A Study on the Transport Behaviour of Cobalt (Co) in Mangroves

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Abstract: *Mangroves are a unique habitat rich in biodiversity. They are known as the plant army of the land. Present study is an attempt to simulate the accumulation and transport behaviour of cobalt by mangroves in sewage sludge included soil. Plants found on such fields absorb heavy metals, which causes phyto-toxicity. This manuscript is based on the dynamic macroscopic numerical model for heavy metal movement. The model is applied for simulating cobalt transport by Common Derris (Derris trifoliate) and Sea Holly (Acanthus ilicifolius) using measured field information. The controlling non-linear differential equations are settled numerically utilizing MATLAB.*

Key Words: *Simulation, Cobalt, Derris Trifoliate, Acanthus Ilicifolius, Phyto-toxicity, MATLAB.*

Introduction

Mangroves are evergreen plants that grow in the tidal range of the sea and at the confluence of rivers and backwaters. Mangroves are the guards of the land and the coast. So conservation of the mangrove forests is essential for maintaining the natural equilibrium. Here in the study, it is planned to simulate the transport behaviour of cobalt metal in Common Derris (Derris trifoliate) and Sea Holly (Acanthus ilicifolius) following well-established dynamic macroscopic numerical model. Extensive interests in environmental issues have led to active research on the adoption and take up of heavy metals in the environment. [1, 2, 3].

Accumulation of heavy metals in plants depends on their chemical nature, plant species and soil type. Plants contain organic and inorganic ingredients. A lot of research work has already been processed on the biotic constituents of plants while very little attention has been paid on the role of minerals in the medicinal use of plants. Numerous plants are discovered to be wealthy in at least one individual mineral and accordingly giving a potential connect to the remedial activity of the medication.

Here, a model has been developed for simulating water movement in "*unsaturated zones"* by integrating the "*one-dimensional transient unsaturated water flux equation (Richard's equation)"* with a root water withdrawal term (sink) and also use an equation which says the passage of heavy metal in the soil column and plant roots. Both the controlling *"non-linear partial differential equations"* are settled numerically by the "*implicit finite difference method* using *Picard's iterative technique".*

Model Description

The present model is based on Richards's equation. It has been introduced by *"Richards (1931*)" who has suggested that, *"the Darcy's law originally devised for saturated flux in porous media is also applicable to unsaturated flux in porous media [5]".* Here we have considered the "*unsaturated zone*"; it is the intermediate area between the land surface and the water bed.

Controlling Equation for Water Flux and its Take-up by Root

The generalized equation of water flux in isotropic media is [4],

$$c\,(l)\frac{\partial l}{\partial t} = \frac{\partial}{\partial \xi}\left[k(l)\left(\frac{\partial l}{\partial z} - 1\right)\right] - Z(\xi\,,t) \qquad 1$$

Here l is the pressure level, $c(l)$ is the soil wetness proportion, $k(l)$ is the pressure level waterpower conductivity and ξ is the soil depth taken to be progressive upwards. The 1-D function $Z(\xi,\ t)$ is *"the sink term for water withdrawal"* and is expressed as *"the volume of water per unit volume of soil per unit time"*. The solution of above equation (Eqn. 1) requires "*soil wetness holding parameters and the waterpower conductivity"*. Since they are irregular functions of l, obvious expressions developed *by "van Genucthen [6] and van Genucthenet al. [7]"*, established by experimental data set, are taken here. *These expressions can be written respectively as*

$$\frac{\phi\,(l) - \phi(r)}{\phi_s - \phi_r} = \frac{1}{(1 + (\beta\, l)^n)^{\,m}} \qquad 2$$

$$k\ \ (l) = \frac{[1-(\beta l)^{n-1}\{1 + (\beta\, l)^n\}^{-m}\,]^2}{[1 + (\beta\, l)^{\,n}]^{\frac{m}{2}}} \qquad 3$$

Here $\phi(l)$ is the water holding function, defining *"the water content as a function of the soil water pressure",* ϕ_s and ϕ_r are the saturation and remnant wetness content respectively β, n and m are the curve contour parameters and k_s is the saturated waterpower conductivity of the soil. Differentiating Eqn. (2) partially with respect to l gives *the expression for soil wetness proportion as*

$$c(l) = \frac{\partial \phi}{\partial l} = \frac{(1-n)\beta^n\, l^{n-1}\,(\phi_s - \phi_r)}{[1 + (\beta l)^{\,n}]^{\,m+1}} \qquad 4$$

"The root water withdrawal function is a sink term" in Eqn. (1). Many expressions for that sink term are available in the literature, *"the linear root water take-up model proposed by Prasad [8]"*, is used here as it is confirmed by several field conditions. *The equation is*

$$Z(\xi,\ t) = \frac{2\ T_p(t)}{Z_{\ max}} \gamma\ (\ l)[1\ -\ \frac{\zeta_r}{\zeta_{max}}] \qquad 5$$

Here T_p is the prospective transpiration rate, ζ_r is the root length at the given time, ζ_{max} is the extreme rooting depth and $\gamma(l)$ is the pressure head dependent reduction factor. The value of the *"sink term at any time gives the take-up rate at the top of the root"*. In the water take-up equation (Eqn. 1*), "the water withdrawal rate is proportional to the root depth* Z_r*, which is a function of time."*

Empirical equations have been framed by many researchers to forecast the root growth with time. Among various expressions, *"the one suggested by Borg and Grimes [9]"* is accepted since it has been developed after widespread *regression analysis using more than 100-field observations,*

$$\zeta_r = \frac{1}{2}\ \zeta_{max}\,[1 + [\ sin\ (\frac{303}{100}\frac{DAP}{DTP} - \frac{147}{100})\ ] \qquad 6$$

Here "DAP *and* DTM *are respectively the days after planting and days to maturity of the plant under consideration*", here in this equation root spreading with depth is not considered.

Controlling equation for heavy metal passage and its take-up by plant

The Controlling "1-D equation for heavy metal movement through soil" can be written as [10]

$$\frac{\partial}{\partial t}(\delta\,\lambda_s)+\frac{\partial}{\partial t}(\phi\,\lambda_w)=\frac{\partial}{\partial z}\left(\phi\,\psi\,\frac{\partial\lambda_w}{\partial z}-\chi\lambda_w\right)+\Omega_p \qquad 7$$

Here *"the bulk density"* of the soil is δ, mass of the heavy metal in the soil column is λ_s, *"volumetric wetnesscontent*" is ϕ, the concentration of heavy metal in water phase is λ_w and the hydrodynamic dispersion coefficient is ψ , which is a function of pore velocity υ. χ is the Darcy velocity and Ω_P is the heavy metal take-up by plant roots. The pore water velocity and hydrodynamic dispersion coefficient can be written respectively as,

$$\upsilon=\frac{\chi}{n} \qquad 8$$

$$\psi=\omega\,\upsilon+\tau \qquad 9$$

Here n is the *"porosity of the soil"*, ω is the *"elongated dispersity"* and τ is the *"molecular diffusion coefficient". The Darcy velocity χ is given by*

$$\chi=k\,(l)\left(\frac{\partial l}{\partial z}-1\right) \qquad 10$$

Usually, many heavy metals in the soil will combine together. Since most of these heavy metals are divalent cations, they strive for adsorption sites, but it is very challenging to understand which heavy metals are more homogeneous than other heavy metals used for plant absorption, and the result is not globalized [10]. Therefore the passage behavior of a single heavy metal that is Cobalt is considered here. The heavy metal in soil solution is presumed to be *"governed by linear isothermal adsorption and is related to the soil heavy metal concentration [11].*

$$\lambda_w=\kappa_d\lambda_s \qquad 11$$

Here κ_d is the *"barrier coefficient*". The heavy metals take-up builds on soil and plant attributes. The analytical models are developed on the movement of the heavy metal ions in the plant roots by *"mass flux and diffusion"* along the congregation acclivities. The absorbed ions by roots expected to follow a *"Michaelis–Menton type relationship". The expression is modified for soil pH by taking into account a pH factor in the take-up term in the form as [11],*

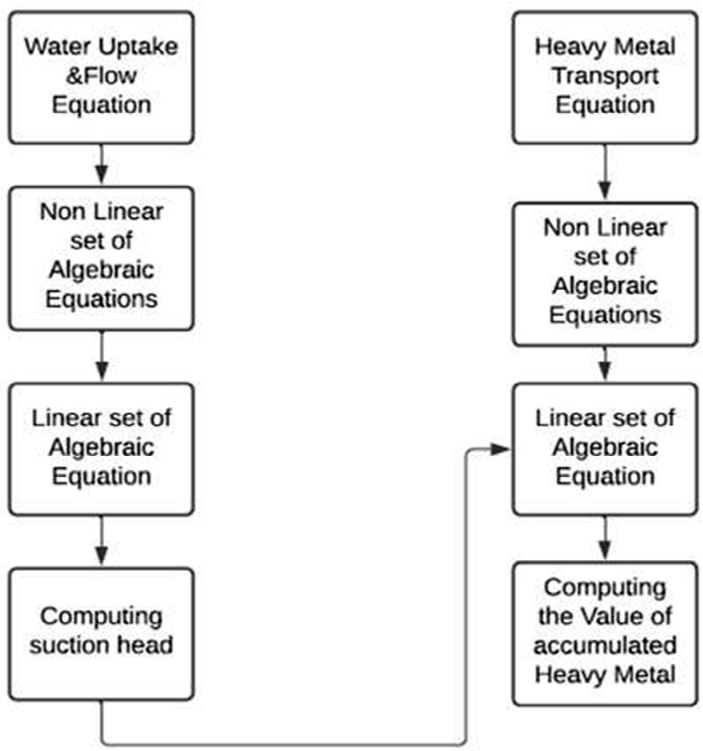
$$\Omega(p) = \Pi_{pH} \frac{\Psi_{max}\ \lambda_w}{\kappa_m + \lambda_w}$$

Here is Ψ_{max} the take-up rate at extreme concentration, κ_m is the *"Michaelis and Menton constant",* and Π_{pH} is pH value of the soil.

Results and Discussions

Equations 1-12 form the comprehensive set of controlling equations. We have to solve them to simulate/model the heavy metal take-up. Since the equations are *"non-linear partial differential equations"* analytical solutions are very difficult, hence numerical methods have been used to solve them. The various steps for the numerical solution are given below.

Figure 1: Steps for Solving the Controlling Equations



All the equations are solved using MATLAB (R2016a) and the code is written based on the above steps.

Initial and Boundary Conditions

The Controlling equation for flux is first solved using the initial and boundary conditions, which can be taken as: "

$$\frac{\partial}{\partial \xi}\left(\frac{\partial l}{\partial \xi}\right) = 0\,, \qquad at\ t = 0$$

$$l(0,t) = 0\,m, \qquad at\ floor\ \ level$$

$$l(L,t) = 0.30m\ at\ floor\ surface"$$

After solving the Controlling equation for flux, then we need to calibrate the collective water take-up by using the *"transpiration rate"*. Then the *"Controlling equation for heavy metal passage"* is solved by using the following conditions.

$$\lambda_w(\xi, 0) = 0\ \mu g\ /\ ml\ initillay\ at\ t = 0$$

$$\lambda_w(\xi, t) = 0\ \mu g/\ ml\ initillay\ at\ groundwater\ level$$

$$\lambda_w(L, t) = 5000\ \mu g\ per\ ml\ at\ ground\ surface"$$

The *"model parameters"* are given in *"Table 1"*, the "*plant parameters"* are given in *"Table 2"*, the *"soil parameters"* are given in *"Table 3"* and the *"simulation/take-up parameters"* are given in *"Table 4"*. *The model parameters* are taken from *"Rao et. al.* and *Verma et. al. [12, 13]. The soil and plant parameters* are taken from *A. Badarudeen et. al,* and *N.F.Y. Tamet. al. [14, 15]".*

Table 1. Model Parameters

Parameter	Symbol	Value	Unit
Tallness of unsaturated zone	L	300	cm
Space period	Δz	10	cm
Time period	Δt	1	h
Empirical contour factor	n	1.5	cm^{-1}
Empirical contour factor	m	1	—
Empirical contour factor	β	0.000534	—
Pressure head dependent reduction factor	$\beta(l)$	1	

Table 2. Plant Parameters

Parameter	Symbol	MG1	MG2	Unit
Plant maturity period	DTM	30	45	days
Water demand	W	80	90	cm
Extreme rooting depth	ζ_{max}	100	200	cm
Total Cobalt collected in plant	λ_w	100	26	μg / kg
Cobalt buildup in the soil (dry weight basis)	λ_s	52	52	μg / kg

Table 3. Soil Parameters

Parameter	Symbol	Value	Unit
Saturated wetness value	ϕ_s	1.5	–
Remnant wetness value	ϕ_r	0.37	–
Saturated waterpower conductivity	k_s	2.5	cm / h
Bulk density of soil	δ	1.08	g/cm^3
Soil pH factor	pH	5.5	–
Dispersion coefficient	ω	0.008	cm
Diffusion coefficient	τ	0.002	cm^2/s
Barrier coefficient	κ_d	1.4	–

Table 4. The Simulation/Take-up Parameters

Parameter	Symbol	Unit	MG1	MG2
Transpiration rate	$T_p(t)$	cm/ h	0.85	0.65
Extreme take-up rate	Ψ_{max}	g /ml/ h	0.00000418	0.000002
Michaelis Menton constant	κ_m	g / ml	0.0000395	0.00003

The various plots obtained from the simulation are shown below. The simulation/take-up parameters are found by the methods discussed here. To find the transpiration rate, the model is run for a number of times till the collective water take-up matches with the water demand given in *Table 2*. Also the values of Ψ_{max} and κ_m are found by running the model for a number of times till the computed collective metal take-up by the plant root matches with the restrained total Cobalt in the plant root given in *Table 2*. While simulating the model we could find the value of Ψ_{max} is more significant than K_m. So we first made κ_m as constant (while fixing it as a constant care is taken to fix its value always less than the value of λ_w).

Figure 2. Transport Behaviour of Cobalt in MG1

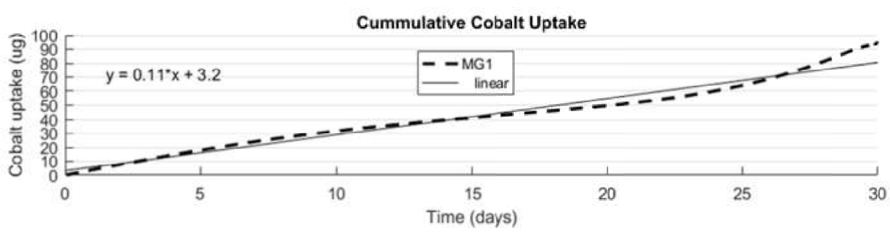
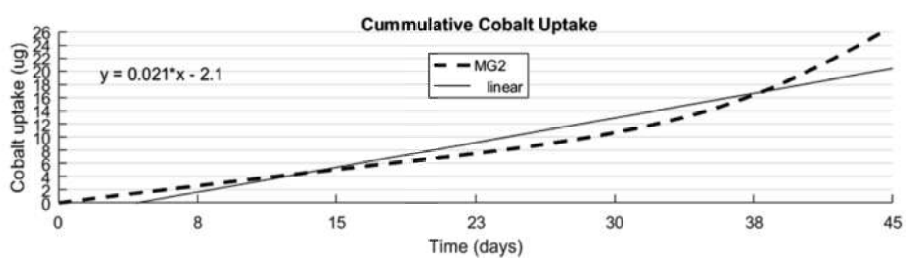


Figure 3. Transport Behaviour of Cobalt in MG2



Here MG1 and MG2 are Derris trifoliate and Acanthus ilicifolius respectively. The dashed curve represents the cumulative Cobalt uptake. The solid line is the suitable linear curve fitting graphs. In the soil sample the amount of Cobalt was 52. $\mu g/kg$. The amount of Cobalt in MG1 is 100$\mu g/kg$ and in the case of MG2 is 26. The variations of transport behaviour of Cobalt in MG1 and MG2 are clear from the plots. In MG1 traces of more amount of Cobalt is found and the corresponding transport behaviour of Cobalt is different from that of MG2.

Conclusion

The controlling equations (Equations 1 and 7) are unraveled to simulate the behavior of cobalt take-up in Common Derris (Derris trifoliate) and Sea Holly (Acanthus ilicifolius). This model is built on realistic filed conditions and can be used to forecast the behavior of cobalt take-up in different plants. The cobalt take-up plot helps to understand the heavy metal take-up rate of the concerned plant. Hence, this model is helpful to demonstrate and predict which plant is to be grown in a specific heavy metal contaminated site to extract that particular heavy metal and thus reducing the heavy metal contamination of the associated soil. The model is helpful to identify bio-indicators among various plants and thereby mitigation of heavy metal contamination of the environment. The model may also be helpful to predict the long term environmental pollution primarily due to heavy metal accumulation.

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