guidelines. Volume 1. Domestic Use (2nd edn). Department of Water Affairs and Forestry, Pretoria.

DENG H, YE ZH and WONG MH (2004) Accumulation of lead, zinc, copper and cadmium by 12 wetland plant species thriving in metal-contaminated sites in China. *Environ. Pollut.* **132** (1) 29–40. https://doi.org/10.1016/j.envpol.2004.03.030

DUNCAN M (1999) Pastures and acid soils. Leaflet No. 6. New South Wales Acid Soil Action Programme. URL: http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/162925/acid-soil.pdf (accessed 12 August 2014).

FISCHER RA and FISCHENICH JC (2000) Design recommendations for riparian corridors and vegetated buffer strips. No. ERDC-TN-EMRRP-SR-24. U.S. Army Engineer Research and Development Center, Environmental Laboratory, Vicksburg, MS.

FITAMO D and LETA S (2010) Assessment of plants growing on gold mine wastes for their potential to remove heavy metals from contaminated soils. *Int. J. Environ. Stud.* **67** (5) 705–724. https://doi.org/10.1080/00207233.2010.513587

GREGORY SV, SWANSON FJ, MCKEE WA and CUMMINS KW (1991) An ecosystem perspective of riparian zones. *Bioscience* **41** 540–551. v

JONTOS R (2004) Vegetative buffers for water quality protection: an introduction and guidance document. Connecticut Association of Wetland Scientists White Paper on Vegetative Buffers. Draft version 1.0. Connecticut Association of Wetland Scientists (CWAS). 22 pp.

MAYS PA and EDWARDS GS (2001) Comparison of heavy metal accumulation in a natural wetland and constructed wetlands receiving acid mine drainage. *Ecol. Eng.* **16** (4) 487–500. https://doi.org/10.1016/S0925-8574(00)00112-9

MCCAULEY CA, O'SULLIVAN AD, MILKE MW, WEBER PA and TRUMM DA (2009) Sulfate and metal removal in bioreactors treating acid mine drainage dominated with iron and aluminium. *Water Res.* **43** (4) 961–970. https://doi.org/10.1016/j.watres.2008.11.029

MERTENS J, VERVAEKE P, DE SCHRIJVER A and LUYSSAERT S (2004) Metal uptake by young trees from dredged brackish sediment: limitations and possibilities for phytoextraction and phytostabilisation. *Sci. Total Environ.* **326** (1) 209–215. https://doi.org/10.1016/j.scitotenv.2003.12.010

MUCINA L and RUTHERFORD M (2006) The Vegetation of South Africa, Lesotho and Swaziland. *Strelitzia* **19**. South African National Biodiversity Institute, Pretoria.

MYBURGH WJ and BREDENKAMP GJ (2004) Macro-channel riparian vegetation of the Olifants River System in the Grassland Biome, Mpumalanga. *Koedoe* **47** (1) 41–54. https://doi.org/10.4102/koedoe.v47i1.71

NEWMAN BK and WATLING RJ (2007) Definition of baseline metal concentrations for assessing metal enrichment of sediment from the south-eastern Cape coastline of South Africa. *Water SA* **33** (5) 675–691.

O'NIELL WL and NZENGUNG VA (2004) In-situ bioremediation and phytoremediation of contaminated soils and water: three case studies. *Environ. Res. Eng. Manage.* **30** 49–54.

OBERHOLSTER PJ, MYBURGH JG, ASHTON PJ and BOTHA AM (2010) Responses of phytoplankton upon exposure to a mixture of acid mine drainage and high levels of nutrient pollution in Lake Loskop, South Africa. *Ecotox. Environ. Saf.* **73** 326–335. https://doi.org/10.1016/j.ecoenv.2009.08.011

REMON E, BOUCHARDON JL, CORNIER B, GUY B, LECLERC JC and FAURE O (2005) Soil characteristics, heavy metal availability and vegetation recovery at a former metallurgical landfill: Implications in risk assessment and site restoration. *Environ. Pollut.* **137** 316–323. https://doi.org/10.1016/j.envpol.2005.01.012

TANGAHU BV, SHEIKH ABDULLAH SR, BASRI H, IDRIS M, ANUAR N and MUKHLISIN M (2011) A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. *Int. J. Chem. Eng.* **2011** 939161. https://doi.org/10.1155/2011/939161

TANNER CC (1996) Plants for constructed wetland treatment systems — A comparison of the growth and nutrient uptake of eight emergent species. *Ecol. Eng.* **7** 59–83. https://doi.org/10.1016/0925-8574(95)00066-6

TILMAN D, KNOPS J, WEDIN D, REICH P, RITCHIE M and SIEMANN E (1997) The influence of functional diversity and composition on ecosystem processes. *Science* **277** 1300–1302. https://doi.org/10.1126/science.277.5330.1300

TIWARY RK (2001) Environmental impact of coal mining on water regime and its management. *Water Air Soil Pollut.* **132** 185–199. https://doi.org/10.1023/A:1012083519667

USEPA (United States Environmental Protection Agency) (2000) Introduction to phytoremediation. EPA/600/R-99/107. Environmental Protection Agency, Washington, D.C.

VYMAZAL J (2011) Plants used in constructed wetlands with horizontal subsurface flow: a review. *Hydrobiologia* **674** 133–156. https://doi.org/10.1007/s10750-011-0738-9

WANG H and JIA Y (2009) Bioaccumulation of heavy metals by *Phragmites australis* cultivated in synthesized substrates. *J. Environ. Sci.* **21** 1409–1414. https://doi.org/10.1016/S1001-0742(08)62433-X

WANTZEN KM and MOL JH (2013) Soil erosion from agriculture and mining: a threat to tropical stream ecosystems. *Agriculture* **3** 660–683. https://doi.org/10.3390/agriculture3040660

WELSCH DJ (1991) Riparian forest buffers. United States Department of Agriculture-Forest Service Publication Number NA-PR-07-91. US Department of Agriculture, Radnor, Pennsylvania.

WONG MH (2003) Ecological restoration of mine degraded soils, with emphasis on metal contaminated soils. *Chemosphere* **50** 775–780. https://doi.org/10.1016/S0045-6535(02)00232-1

YOON J, CAO X, ZHOU Q and Ma LQ (2006) Accumulation of Pb, Cu and Zn in native plants growing on a contaminated Florida site. *Sci. Total Environ.* **368** 456–464. https://doi.org/10.1016/j.scitotenv.2006.01.016