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Mechanistic Approach for Modelling Soils and Aquifers Salinization Risks – A Literature Review in Semi-arid Regions

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Abstract

Semi-arid regions face problems of soils and aquifers salinization. The studying approaches of salinization risks are based on the modeling of water movement and salt transfer. The closest approach to reality is the deterministic-mechanistic approach. In this paper, cases of salinization of soils and aquifers are presented to show the magnitude of the phenomenon on a global scale. Then, the mechanistic deterministic approach is detailed by the development of mathematical equations and by the presentation of its advantages and limitations.

Keywords

Soil, Aquifer, Salinization, Modelling, Literature Review

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1. Introduction

Arid and semi-arid regions are facing the risk of soils and aquifers salinization, in particular in irrigated areas where the water used is saline. This salinization has a harmful effect on the main physical properties of the soil, which is a potential danger for the crops. This is why several studies have dealt with the action of salts in the ([1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13]). In the long term, the risk of salinization may be more prevalent especially with the overexploitation of groundwater resources and may affect the aquifer with the deeper penetration of salts due to water infiltration by irrigation or precipitation ([14], [15], [16]). This phenomenon has been observed by several researchers in the world ([17], [18], [19], [20], [21], [22], [23], [24]) and in Tunisie ([25], [14], [26], [27], [28]) in particular, in Central Tunisia [29], where salinization of soils and aquifers is fairly widespread. In order to evaluate soils and aquifers salinization, modeling can be a useful tool ([17], [18], [20], [23]). It allows a better understanding of the transport process in the vadose zone. The deterministic mechanistic approach appear to the most reliable ([30], [31], [32], [33]). In this paper, a state of the art of the problems of soils and aquifers salinization is presented. In a second part, the mechanist approach for modelling water and salts transfer process is developed.

2. Field Observations of Groundwater Contamination by Salts in the World

Water infiltration through the vadose zone will increase salts movement in depth. The infiltration of surface water supplies an important part of the underground water tables. As a result, the concentration of salts in the water table can be high. According to [4], the use of high salinity waters for irrigation brings the salts back to the surface, causing them to accumulate during the dry season and then re-entering the subsoil with rainwater, hence degradation of aquifers quality

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and consequently the risks of soil salinization. [15] and [16] also discuss the impact and risk on the water table caused by this transfer of salts, especially in irrigated areas with poor quality water. The effect of degradation of groundwater quality is exacerbated by overexploitation of the aquifer for intensive irrigation. This phenomenon was observed in the Al-Wafra plain in Kuwait by [19] and [20] in a citrus-growing plain in Cyprus where it showed that the salts brought back by agricultural practices are found by deep percolation in groundwater. It used a method to directly simulate the recycling of solutes from the soil to the aquifer. This method is based on the advection-dispersion equation and the applied balance equations for the overall solute concentration. [18] quantified the flows of water and salts that affect the groundwater of a plot in the Tragowel Plain of Australia characterized by intensive irrigation, based on a MKSE reservoir model. The carried out simulations allowed them to quantify the water flows that infiltrate the water table and their quality. [22] revealed problems of contamination of the aquifer by nitrates and salts in an irrigated perimeter of the Bardenas region in Spain following intensive irrigation and overexploitation of groundwater resources. They used a hydrogeological model (BAS-A) to map the best scenarios for irrigation management in this perimeter. [24] analyzed the risk of salinization of the aquifer in a southeastern plain of Queensland (Australia) following intensive irrigation and overexploitation of groundwater resources. They used airborne electromagnetic measurements to establish three-dimensional maps of the salt distribution, which allowed them to predict the potential movement of salts. [17] coupled a hydrogeological model that predicts underground flows and an agronomic model that quantifies the crop response to irrigation with brackish water in a plot in southern Australia and has established correlation relationships between the crops yield and the quantity of salts observed in the groundwater, which allowed them to design an appropriate scenarios management of irrigation with less risk of soils and aquifers salinization. In Tunisia, according to [14], many farmers in the Mornag plain have noticed degradation in the water quality of their wells resulting from the use of salt water from the Mejerda river. According to [26], the salts of irrigation water accumulated in the Korba perimeter for several years in the unsaturated zone of the subsoil were leached in a particularly rainy season (1995-1996) leading to salinization of the water table.

In several cases, aquifer pollution by salts is the result of a combination of several factors driven by intensive agricultural activity and overexploitation of water resources. [20] associates the marine intrusion with problems of recycling solutes to the groundwater. The same approach was used by [23] who studied the phenomenon of marine intrusion in a coastal aquifer in the Therace region of Greece. The intrusion is aggravated by the intensive pumping of water in the absence of an adequate mode of water management in the region. They applied the PHREEQC model successfully for the simulation of the system determined the extension of the saline front that extends to about 6 km from the coast. According to [21], the only water resources available in the Sidi Moussa region of Morocco correspond to groundwater. This region is characterized by a strong market gardening activity based on irrigation by these waters. The overexploitation of the latter has caused a reduction in the piezometric level, a reversal of the direction of underground flow and problems of marine intrusion into the coastal aquifer, overexploited especially during dry seasons. This has led to pollution of the water table by an increase in salinity.

3. Mechanistic Approach for Modelling Water Flow and Salts Transport Through the Vadose zone

The complex interactions in the unsaturated zone between the water flow, salinity, crops and recycling possibilities as a function of geo-hydrological conditions and drainage conditions can no longer be appreciated by simple concepts and analytical solutions and FAO guidelines [33]. The solutions to these problems require the use of numerical models to solve both the transport phenomena of water and solutes. Mechanistic deterministic models assume that the system behaves in such a way that the appearance of a series of event data always leads to the same result ([34] and [35]). They take into account the physical mechanisms currently known and understood. They are essentially research tools to test hypotheses or better understand the processes involved.

Equations

Darcy's law, coupled with the continuity equation, yields the Richards equation which simulates the transfer of water into the soil [30]. The mathematical expression is as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial h}{\partial z}+1\right)\right] \quad (1)$$

where h is the water pressure head [L], θ is the volumetric water content [L3L-3], K is the unsaturated hydraulic conductivity [LT-1], t is the time and z is the spatial coordinate. The analytical resolution of this equation is possible with simplifying assumptions in steady [36]. In general, a numerical integration is necessary.

The transport of solutes is more complex. [37] have shown that the transport of salts results from the superposition of an advective flux (a piston effect linked to the movement of the water), the mechanical dispersion effect (This phenomenon is related to the movement in the porosity that leads to a stirring of the particles) and to the molecular diffusion (the agitation of the particles tends to homogenize the solute concertation in a certain volume of soil). With the same assumptions as for the Richards equation, the transport of solutes results in the equation of advection-dispersion [35]:

$$\frac{\partial \rho.S}{\partial t}+\frac{\partial \theta.C}{\partial t}=\frac{\partial}{\partial z}\left\{\theta.D.\frac{\partial C}{\partial z}\right\}-q\frac{\partial C}{\partial z} \quad (2)$$

where z is the spatial coordinate, C and S are solute concentrations in the liquid [ML^{-3}] and solid [MM^{-1}] phases, respectively, q is the volumetric flux density [LT^{-1}], D is the dispersion coefficient [L^2T^{-1}] and ρ is the bulk soil density [ML^{-3}].

Hydraulic Properties

According to [38] knowledge of the hydraulic properties of soils is essential for understanding and quantifying the physical and chemical processes involved in the movement of water and the transport of solutes in the unsaturated zone of the soil. The relationships that describe them are highly non-linear and very varied from one layer of soil to another. Several analytical models have been developed to describe these relationships in a simpler way than reality. The most commonly used equations are those of van Genuchten and Mualem, which describe the retention curve and the hydraulic conductivity curve. The relationship expresses the variations in the intensity of the capillary forces as a function of the water content. The expression of the model of van Genuchten and Mualem for the retention curve is:

$$\theta(h)=\begin{cases}\theta_r+\dfrac{\theta_s-\theta_r}{1+\left|\alpha h^n\right|^m} & h<0\\ \theta_s & h\geq 0\end{cases} \quad \text{where } m=1-\frac{1}{n} \quad n>1 \quad (3)$$

where θ_r is the residual water content [$L^{-3}L^{-3}$], θ_s is the saturated water content [$L^{-3}L^{-3}$], h is the water pressure head [L], α [L^{-1}] and n [-] are shape parameters.

The MVG equation (Mualem and van Genuchten, 1980) to describe the hydraulic conductivity curve is:

$$K(h)=\begin{cases}K_s r S_e^{1/2}[1-(1-S_e^{1/m})^m]? & h<0\\ K_s & h\geq 0\end{cases} \quad (4)$$

where: $m=1-\frac{1}{n}$ $n>1$ et $S_e=\frac{\theta-\theta_r}{\theta_s-\theta_r}$, Ks is the saturated hydraulic conductivity [LT^{-1}], Se is the effective saturation [-], and r is the pore connectivity parameter [-], equal to 0.5 [39].

The most sensitive parameter in the water flow is n, followed by α and Ks [40]. [41] showed that the calculation of soil water fluxes is more sensitive to changes in parameters n and. The parameters of the Mualem-van Genuchten equations are determined by adjusting some experimental measurements of the retention curve or the hydraulic conductivity curve on the theoretical curves of the models. The RETC software [42] performs this adjustment ([38], [43]). Several methods exist for measuring these relationships in the laboratory and field ([44], [43]). All these methods are tedious, time-consuming and not precise because of the spatial heterogeneity of these properties in the soil layers ([45], [46]), the disturbance of materials and the delicacy of the measuring devices ([44], [38]).

Boundary conditions

Regardless of the type of approach, the initial and boundary conditions have to be defined once the equations have been set. This presupposes knowledge of the state of the system at a given moment and the possibility of defining the limits of this system. In the case of saline soils, simplistic boundary conditions are preferred, for example, based on the presence of a water table at the base of the profile and the absence of surface runoff ([30], [32]).

4. Advantages and Disadvantages of the Mechanistic Approach

Advantages

The numerical models used in the simulation of water flow and solute transport simulate the movement of water in the soil despite the heterogeneity of the flow due mainly to the variation of the hydraulic conductivity between the layers of the soil ([32], [33]). Furthermore, according to [47] and [31] numerical models can be coupled with in situ sensors (soil moisture, evapotranspiration ...) for their calibrations. They also offer the possibility to vary the parameters of the models and to see the results makes it possible to better understand the phenomena of transfers. The simulation of different scenarios represents an alternative solution for the management of water resources and offers the possibility of identifying the best management strategy. Finally, the large number of existing models facilitates the appropriate choice for each problem to be solved [33].

Disadvantages

Hypothesis of one-dimensional flow is acceptable in the case of flat and horizontal areas receiving rainwater and submersion irrigation. The movements of the water are then essentially vertical. However, in the presence of a slope, account must be taken of lateral transfers [34]. In addition, according to [47] and [31] the hypothesis of a moisture and a constant flux over time for the upper layer, which is very far from reality, since most of the saline soils are under alternating periods of drying and periods of wetting whether by rain or by irrigation. Unlike upper-boundary conditions, lower-boundary conditions have not progressed equally well and are still poorly developed [47]. According to [33] numerical models contain a large number of parameters, some of which are difficult to obtain, which does not allow an adequate adjustment with the actual data and offers multiple calibration possibilities.

Other phenomena are neglected:

The isothermal conditions are assumed: the irrigation water has a temperature equal to that of the soil and the whole of the profile has the same temperature. In reality, temperature differences well above 15 °C can be observed between day and night, especially in the first 25 cm of the soil [48]. These variations lead to a change in the hydrodynamic characteristics of the soil.

The swelling of certain clay soils, responsible for the variation of the poral space and the presence of cylindrical macropores or vertical cracks which favor deep percolation [34].

The presence of air in the matrix of the soil which blocks the flow of water and the hysteresis phenomena associated with the humectation-dissection alternations [31].

According to [35], global water transfer models, which do not take into account the existence of a still water phase, are poorly adapted to clay soils, unlike two-phase models. The spatial variability of the hydrodynamic properties is not represented either [38]. The soil is cut into horizontal fractions within which the hydrodynamic coefficients remain invariant [47].

5. Conclusion

The problem of soils and aquifers salinization due to irrigation with saline water is widespread issue in the world. It is aggravated by overexploitation of groundwater or associated with other phenomena such as marine intrusion in coastal areas. However, the study approaches adopted are either pedological or agronomic approaches addressing salinization problems in surface layers, or hydrological approaches studying the aquifers. Some authors have used balance equations (for salts or have coupled hydrological and agronomic models to quantify these transfers. However, the results obtained can not be precise because they do not take into account the entire vadose zone, an invetible compartment in the vertical movement of the salts. It is for this reason that a local modeling of the dynamics of water and salts at depth integrating the zones below the topsoil is interesting to consider. However, the difficulty lays both in obtaining the parameters and the input variables of the models and also in their validation. This is why a proper characterization of the soil is a prerequisite for the success of the simulation, especially in defining the hydrodynamic parameters that play a primordial role in the movement of water

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