論文の内容の要旨

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論文題目　**Effects of shallow groundwater fluctuations on soil surface salt accumulation in arid and semi-arid areas**

（乾燥地・半乾燥地における浅層地下水振動が塩類集積に及ぼす影響）

Shallow groundwater tables and associated salinity problems have become dominant features in agricultural areas around the world. This is especially so in arid and semi-arid regions where rising water tables and associated soil salinization are an increasing agricultural and environmental threat. Groundwater has the ability to mobilize and transport soluble salts when it moves through the soil profile. Once the water table reaches a critical depth below the ground surface, evaporation of this water can occur via capillary rise, transporting soluble salts with it to the soil surface. Over time, this leads to an accumulation of salts at soil surface and subsequent land degradation as well as losses in production. Whilst there have been several studies on ground water associated salinity, the movement of groundwater in particular with respect to recharge events and its impact on soil surface salt accumulation phenomenon still remains to be clarified. “How can we explain shallow water table behavior in response to added water events?”, “Can we solve the salt accumulation problem by controlling the groundwater level?” are the two main questions to be addressed in this study. Responses to these questions will lead to get more awareness on soil surface salt accumulation phenomenon dominated by shallow water table fluctuations. Ultimately, this will help to overcome the

substantial knowledge gap concerning this issue and to suggest appropriate management practices which may save costly reclamation efforts and further land losses.

The general objective of this research is to elucidate soil surface salt accumulation phenomenon induced by saline shallow groundwater fluctuations under arid and semi-arid climate. Specifically, it aims at (i) assessing and analyzing short term groundwater fluctuations in salt affected areas in Tunisia (case study Metouia Oasis), (ii) investigating and modeling shallow groundwater responses to recharge events under controlled conditions at laboratory scale and (iii) elucidating the salt accumulation phenomenon under shallow groundwater conditions. To achieve these objectives a methodology based on field investigations in salt affected areas in Tunisia, laboratory experiments and modeling investigations concerning shallow groundwater fluctuations and salt accumulation, was followed.

Field investigations were conducted in two salt affected areas in Tunisia, namely, Dhraa Tamar (Middle West) and Metouia Oasis (South East). These investigations showed that in such arid and semi-arid environments with saline shallow groundwater tables, the capillary rise of water and salts from the groundwater to the soil surface seems to be a major contributor to salt accumulation within soil profile. Metouia Oasis was subject to a high measurement frequency based assessment (30 minutes interval) of shallow groundwater fluctuation from March to November 2009. The resulted hydrograph showed a dynamic groundwater level fluctuation which was the consequence of climatic conditions as well as several hydrological processes taking place in the observation site and in the upstream areas. Interestingly, water table has been shown to rise during rainless periods owing to lateral subsurface groundwater inflow from irrigated upstream areas in the Oasis. At seasonal basis, groundwater was characterized by a declining phase during spring and summer seasons followed by a rising phase starting from mid-October corresponding to the starting of fall and winter seasons. At daily basis, the hourly changes in water table levels showed an evident diurnal variation throughout the day characterized by a downward trend during daytime induced by the high evaporative demand and an upward trend during night time when less evapotranspiration is occurring. Further, the hydrograph was characterized by several rapid water table rises following recharge events followed by extended periods of water table declines. Such behavior was attributed to the reverse Wieringermeer effect (RWE) which reflects high and rapid water table rise due to small water input.

To get better understanding of the groundwater behavior at the site, we needed to know more about shallow groundwater response to recharge events, specifically in relation to RWE. Hence, experimental and modeling investigations of shallow water table fluctuations inside sandy (Toyoura sand) and clayey (Chiba light clay) soil columns in response to surface and sub-surface recharge events have been carried out. Experimental results showed that small application of water could raise the shallow water table level more than 100 times in depth in the case of Toyoura sand and more than 50 times in the case of Chiba LiC, reflecting a reverse Wieringermeer effect response type of groundwater. This response was dependent on the way of water supply. Hence, in the case of surface recharge the water table response was rapid and large while it was gradual and less pronounced when sub-surface recharge was applied. Nevertheless, the RWE was observed for both surface and sub-surface recharge events. This phenomenon occurs when the water table depth is less or equal to the capillary fringe height. Further, water table rise was associated with a prompt change of pressure head values which exhibited instantaneous fluctuations of centimeters due to the addition of millimeters of water. The recharge volumes leading to such disproportionate water table rise were successfully estimated using a simple analytical model based on the moisture retention curve of the soil and considering the hysteresis effect on soil water dynamics within the capillary fringe zone. Simulations based on this model suggested that the soil water movement inside the soil column was mainly upward from the lower part being wetting up after water supply and that the shallow groundwater had a great effect on the vertical distribution of soil water content and soil water potential. Simulations based on non hysteretic models failed to predict the recharge volumes by either highly overestimating or underestimating the measured data.

To fully understand the effects of saline shallow groundwater on soil salt accumulation as observed at field scale we carried out two laboratory experiments simulating soil salinization under fluctuating and stable saline shallow water tables. Water and salt dynamics as well as evaporation rate were monitored and analyzed for both conditions. The analysis of salt profiles observed in soil columns under controlled conditions showed an enhancement of the build-up of soluble salts in soil columns where groundwater was fluctuating compared to those with constant water table. This suggests that soil salinization can be rapid in areas with fluctuating saline shallow groundwater and can not be accurately predicted if such behavior of groundwater was not considered in the modeling process.

Based on these experimental results, the numerical model HYDRUS-1D was first validated and then used to carry out various numerical scenarios. The results showed that groundwater fluctuation caused more salt to accumulate at soil surface compared to that caused by a stable groundwater. By reducing the evaporation rate through a decrease of the temperature intercepted at soil surface, a significant reduction of salt concentration at soil surface was observed. Moreover, frequent irrigations with small quantities were effective to reduce soil surface salt accumulation induced by saline shallow groundwater.

Furthermore, numerical simulations using the model HYDRUS-1D were carried out in order to investigate the effect of saline shallow groundwater fluctuations on soil surface salt accumulation in Metouia Oasis based on shallow groundwater behavior and quality as well as on climatic conditions prevailing in the Oasis. Three cases simulating field observations were considered: stable water tables at depths 60 cm and 115.5 cm and fluctuating water table between these two depths. The results showed that the fluctuating groundwater has the ability to mobilize and transport soluble salts rapidly when it moves through the soil profile compared to a stable water table. Moreover, the increase of salt concentration toward soil surface was progressive in the case of scenarios with constant water table and rapid and variable in the case of fluctuating water table. These results can be explained by differences in transport mechanisms between the cases with stable water table and the one with fluctuating water table. In the former the salt is transported toward soil surface mainly by capillary rise of saline groundwater and secondary by molecular diffusion. In the case of fluctuating water table a piston like flow of groundwater is the main process inducing rapid and high salt movement in the soil profile. This suggests that in order to solve the soil salinization problem associated with saline shallow groundwater, the water table must be stabilized at harmless levels and the groundwater fluctuation has to be dampened and retarded by control of groundwater recharge.