



Long-term impact of primary domestic sewage on metal/loid accumulation in drainage ditch sediments, plants and water: Implications for phytoremediation and restoration

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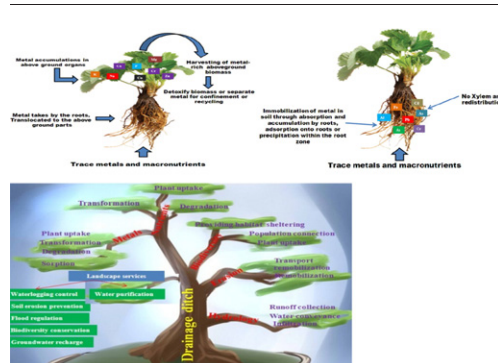
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HIGHLIGHTS

- Evaluation of possibilities for phytoextraction and phytostabilization in vegetated drainage ditch plant.
- Significant accumulation of metal/loid in ditch sediment to exceed legal background levels in soil.
- Metal/loid uptake and translocation in ditch plant biomass are limited.
- Seasonal patterns and time of maximum standing stock vary for each metal/loid.

GRAPHICAL ABSTRACT



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ABSTRACT

We evaluate the long-term performance of a vegetated drainage ditch (VDD) treating domestic sewage with respect to heavy metal/metalloid (HM/M) accumulation in sediments, plants and water. VDD sediment contained significantly higher macro and trace elements compared to an agricultural ditch (AD) sediment. However, concentrations of HM/Ms in VDD sediment were below the ranges considered toxic to plants. Most HM/Ms were efficiently removed in the VDD, whereby removal efficiencies varied between 11% for Al and 89% for K. Accumulation of HM/Ms varied among species and plant parts, although sequestration by plants represents only a small proportion (<1%) of the inflow load. Accumulation of Al, As, Cd, Pb, Cr, Fe and Ni in VDD plants were mostly distributed in the roots, indicating an exclusive strategy for metal tolerance. The opposite was found for Zn, Cu, K, Ca, P, K, Na, N and Mg, which were accumulated either in the stems or leaves. Overall, concentrations of metals in sediment showed significant positive correlations with those in ditch plants. None of the studied species were identified as metal hyper-accumulators (i.e. >10,000 mg kg⁻¹ of Zn or Mn). Nevertheless, the high translocation factor (TF) values for Mn, Ni, Cu, Zn, Na, Mg, P, K and Ca in the ditch plants make them

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suitable for phytoextraction from water/soil, while the low TF values for Pb, Cd, As, Fe, Cr and Al make them suitable for their phytostabilization.

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1. Introduction

Drainage ditches are one of the human-made water bodies often used to collect surface runoff from surrounding plots and roads (Buchanan et al., 2012; Carluer and Marsily, 2004). Their presence grows in proportion to the expansion of anthropogenic land use. They can act as primary conduits of untreated human sewage in the absence of treatment facilities (Kumwimba et al., 2016a, b, c, d; Kumwimba et al., 2015). In recent years, great strides have been made to reduce the discharge of nutrients into the aquatic environment with various counter-measures such as constructed wetlands, retention basins, buffer zones and stiff grass hedges (Bouldin et al., 2004; Cooper et al., 2004; Kröger et al., 2007, 2008, 2011; Moore et al., 2000, 2006; Needelman et al., 2007). Scientists now promote the utilization of ditch systems as innovative and cost effective alternatives for minimizing nutrient runoff from agricultural fields (Cooper et al., 2004; Kröger et al., 2008). There is growing interest in treating domestic sewage through vegetated (eco) ditches as the most attractive alternative to conventional treatments technologies (Kumwimba et al., 2016a, b, c, d; Wu et al., 2014). However, despite their potential importance in treating polluted water, their role in nutrient reduction strategies has only been partially assessed to date and remains a hot topic of interest.

Drainage ditches in North America, Europe and developing countries are mostly applied for the treatment of agricultural runoff pollution and pesticides (Bennett et al., 2005; Bouldin et al., 2004; Chen et al., 2015; Cooper et al., 2004; Flora and Kröger, 2014; Fu et al., 2014; Kröger et al., 2007; Kröger et al., 2008; Moore et al. 2010; Zhang et al., 2013). They have been widely assessed for nitrogen, phosphorus, and suspended solids removal, but information on heavy metals/metalloids (HM/Ms) remains somewhat limited or unknown. Field studies of these systems have been already demonstrated for agricultural wastewaters, domestic sewage and storm water (Kröger et al., 2008; Kumwimba et al., 2016a, b, c, d; Luo et al., 2009; Wu et al., 2014). However, this technique has not yet been sufficiently assessed for the treatment of domestic sewage contaminated with HM/Ms. In addition, no work has been carried out to assess the accumulation of HM/Ms in drainage ditch sediment and release to the water column, apart from two studies that reported the distribution of some metals in sediment and water in different land use areas (Kumwimba et al., 2016c, d; Zhang et al., 2004).

Accumulation of HM/Ms in vegetated ditches treating domestic sewage is not a topic of priority, mainly because the concentrations of HM/Ms are supposed to be significantly lower. Moreover, presently there are no discharge standards for HM/Ms in eco (vegetated) ditches. As a result, HM/Ms have been neglected historically in most treatment ditches. Nevertheless, HM/Ms in domestic sewage may be associated with fine particulate matter, and the long-term deposition of sewage to aquatic ecosystems often results in the accumulation of high levels of HM/Ms in sediments (Rattan et al., 2002) and ditch plant species. Therefore, the reservoirs or lakes into which drainage ditches are diverted must be protected from HM/Ms due to their toxicity, abundance and long-term persistence in the environment.

In aquatic systems, metals have a high affinity for particulate matter and will, therefore, accumulate in surface sediments (Sundaray et al., 2011). Once deposited, however, chemical and biological processes may allow HM/Ms to be desorbed from surface sediments and released into the water column (Li and Davis, 2008). Because of adsorption, hydrolysis and co-precipitation, only <0.1% of free metal ions actually dissolve in the water, and >99.9% are bound to the particles in sediments and soil (Gaur et al., 2005). These HM/Ms are removed partly by accumulation in the biomass of plants. Therefore, sediments may serve as

a metal pool that can release metals to the overlaying water via natural and anthropogenic processes, causing potential adverse health effects to the aquatic ecosystems (Singh et al., 1997). Information about the abilities of various ditch plants to take up and translocate metals can give insight into selecting suitable plants for drainage ditch phytoremediation. However, quantitative information comparing the performance of different ditch plant species in eco ditches is rare.

Eco ditches encompass several processes and mechanisms in the removal of contaminants (Fig. S1) such as sorption, sedimentation, evaporation, precipitation, transformation, adsorption, plant uptake, filtration and microbial metabolic activities (Kumwimba et al., 2016a, b). The aquatic plants in ditches play important roles to effectively decrease the flow velocity, increase agrochemical retention, and subsequently provide better conditions for pollutants removal in ditches (Kröger et al., 2007). Accumulation levels of HM/Ms increase with the operational lifetime of the system. Therefore, understanding the differences in HM/Ms accumulation among species is imperative to assess the best species for use in the restoration of polluted aquatic ecosystems and to develop suitable management alternatives.

In this study, accumulation of HM/Ms in vegetated drainage ditch (VDD) sediment and different plant parts (roots, stems and leaves) were assessed in order to determine the biogeochemical processes and mobility as well as removal mechanisms for metals removal in VDD treating primary domestic sewage after 10 years of operation. The possibilities for phytoextraction and phytostabilization in VDD plant communities were also evaluated. The specific objectives of the research presented in this study were to (1) explore the differences in HM/M accumulation by 9 dominant ditch plant species in a VDD impacted by primary domestic sewage; (2) investigate the fate and uptake of domestic sewage-related metal and arsenic in sediments by root and shoot organs of ditch species and (3) examine the enrichment and translocation potentials of these species to metal and arsenic. It is hypothesized that untreated domestic sewage would increase pollutant inputs, increasing the concentrations of HM/Ms in sediment and water above the background concentrations of soils in China. We predict that these higher levels would be reflected in HM/M concentrations in ditch plants. Furthermore, the concentrations of metals are expected to vary between different plant parts, with higher concentrations in the root and shoot parts. For the above reasons, it is very important to comprehensively understand the HM/M contamination status in the agricultural drainage ditch of Sichuan Basin to provide a reference for the large-scale control and management of HM/Ms. This study would provide the latest and most significant information related to the long-term effect of primary domestic sewage on macronutrients and HM/Ms accumulation in drainage ditch sediments, plants and water.

2. Materials and methods

2.1. Description of the study sites, sampling and plant materials

The VDD (Fig. 1) is located in Jieliu catchment (105°27'24"E, 31°16'31"N) in the hilly Sichuan Basin, China. The catchment is a representative headwater urbanized catchment of the Jialing River, which is a first-order tributary of the Yangtze River. The site has a subtropical monsoon climate with a mean annual temperature of 17.3 °C and a mean precipitation of about 826 mm. The average air temperature at the site in January is 2 °C. The lowest and highest average monthly temperatures are −6 °C (in February) and 38 °C (in August). The VDD was designed and built in the downstream section of the catchment for primary domestic sewage treatment. However, it receives storm water, as

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